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Exploring the drivers and effects of biodiversity change in the coast of Cantabria and Santander Bay (Southern Gulf of Biscay)

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Abstract

Coastal zones are complex socio-ecological systems that present significant challenges for sustainable management. In this study, a bow-tie approach was applied to the coast of Cantabria to analyse the connections between drivers of change, biodiversity loss, and socio-economic consequences. The two most prominent drivers identified by stakeholders were large-scale tourism and harbour infrastructure development. These were associated with biodiversity impacts, including species and habitat loss, and the spread of non-native invasive species facilitated by human activities. Stakeholders and scientists identified multiple consequences of biodiversity change across ecological, social, economic, and governance dimensions. Based on the bow-tie analysis, a set of prevention and mitigation measures was proposed to enhance governance responses and reduce biodiversity-related damage in the study area.

Keywords: *bow-tie analysis, coastal ecosystems, estuaries, biodiversity change, tourism, harbour infrastructures.*

1. Introduction

Coastal ecosystems have long attracted human settlement due to their high biodiversity, and their capacity to support well-being and economic growth. These areas represent a valuable source of ecosystem goods and services, including provisioning, regulating, and cultural services. It is therefore no coincidence that a large portion of the population is concentrated along the coast, accompanied by significant urban and industrial development. However, this development also generates pressures that affect ecosystems and their biodiversity, and consequently, human societies.

In recent decades, large-scale tourism has emerged as a phenomenon that can pose a serious threat to biodiversity, especially in areas with high tourist demand. The temperate coastal regions of Europe, such as the Gulf of Biscay, are among these tourism hotspots. High population densities, even if seasonal, can trigger biodiversity changes, ranging from degradation of beaches and dune habitats to the spread of non-native invasive species. Tourism-driven development is often accompanied by the expansion of urban areas, recreational activities, and transport infrastructure, which broadens the spectrum of pressures, impacts, and consequences for ecosystems and local human communities.

The complex network of interactions between humans and nature present significant challenges for the sustainable management and planning of coastal socio-ecological systems. For this reason, the objective addressed in this study is to apply the bow-tie methodology to analyse the effects of anthropogenic activities on estuarine and coastal biodiversity in the southern Gulf of Biscay and their socio-economic consequences. Based on this analysis, prevention and control measures are proposed to improve governance responses to mitigate the impacts of anthropogenic activities and the consequences of biodiversity change.

2. Methodology

2.1. Study area

This study was carried out in the coast of Cantabria, located in the northern Iberian Peninsula (Figure 1). This region is characterized by a high ecological and social value. Within a relatively small stretch coastline (284 km long), a wide variety of habitats is present. Sandy beaches and rocky cliffs form a complex mosaic, whose continuity is interrupted by seven small estuaries where freshwater reach the sea (i.e., estuaries of San Martín de la Arena, Mogro, Santander, Ajo, Joyel, Victoria and Santoña). The ecological value of this coast is recognized at regional, national and European scales. In particular, a significant portion of the coastline in the Cantabria region is protected under the European Natura 2000 network, including the Special Areas of Conservation (SACs) “Dunas de Liencres y Estuario del Pas”, “Dunas del Puntal y Estuario del Miera”, “Costa Central y Ría de Ajo”, and “Marismas de Santoña, Victoria y Joyel”.

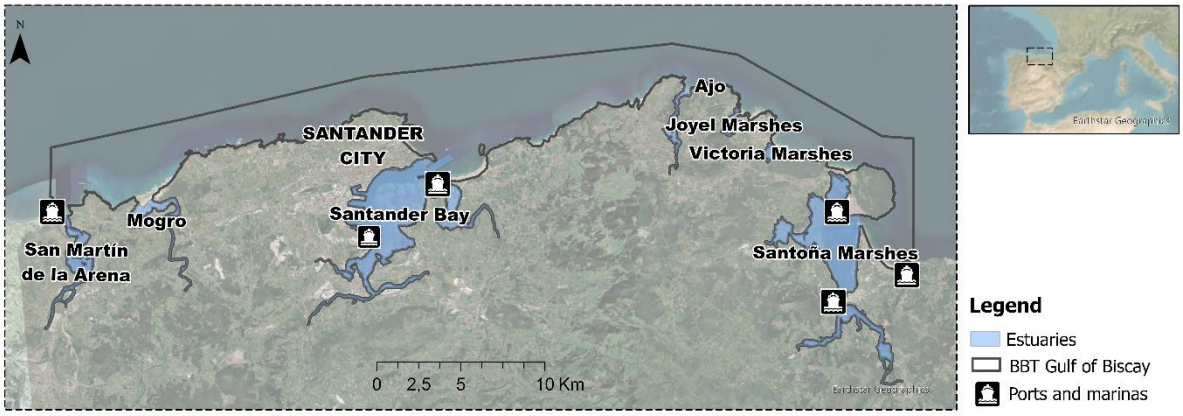

Figure 1. Location of the coast of Cantabria in northern Spain (Southern Gulf of Biscay).

The Santander Bay, protected under the previous mentioned SAC “Dunas del Puntal y Estuario del Miera”, is one of the most important and largest estuaries in the region. It is located in a highly populated area (Santander city), whose development and well-being are highly dependent of the goods and services provided by the bay. The bay has been traditionally functioned as a natural harbour and currently hosts one of the major commercial ports within the Spanish national system (Medina et al., 2007). Since 1837, significant dredging and land reclamation activities have shaped its history. In addition to serving as an entrance, navigation, and anchorage area, the port waters are primarily dedicated to commercial and fishing activities. Urban development and various industrial operations have posed significant threats to Santander Bay. Additionally, fishing and shellfishing also take place in the bay. Within the intertidal zone, professional fishermen harvest various species (e.g., bivalves of the genus *Ruditapes*) using traditional techniques (Juanes et al., 2012).

2.2. Bow-tie analysis

A bow-tie risk analysis framework was applied to coastal and estuarine ecosystems in the study area (Franco et al., 2025). Through this approach, drivers of change, events of biodiversity change and socio-economic consequences relevant to the study area were identified, and connections between them were established. The bow-tie was developed by combining stakeholder consultation and expert judgment. Key pressures and consequences of biodiversity change were selected based on stakeholder input gathered through the MARBEFES project. Building on this, the bow-tie was completed from a scientific perspective. We used standardised vocabulary and classification to identify activities, pressures, central events, impacts and consequences.

3. Results of bow-tie analysis

The bow-tie framework applied to the coast of Cantabria captures the connections between drivers of change, biodiversity loss and socio-economic consequences relevant to the area and for stakeholders (Figure 1). It also identifies the potential opportunities for managing both the causes and the consequences of biodiversity change.

3.1. Drivers of biodiversity change

The primary drivers of change related to biodiversity loss in the coast of Cantabria have been identified through consultations with key stakeholders in the MARBEFES project, including national, regional and municipal authorities, managers of protected areas, fisheries associations, port authorities, industry and private sector representatives, researchers, and subject-matter experts and NGOs. They identified two main drivers of biodiversity change in the study area: large-scale tourism and harbour infrastructure development.

Tourism is an increasing driver of change that affect to all the coastal area in the region of Cantabria. The ecological value, beauty and recreative potential of this coastline, added to the soft climatic conditions, determine an increase trend in national and international tourism, especially during the summer season. Touristic and recreational activities are mainly related with beach swimming, water sports, motor boating, fishing and sailing (Zabala et al., 1999). Urban development, tourism infrastructure, and overcrowding of natural areas are the main sources of pressure on biodiversity. These activities contribute to increased pollution, habitat and species disturbance, and the illegal extraction of natural resources.

Harbour infrastructure development refers to shipping marinas and the commercial port located in the Santander Bay. The port of Santander has also many regular shipping lines. The shipping, and then harbour infrastructures, is expected to increase in a future scenario of more intense large-scale tourism. In the last decades the Santander port has increased its physical capacity, up to covering 3 km^2 of land surface, 34.43 km^2 of water surface and about 7 km of berthing line nowadays (Juanes et al., 2020). Significant land claimed areas have been historically gained to the estuary, with main docks located on the west side of the bay. Additionally, the estuarine mouth and channel to the docks are periodically dredged to allow navigation. These activities associated with harbour infrastructures give rise to multiple pressures on biodiversity, mainly pollution, habitat loss and alteration, and input of non-native species.

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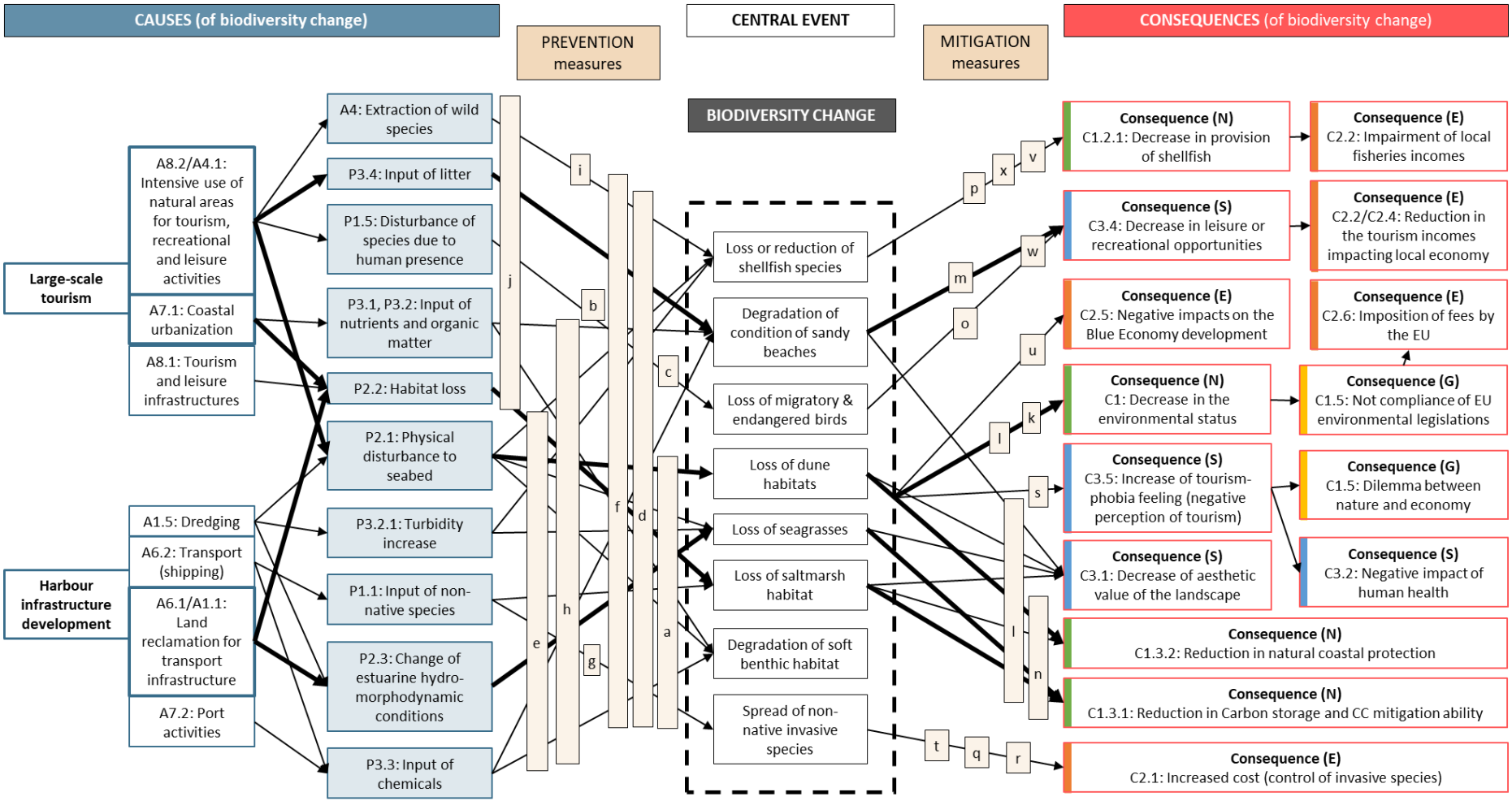

Figure 2. Bow-tie diagram showing the eight major biodiversity change events identified in the coast of Cantabria, driven by large-scale tourism and harbour infrastructure development, and their corresponding consequences across nature (N), society (S), economy (E) and governance (G). Codes of prevention and mitigation measures are listed in Table 1. Codes of activities (A), pressures (P) and consequences (C) follow the standardised vocabulary and classification indicated in Franco et al. (2025).

3.2. Events of biodiversity change

Both drivers of change, tourism and harbour infrastructures, were related with eight specific events of biodiversity change: (1) Loss or reduction of shellfish species; (2) Degradation of condition of sandy beaches; (3) Loss of migratory and endangered birds; (4) Loss of dune habitats; (5) Loss of seagrasses; (6) Loss of saltmarsh habitats; (7) Degradation of soft benthic habitats; (8) Spread of non-native invasive species (Figure 2).

These eight central events in the bow-tie highlight different patterns of biodiversity loss. Habitat changes, together with the decline of ecologically and commercially important species, are closely linked to human activities, including the intensive use of natural areas for tourism and recreational purposes, coastal urbanization, and port-related activities such as dredging, shipping, and land reclamation. In addition, the increasing spread of non-indigenous species has intensified competition with native species, further contributing to their decline. This case serves as an example of a close interaction between human and nature in coastal areas, where ecosystems and their natural resources must be properly managed to ensures long-term sustainability.

Loss or reduction of shellfish species

The growing tourism in the region in recent years, which is expected to continue in the future, has led to an increase in recreational shellfish harvesting and illegal poaching (Activity A4 in Figure 2). Several species targeted by these activities are especially vulnerable, as they have small population sizes, likely due to the combined effects of various environmental and human-related factors. One such species is the grooved carpet shell (*Ruditapes decussatus*), which has historically held high economic and cultural value for local communities, particularly around the Santander Bay and the Santoña Marshes. Since 2005, a gradual and significant decline in the number of individuals of this species has been observed in both estuaries. Nevertheless, harvesting pressure and demand for consumption remain high. Other species that are highly valued by both legal and illegal shellfish gatherers include goose barnacles (*Pollicipes pollicipes*), periwinkles (*Littorina* spp.), razor clams (*Ensis* spp.) and sea urchins (*Paracentrotus lividus*), among others.

In addition to direct harvesting pressure, there are indirect impacts resulting from habitat degradation affecting shellfish species. Many of these species inhabit estuarine sediments, where both touristic and port activities exert direct pressure, physically disturbing soft-bottom habitats through trampling, boat anchoring, and other mechanical actions (Pressure P2.1 in Figure 2). Furthermore, dredging of estuarine channels to facilitate port traffic (e.g., periodic dredges in the Santander Bay) increases water turbidity in the estuary (Pressure P3.2.1 in Figure 2), which can negatively affect filter-feeding organisms such as clams (e.g., *Ruditapes decussatus*).

Degradation of condition of sandy beaches

Beaches are among the main tourist attractions in the region for recreational and leisure activities. 38 beaches are identified within the study area, ranging from relatively large sand systems (111,83 ha) to small ones (0,09 ha). The number of beach users has steadily increased in recent years, which in turn leads to greater litter accumulation on the sand (Pressure P3.4 in Figure 2). In addition to beach litter pollution, bathing waters are also

affected by chemical and organic contamination resulting from urban development in nearby areas, as well as from port activities (Pressures P3.1, P3.2 and P3.3 in Figure 2).

Loss of endangered species and migratory birds

The main pathway for migratory birds traveling from the Arctic and Northern Europe to Southern Africa is the East Atlantic Flyway, which passes through the north of the Iberian Peninsula. In this area, the Santoña Marshes is the most important wetland for waterbirds, with the greatest number of species (up to 86) and individuals (greater than 20,000), according to the Information sheet of Ramsar Wetland (RIS) for the Marismas de Santoña (1999). Migratory birds use this wetland to rest, breed, feed, and overwinter.

The large-scale tourism and the increase in outdoor recreational activities generates an intensive and widespread use of natural coastal areas, including cliffs and wetlands (Pressure P1.5 in Figure 2), which are critical habitats for migratory and endangered waterbirds. These activities disrupt foraging and breeding behaviours of birds and may alter their migration patterns. Coastal recreational activities that potentially affect birds are walking, wildlife observation, boating, kayaking, and jet skiing, among others. The degree of human disturbance of birds is determined by noise level and the number of people, but impacts also depends on the species involved, the timing of disturbance events (i.e., seasonal factors, such as breeding season and migration periods), and the habitat (i.e., location factors, such as migration staging sites).

In the Santoña Marshes, a direct impact of anthropogenic disturbance on the endangered Eurasian spoonbill (*Platalea leucordia*) was documented by Navedo et al. (2009). Their study found that human noise and recreation kayaking disturbed around 50% of the spoonbills stopping in the marshes during migration, potentially threatening the migratory success of 10% of the Atlantic population of this species.

Loss of sand dune habitats

The dunes in the study area covers a total of 129,73 ha across 15 dune systems, which include primary (dominated by *Ammophila arenaria* and *Elymus farctus*), secondary and tertiary dunes. The bigger and most developed dune systems are the Liencres dunes, located in the mouth of the Mogro estuary, and the Somo dunes, located in the mouth of the Santander Bay. As previously mentioned, the growing number of beach users also leads to increased trampling pressure on dune habitats, affecting both vegetated and non-vegetated dunes (Pressure P2.1 in Figure 2). This pressure contributes to dune erosion and the loss of vegetation cover, which in turn accelerates the erosion process. The absence of vegetation makes dunes more vulnerable to extreme erosion events caused by waves and wind, and significantly hinders their recovery, making it slower and more difficult.

Loss of seagrasses

The study area host seagrass meadows of *Zostera noltii* and *Zostera marina*, the latter being restricted to Santander Bay and Santoña Marshes. They cover soft-bottoms of the low tidal and shallow subtidal zones within estuaries. A decline in seagrasses was reported up to the early 2000s, followed by a recovery trend observed across the Cantabria coast up to now (Calleja et al., 2017).

While seagrass meadows are currently at a peak of spatial expansion at a regional scale, they remain vulnerable to localized anthropogenic pressures that may affect specific meadows at a local scale (Ondiviela et al., 2015). Seagrasses in the study area are threatened by a range of human-caused pressures, including physical damage and habitat disturbance (Pressures P2.1 and P2.3 in Figure 2), as well as changes in water quality and light availability caused by turbidity (Pressure 3.2.1 in Figure 2). Dredging operations contribute to all of these pressures by increasing turbidity, removing sediments from the seabed, and altering the estuarine hydrodynamic and morphodynamic. These changes are also driven by land reclamation linked to harbour infrastructure development. Additionally, important seagrass meadows are located in areas with easy public access, which are frequently used for recreation, such as walking, kayaking, sport boating, sport fishing and snorkelling. These activities disturb the seabed and cause direct damage to seagrass plants.

Loss of saltmarsh habitats

Historically, the growth of the population and the urban development in the coastal areas has taken place, to a certain extent, through the occupation of intertidal areas, mainly around estuaries (Pressure P2.2 in Figure 2). A clear example is the expansion of the city of Santander and the commercial port of Santander, which were partly built occupying the right side of the Santander Bay (Juanes et al., 2020). In this and all the other estuaries across the north of Spain, land claimed areas have preferentially occupied saltmarsh areas (Rivas and Cendrero, 1991). It is estimated that around 28 km^2 in the coast of Cantabria have been lost due to direct human intervention (i.e., draining, filling and reclamation). This represents 36% of the estuarine and wetland zones in the region (San Martín de la Arena: 152 ha, 29%; Mogro: 135 ha, 37%; Santander Bay: 1402 ha, 37%; Joyel: 64 ha, 42%; Victoria lagoon: 32 ha, 37%; Santoña Marshes: 996 ha, 34%) (IHCantabria, 2006).

On the other hand, the introduction of non-native species (Pressure P1.1 in the Figure 2), often facilitated by maritime transport-related activities, can significantly alter the ecological condition, processes, and structure of saltmarsh habitats. A notable example is the invasive shrub *Baccharis hamilifolia*, which mainly colonizes subhalophille saltmarshes along the coast of Cantabria (Calleja et al., 2019). Another is the graminoid *Spartina anglica*, recently detected in northern Spain, which competes with native species of the pioneer and low saltmarsh zones in estuaries.

Degradation of soft-benthic habitats

Soft-bottom benthic habitats are the most widespread in the study area, encompassing both coastal and estuarine ecosystems. They harbour biological communities with a high biodiversity, which directly depends on the quality of the sediment. Sediment enrichment, whether by nutrients or organic matter, and chemical pollution are the main threats to these habitats, particularly in estuarine environments (Díaz and Rosenberg, 2008; Puente et al., 2022) (Pressures 3.1, 3.2 and 3.3 in Figure 2). Urban, port, and industrial development within the coast of Cantabria is concentrated around estuaries, which receive water and waste discharges from these activities. An example of a highly polluted estuary is San Martín de la Arena, characterized by historical chemical contamination of its sediments, resulting from industrial activity in its watershed (Irabien et al., 2008). Similarly, the Santander Bay supports the most intense urban and port development in the study area, along with significant industrial activity concentrated in the inner part of the estuary (Juanes et al., 2020). Regarding organic

pollution, the Santoña Marshes receive effluents from the fish processing industry, a characteristic activity of local populations. In recent decades, the implementation of environmental legislation promoted by the European Union has contributed to improving the chemical quality of sediments in estuarine and coastal areas (e.g., Water Framework Directive 2000/60/EC).

Direct sediment disturbance represents another pressure threatening these habitats and the biodiversity they support (Pressure 2.1 in Figure 2). Such disturbance is associated with port operations (e.g., dredging) as well as recreational and leisure activities (e.g., mooring and walking), which may intensify under scenarios of large-scale tourism growth.

Spread of non-native invasive species

The ecological balance of the coast of Cantabria is increasingly threatened by the introduction of non-native invasive species (Pressure P1.1 in Figure 1), primarily associated with maritime transport and shipping (Activity 6.2 in Figure 1). Of the 25 invasive species detected in the ports with regular navigation lines with the port of Santander, 4 species are already present in the surrounding environment of the Bay, namely *Codium fragile, Sargassum muticum, Asparagopsis armata* and *Rugulopteryx okamurae*, the latter first recorded in 2024 (IHCantabria, 2022). Among them, the recent arrival of the macroalga *R. okamurae* on the eastern coast and in the Bay of Biscay is particularly noteworthy due to its rapid expansion and strong colonization capacity. As previously observed in other areas of southern Spain, particularly in the Gulf of Cádiz where the species first appeared, its biomass is overwhelming local ecosystems and has generated significant economic burdens due to beach clean-up operations and its impacts on fisheries (Mogollón et al., 2024). Its continued spread in northern Spain now poses a growing threat to local biodiversity (Díaz-Tapia et al., 2025), underscoring the urgent need for coordinated monitoring and management strategies to mitigate both its ecological and economic impacts.

Regarding estuaries, in northern Spain, the Pacific oyster (*Magallana gigas*) has been unintentionally introduced mainly through aquaculture and maritime traffic and is expanding along the coast. In Cantabria, it has been observed that, in several estuaries, the oyster is colonizing the same habitat as the native mussel *Mytilus galloprovincialis* (e.g., artificial structures), although it is not known whether it is displacing the mussel or merely taking advantage of the intertidal space left vacant as the mussel is disappearing from these areas due to other causes.

3.3. Consequences on economy, nature, society and governance

Consequences of biodiversity loss in the study area are classified into four categories: nature, society, governance and economy. The consequences on nature refer to changes in both the composition and functioning of ecosystems, as well as in their capacity to provide ecosystem services. This is the case of the decline in the abundance of certain shellfish species along the coast of Cantabria (e.g., *Ruditapes decussatus*) that has led to a drop in the stocks and alterations in population size structure (Nature consequence C1.2.1 in Figure 2). In the Santander Bay, exploitable clam stocks of *Ruditapes decussatus* has declined from 33.6 Tn of dry weight in 2005 to 8.6 Tn in 2025, and in Santoña Marshes has drop from 71.6 Tn to 9.2 Tn (IHCantabria, 2005 and 2025). Similarly, the loss of coastal vegetated habitats, also known as Blue Carbon habitats, reduces the ability of coastal ecosystems to remove carbon from the

atmosphere (Nature consequence C1.3.1 in Figure 2). Coastal vegetation, mainly saltmarshes and seagrasses in the estuaries of the study area, stores carbon in both aboveground and belowground biomass, which may later be sequestered long-term in sediments. In the Santander Bay and the Santoña Marshes, the highest soil organic carbon stocks were found in high saltmarshes compared to low saltmarshes and seagrasses (Mazarrasa et al., 2023). In addition, coastal vegetation, together with dune systems, contribute to the attenuation of water energy (e.g., wave attenuation), thereby protect the coastline from flooding (Bouma et al., 2014; Ondiviela et al., 2014) (Nature consequence C1.3.2 in Figure 2). Overall, all events of biodiversity change considered in the bow-tie have consequences for nature, leading to a decline in the health of the coastal ecosystems (Nature consequence C1 in Figure 2). The health of coastal ecosystems is assessed combining indicators of the structure and the functioning of ecosystems and their biological components. As a result, it is obtained the ecological status according to the Water Framework Directive 2000/60/EC, the environmental status based on the Marine Strategy Framework Directive 2008/56/EC and the conservation status in agreement with the Habitat Directive 92/43/EEC. For example, in 2024 all coastal and transitional water bodies of the study reach the good ecological status/potential or higher, except estuaries of San Martín de la Arena and Ajo that have a moderate ecological status (IHCantabria, 2024). The compliance of this European legislation is obligatory under the risk of fees imposition by Europe (Economic consequence C2.6 in Figure 2).

The main social consequences are related to the decline in the recreational and aesthetic value of the coast when natural habitats are lost or degraded (Social consequences C3.1 and C3.4 in Figure 2). Clean and natural sandy beaches are highly valued by both local populations and tourists, as are coastal wetlands that support healthy bird populations, including a high diversity of endangered and migratory species. The loss of these qualities in coastal ecosystems may reduce the attractiveness of the area for tourism, which could have a relatively positive effect by alleviating tourism-phobia (i.e., negative perceptions of tourism) (Social consequence C3.5 in Figure 2) and potentially improving the health and well-being of the local population (Social consequences C3.2 in Figure 2).

A reduction in the tourism income as a consequence of nature degradation directly impacts the local economy (Economic consequences C2.2 and C2.4 in Figure 2). Furthermore, the potential trade-offs between tourism, along with its associated economic benefits, and nature conservation brings the nature–economy dilemma back to the forefront, a matter of high important for governance (Governance measure C1.5 in Figure 2). Additional economic consequences are also linked to previously mentioned nature consequences, such as the decline in local fisheries income due to reduced shellfish stocks (Economic consequence C2.2 in Figure 2) or the rising costs of implementing control measures for invasive species (Economic consequence C2.1 in Figure 2). Finally, biodiversity changes affecting any or all elements included in the bow-tie can negatively impact Blue Economy development through consequences in a large variety of economic sectors, such as fisheries, coastal tourism, shipping and ports (Economic consequence C2.5 in Figure 2).

3.4. Prevention and mitigation measures

A set of prevention and mitigation measures was proposed to mitigate biodiversity impacts and their associated consequences (Table 1). These measures were classified into five categories: nature protection, knowledge building, governance, economic controls, and cultural and social measures. Nature protection includes measures aimed at reducing the

damage or impact of anthropogenic activities on coastal ecosystems, as well as restoring and recovering degraded habitats, often in combination with the development and implementation of regulations, strategies and plans under the category of governance measures. The promotion of scientific research and data collection falls under knowledge building measures, while educational initiatives, public engagement, and outreach activities are part of the social and cultural measures category. The final group comprises economic measures, which include fees and sanctions, but also subsidies and investments.

	PREVENTION MEASURES			MITIGATION MEASURES		
NATURE PROTECTION	a	C1.1	Protection and conservation of habitats.	k	C1.1	Nature conservation/management.
	b	C1.3.1	Reducing carrying capacity to control temporal overcrowding.	l	C1.2	Habitat restoration.
	c	C1.3.8	Adapt seasonality of activity based on species/habitat ecology (e.g., reproduction migrations, recruitment).	m	C1.2	Remove litter from beaches regularly combining citizen participation and local authorities.
				n	C1.2.1	Development of national and regional plans for coastal adaptation and mitigation to climate change.
				o	C1.2.3 C1.2.1	Bird habitat creation/restoration.
				p	C1.3.6	Development of local management plans that consider spatial and temporal planning with flexible spatial limits for management to improve habitats and productivity, including offsetting and No-take Zones.
KNOWLEDGE BUILDING	d	C3.1	Monitoring impacts on environment and local population of regulated uses and activities.	q	C3.3	Research to fight invasive species.
	e	C3.5	Communication and co-working.	r	C3.4	Research into early warning systems for invasive species.
				s	C3.5	Communication and co-working.
GOVERNANCE	f	C4.2	Legislation to reduce pressure by controlling/regulating activities.	t	C4.2	Development and implementation of regional strategic plans for the management and control of non-native invasive species.
	g	C4.1.3	New EU Invasive Alien Species Regulation.	u	C4.3.6	Development of a regional strategy for Blue Economy and Blue Tourism.
	h	C4.3.3	Updating risk assessment and prevention measures.			
ECONOMIC CONTROLS	i	C5.2 C1.3.1	Setting prohibitions and restrictions to species extraction, with economic fees and sanctions.	v	C5.1 C5.1.6	Subsidies and investment to shellfisheries and to promote alternative species.
CULTURAL & SOCIAL MEASURES	j	C6.1	Raising awareness of the value of the environment and culture.	w	C6.3	Diversification of touristic resources: naval, historic, cultural and heritage values.
				x	C6.4	Educating society and shell-fisherman to change species consumption and to exploit alternative species.

Table 1. List of prevention and mitigation measures belonging to five categories (Nature protection, Knowledge building, Governance, Economic controls, and Cultural and social measures), with the corresponding codes indicated in Figure 1 (from “a” to “x”) and the codes according to the standardized list of control measures (e.g., C1.1) proposed by Franco et al. (2025).

4. Conclusions

The bow-tie approach applied to the coast of Cantabria provides a structured analytical tool to explore and understand the links between drivers of change, biodiversity loss, and socio-economic consequences relevant to the study area and its stakeholders. Large-scale tourism and associated infrastructure development, mainly harbour and shipping facilities, were identified as key drivers of coastal habitat degradation, species loss, and spread of non-native species. While tourism brings economic benefits, the biodiversity damage associated with intense tourism activity results in a range of social and economic consequences for coastal communities. In this complex scenario, the bow-tie framework has supported the identification of potential opportunities to manage both the causes and consequences of biodiversity change. The targeted selection and planning of prevention and mitigation measures are essential to achieving sustainable management and development in densely populated areas such as the Santander Bay.

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References

Bouma, T.J., van Belzen, J., Balke, T., Zhu, Z., Airoldi, L., Blight, A.J., Davies, A.J., Galván, C., Hawkins, S.J., Hoggart, S.P.G., Lara, J.L., Losada, I.J., Maza, M., Ondiviela, B., Skov, M.W., Strain, E.M., Thompson, R.C., Yang, S., Zanuttigh, B., Zhang, L., Herman, P.M.J. (2014). Identifying knowledge gaps hampering application of intertidal habitats in coastal protection: Opportunities and steps to take. Coastal Engineering, 87: 147-157. https://doi.org/10.1016/j.coastaleng.2013.11.014.

Calleja, F., Galván, C., Silió-Calzada, A., Juanes, J.A., Ondiviela, B. (2017). Long-term analysis of *Zostera noltei*: A retrospective approach for under-standing seagrasses' dynamics. Marine Environmental Research, 130: 3-105.

Calleja, F., Ondiviela, B., Galván, C., Recio, M., Juanes, J. (2019). Mapping estuarine vegetation using satellite imagery: The case of the invasive species *Baccharis halimifolia* at a Natura 2000 site. Continental Shelf Research, 174: 35-47. https://doi.org/10.1016/j.csr.2019.01.002.

Diaz, R.J., Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. Science, 321: 926-928. https://doi.org/10.1126/science.1156401.

Díaz-Tapia, P., Alvite, N., Bañon, R., Barreiro, R., Barrientos, S., Bustamante, M., Carrasco, S., Cremades, J., Iglesias, S., López Rodriguez, M.C., Muguerza, N., Piñeiro-Carbeiro, C., Quintano, E., Tajadura, F.J., Díez, I. (2025). Multiple introduction events expand the range of the invasive brown alga *Rugulopteryx okamurae* to northern Spain. Aquatic Botany, 196: 103830. https://doi.org/10.1016/j.aquabot.2024.103830.

Franco, A., Smyth, K., Elliott, M. (2025). Operationalising bow-tie analysis to assess main concerns about biodiversity change in European Seas. In: C. Arvanitidis, C.H. Olivares, M. Elliott, A. Franco, J. Bremner, A.R. Baziudas, J.M. Weslawski (Eds.). Understanding Causes and Consequences of Biodiversity Change in European Regional Seas. RIO collection 282. https://doi.org/10.3897/arphapreprints.e167392.

IHCantabria (2005). Recursos biológicos marinos. Evaluación de los recursos infaunales 2005. Technical Report. Gobierno de Cantabria, 103 pp.

IHCantabria (2006). Análisis de presiones e impactos de las masas de agua de transición de Cantabria. Technical report. Gobierno de Cantabria. 71 pp.

IHCantabria (2022). Estudio de alternativas para la gestión de emisiones desde buques. Technical Report. Puerto de Santander, 106 pp.

IHCantabria (2024). Red de calidad del litoral de Cantabria. Evaluación del estado de las masas de agua de transición y costeras de Cantabria. Technical Report. Gobierno de Cantabria, 30 pp.

IHCantabria (2025). Recursos biológicos marinos. Evaluación de los recursos infaunales 2025. Technical Report. Gobierno de Cantabria, 79 pp.

Irabien, M.J., Cearreta, A., Leorri, E., Gómez, J., Vigure, J. (2008). A 130 year record of pollution in the Suances estuary (southern Bay of Biscay): Implications for environmental management. Marine Pollution Bulletin, 56 (10): 1719-1727. https://doi.org/10.1016/j.marpolbul.2008.07.006.

Juanes, J.A., Bidegain, G., Echavarri-Erasun, B., Puente, A., García, A., Bárcena, J.F., Álvarez, C., García-Castrillo, G. (2012). Differential distribution pattern of native *Ruditapes decussatus* and introduced *Ruditapes phillippinarum* clam populations in the Bay of Santander (Gulf of Biscay), Considerations for fisheries management. Ocean Coastal and Management, 69: 319-326. https://doi.org/10.1016/j.ocecoaman.2012.08.007.

Juanes, J.A., Gómez, A.G., Rubio, S., García-Castrillo, G., Puente, A., Ondiviela, B., Medina R. (2020). Santander Bay: Multiuse and multiuser socioecological space. Regional Studies in Marine Science, 34: 101034. https://doi.org/10.1016/j.rsma.2019.101034.

Mazarrasa, I., Neto, J.M., Bouma, T.J., Grandjean, T., Garcia-Orellana, J., Masqué, P., Recio, M., Serrano, Ó., Puente, A., Juanes, J.A. (2023). Drivers of variability in Blue Carbon stocks and burial rates across European estuarine habitats. Science of The Total Environment, 886: 163957. https://doi.org/10.1016/j.scitotenv.2023.163957.

Medina, R., Marino-Tapia, I., Osorio, A., Davidson, M., Martin, F.L. (2007). Management of dynamic navigational channels using video techniques. Coastal Engineering, 54 (6-7): 523-537. https://doi.org/10.1016/j.coastaleng.2007.01.008.

Mogollón, S.L., Zilio, M.I., Buitrago, E.M., Caraballo, M.A., Yñiguez, R. (2024). Economic impact of *Rugulopteryx okamurae* (Dictyotales, Ochrophyta) along the Andalusian coastline: the case of Tarifa, Spain. Wetlands Ecology and Management, 32: 19-32. https://doi.org/10.1007/s11273-023-09951-2.

Navedo, J.G., Herrera, A.G. (2009). Perturbaciones antrópicas en una zona de sedimentación clave para las aves acuáticas durante la migración otoñal. El caso de las espátulas en las marismas de Santoña. A Carriza: revista da Sociedade Galega de Ornitoloxía, 4 (2): 43-52.

Puente, A., Gómez, A.G., de los Ríos, A., Galván, C. (2022). Natural stress vs. anthropogenic pressure. How do they affect benthic communities? Marine Pollution Bulletin, 181: 113935. https://doi.org/10.1016/j.marpolbul.2022.113935.

Ondiviela, B., Losada, I.J., Lara, J.L., Maza, M., Galván, C., Bouma, T., van Belzen, J. (2014). The role of seagrasses in coastal protection in a changing climate. Coastal Engineering, 87: 158-168. https://doi.org/10.1016/j.coastaleng.2013.11.005.

Ondiviela, B., García-Castrillo, G., Recio, M., Puente, A., Juanes, J.A. (2015). Praderas de angiospermas marinas de Cantabria. In: Ruiz, J.M., Guillén, J.E., Ramos Segura, A. & Otero, M.M. (Eds.). Atlas de las praderas marinas de España. IEO/IEL/UICN, Murcia-Alicante-Málaga: 567-594 pp.

Rivas, V., Cendrero, A. (1991). Use of Natural and Artificial Accretion on the North Coast of Spain: Historical Trends and Assessment of Some Environmental and Economic Consequences. Journal of Coastal Research, 7 (2): 491-507.

Zabala, A., Rodríguez, J., Pantaleón, M., Revilla, J.A., Tejero, I., Álvarez, C., Juanes, J.A., De la Serna, I. (1999). Saneamiento de la Bahía de Santander. Revista de Obras Públicas, 3389: 29-47.