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Research Article

Identifying causes and consequences of ecosystem decline in the Irish Sea through bow-tie analysis

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Abstract

In this study, we apply the bow-tie risk analysis framework to map the causes and consequences of decline or loss of five key Irish Sea ecosystem components: intertidal sandflats and mudflats, burrowing fauna including Dublin Bay prawn *Nephrops norvegicus*, blue mussel *Mytilus edulis*, commercially harvested fish and wintering waterbirds. Main activities exerting multiple pressures on the Irish Sea ecosystem include energy production from offshore wind farms, tourism and leisure, fishing, transport, agriculture, urban and industrial uses and waste treatment and disposal. All of them can contribute to decline in condition or loss of critical habitats and biota, leading to significant ecological, economic and sociocultural consequences. Understanding these consequences is essential for designing appropriate management responses. The bow-tie approach allows management risks to be identified and highlights the most impactful control points for intervention to prevent or mitigate adverse biodiversity events.

Keywords

biodiversity loss, ecosystem-based management, ecosystem services, habitat loss

Introduction

Coastal and marine ecosystems are experiencing worldwide rapid decline due to multiple stressors ranging from climate change to overfishing, marine litter and eutrophication, amongst many others (e.g. Breitburg and Riedel (2005), Sala and Knowlton (2006), Worm and Lotze (2021)). On a regional scale of Irish, British and Manx waters, the main concerns revolve around environmental impacts of resource exploitation, new coastal and offshore developments, shipping, tourism and recreation and land-originating pollution (from forestry, agriculture, wastewater treatment; Marine Protected Area Advisory Group (2020), Opergy Group (2024)). Fisheries, shipping and discharges from the nuclear sector are particularly notable in the Celtic Seas region (OSPAR 2023). Climate change and its ability to interact with more local pressures will have a further effect on habitats and biodiversity (Küpper and Kamenos 2018, Thorne 2023).

A decline in marine habitats and biota is predicted to negatively impact ecosystem services (i.e. contributions of ecosystems to human well-being), including food provisioning, coastal protection and water filtering and detoxification (Worm et al. 2006). Degraded ecosystems services, in turn, limit society’s ability to benefit from the use of marine resources and interact positively with the marine environment. Understanding these impacts in specific regional contexts is crucial for developing adequate management responses that meet international requirements, national policy and local needs (e.g. Kok et al. (2016), Bryhn et al. (2020)). In this publication, we apply bow-tie analysis, a conceptual and industry-compliant risk management tool (Cormier et al. 2019), to conceptualise the causes and consequences (ecological, economic and sociocultural) of selected habitats and biota loss within the Irish Sea. Additionally, we identify prevention and mitigation measures that can help address these central issues.

Materials and Methods

Overall methodology

The bow-tie analysis is a management tool that visualises risks by mapping causes, consequences and management controls around a central issue. Its key output is a bow-tie shaped diagram, with a central knot representing a specific risk (e.g. biodiversity loss, habitat degradation), with pathways representing its potential causes (drivers, activities, pressures) and possible reduction or prevention methods on the left side and consequences and mitigation or compensation methods on the right side (Elliott et al. 2017). The bow-tie approach was adapted for the Horizon Europe-funded project Marine Biodiversity and Ecosystem Functioning leading to Ecosystem Services (MARBEFES), where it was applied to 12 European case study sites (BBTs - Broad Belt Transects) in order to identify causes for biodiversity change in different marine settings (Huertas-Olivares et al. 2024). The MARBEFES bow-tie approach uses a PowerPoint template and harmonised vocabulary to conceptualise the drivers, pressures, prevention measures, mitigation measures and impacts of changes in biodiversity (see Franco et al. (2025) for a detailed methodology).

Case study application

In this paper, we apply the bow-tie analysis in the Irish Sea Broad Belt Transect (BBT), defined as the coastal and offshore area delimited by Dublin Bay and Dundalk Bay in Ireland and Liverpool Bay and Morecambe Bay in the United Kingdom (UK) (Fig. 1). This case study spans approximately 20,370 km^2 in size and is located in the central part of the Irish Sea, an ecologically and geographically distinct regional sea. It supports supports several internationally important populations of seabirds and migratory birds; it also contains diverse habitats, such as saltmarshes, seagrass beds, intertidal and subtidal mud sediments, which contribute to key ecological functions, such as carbon sequestration and nutrient cycling. This area faces increasing pressures from human activities, most notably fishing and aquaculture, offshore wind development, maritime traffic, extractive uses, tourism and recreation. Cumulative impacts from these activities, compounded by climate change, are expected to further threaten the area's ecological integrity (The Irish Sea Network 2022).

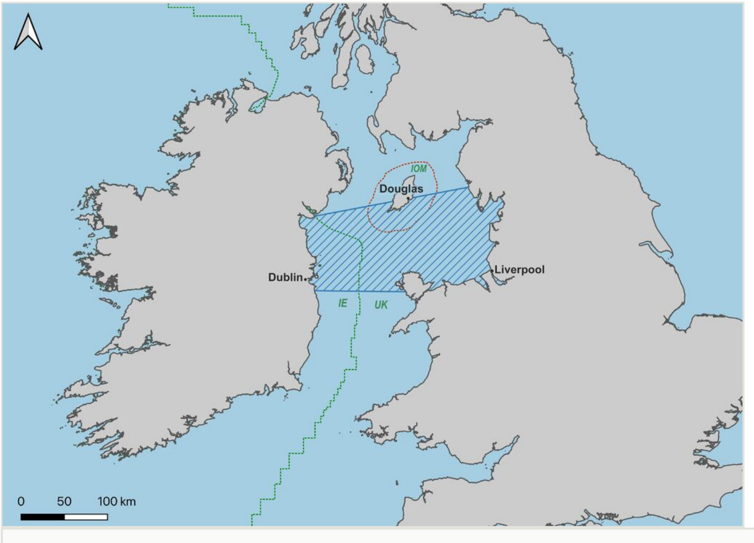

Figure 1.

Study area. Irish Sea Broad Belt Transect (BBT) - blue stripes, border between Irish (IE) and United Kingdom (UK) Exclusive Economic Zones (EEZs) - green lines, the Isle of Man (IOM) territorial sea (12 NM) limits - red line.

This case study encompasses two Exclusive Economic Zones: Irish and British. Another important political boundary is the limits of the territorial sea of the Isle of Man, a self-governing UK protectorate. This shared jurisdiction can pose challenges for effective transboundary management (O'Higgins et al. 2019, Abjean and Carval 2021, Ansong et al. 2022). Considering these challenges and increasing pressures from human activities, combined with the region's ecological importance, this area presents a particularily interesting and complex case study.

For the Irish Sea BBT, the development of the bow-tie model began with the critical step of identifying the key activities impacting biodiversity, which was achieved through stakeholder engagement. The following steps were applied:

1. **Mapping stakeholders** from diverse sectors (e.g. NGOs, academia, local and national authorities, fisheries, offshore renewable energy industry) operating around the Irish Sea and inviting them to in-person interviews. Invitations were distributed in June 2023;
2. **Stakeholder interviews**: In July 2023, two stakeholder sessions were conducted in Dublin and Liverpool, involving a total of 12 participants. Using a semi-structured interview approach, participants were asked to identify *"the main issues and concerns in the area regarding risks to biodiversity that require management of human activities and their associated pressures"* (as suggested in "Bow-tie method adaptation" in Franco et al. (2025); full interview protocol described in Hummel et al. (2023));
3. **Development of a bow-tie model**:
    1. **Identification of drivers**. Following guidelines by Franco et al. (2025), mind maps were created (with Xmind AI mapping tool; production by Basque Centre for Climate Change) based on: (1) the outcomes of the 12 stakeholder interviews and (2) the expert judgement of the authors, each of whom has a background in either environmental, economic or sociocultural studies. The mind maps suggested three main drivers of biodiversity and habitat change: marine renewable energy development; pollution from various sources such as agriculture, wastewater treatment, urbanisation and harbours; and recreational activities; see Suppl. materials 1, 2, 3. These drivers were renamed according to the bow-tie method's harmonised vocabulary to: "production of energy", "cultivation of living resources + transport + urban and industrial uses" and "tourism and leisure + extraction of living resources" (understood as both recreational and professional fishing activities). These terms were then entered into the bow-tie template.
    2. **Identification of pressures**. The main pressures associated with the drivers listed above were identified through a literature review (see Suppl. material 4). Their naming convention follows the bow-tie's method harmonised vocabulary;
    3. **Identification of central events and their relation to drivers and pressures**. Central events (i.e. specific examples of biodiversity or habitat

change) and their relation to the drivers (through pressures) were identified based on expert judgement and verified through literature review (see Suppl. material 4);

4. **Identification of impacts of biodiversity and habitat change**. Expected environmental, economic and societal consequences of change in biodiversity and habitats were selected by the authors from the list of possible impacts listed in the bow-tie method's harmonised vocabulary;
5. **Identification of control measures**. Prevention and mitigation methods were also identified using the authors' expertise and selected from the harmonised vocabulary list. All decisions made in the process are recorded in Suppl. material 4;
6. **Validation**. All authors reviewed and approved the content of the Irish Sea BBT bow-tie.

Results and Analysis

The Irish Sea BBT bow-tie is a complex system with several central events and intertwined pressures stemming from different drivers (Fig. 2). While the central knot is not a complete list of all possible changes in the state of habitats and biodiversity, it is illustrative of practical concerns related to ecologically, economically and culturally important species and habitats, which have the potential to have a profound impact on the socio-ecological system.

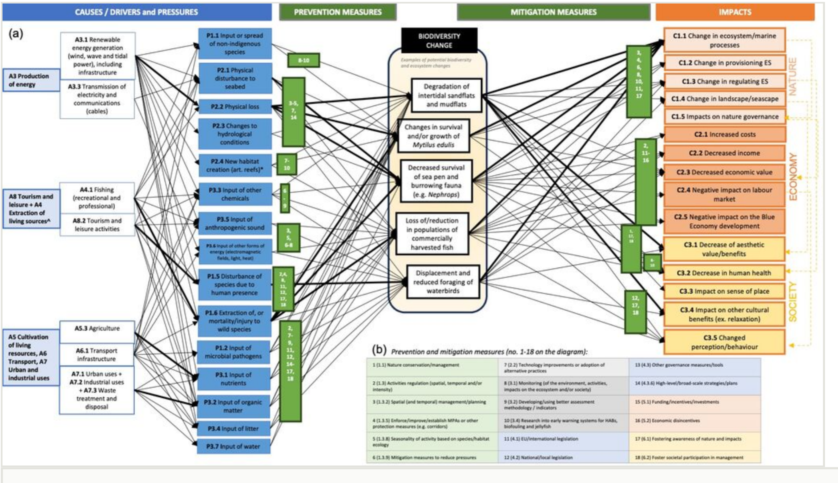

Figure 2.

(a) Biodiversity and habitat change bow-tie for the Irish Sea BBT. Black arrows indicate the direction of change, thickness of arrows - magnitude of change/importance. Dashed yellow arrows indicate connections between different kinds of impacts; **(b)** List of suggested 18 prevention and mitigation measures (controls), related to: nature protection (1-6), technology (7), knowledge building (8-9), governance (11-14), economy (15-16), cultural and social controls (17-18). Each number is followed by a harmonised vocabulary number (Franco et al. 2025).

Central species and habitats

Based on the selection of the drivers, a few main habitats and taxa or functional groups of biota (of major ecological, economic and sociocultural importance) impacted by these drivers were identified: (1) intertidal sandflats and mudflats; (2) burrowing fauna including Dublin Bay prawn *Nephrops norvegicus*; (3) blue mussel *Mytilus edulis*; (4) commercially harvested fish and (5) wintering waterbirds.

(1) **Intertidal sandflats and mudflats**, with a focus on 'mudflats and sandflats not covered by seawater at low tide' (EU Habitats Directive Annex I code 1140). Common Irish Sea intertidal habitats, present in locations such as Dundalk Bay, Malahide Estuary, Dublin Bay in Ireland, Menai Strait and Conwy Bay, Dee Estuary and Morecambe Bay in the UK (NPWS n.d., JNCC n.d.). These habitats provide nursery grounds for many commercially important fish species and feeding and roosting grounds for wintering shorebirds and waders; they also support invertebrate communities due to high organic material content and contribute to nutrient cycling and carbon sequestration (Foster et al. 2013, Paterson et al. 2019). They can also hold aesthetic or recreational value (Foster 2013).

(2) **Burrowing fauna including *Nephrops norvegicus***. Burrowers rework soft sediments through bioturbation, which influences sediment structure and chemistry (Hill et al. 2023). A notable example is the Dublin Bay prawn *Nephrops norvegicus*, a benthic decapod crustacean living in muddy sublittoral sediments, highly abundant in the Western Irish Sea (O'Sullivan et al. 2014). *Nephrops* is also commercially significant as the second most valuable species to be landed by both Irish (DAFM 2022) and British vessels (Seafish 2025).

(3) **Blue mussel *Mytilus edulis***. A very common bivalve species in the British, Irish and Manx waters, blue mussel plays a crucial role in marine ecosystems through water filtration, nutrient cycling and habitat engineering (Norling and Kautsky 2007). It also constitutes a food source for over-wintering waders (Lewis et al. 2019). Since early times, mussels have been harvested for food, bait and also spread on fields as fertiliser (Mac Con Iomaire 2004). Within the Irish Sea BBT, major seed mussel fisheries can be found off Wicklow, in Morecambe Bay and Conwy Bay (Tully 2017, Tyler-Walters 2008), though the Conwy Bay fishery is currently closed due to stock concerns (Welsh Government 2025).

(4) **Commercially harvested fish**. Apart from shellfish, the Irish Sea (ICES Area VIIa) provides landings of commercially important demersal fish species, such as sole, plaice and cod (MMO 2019), although they are mostly a result of bycatch from *Nephrops* fisheries. Importantly, cod stock in the Irish Sea is managed as part of a Cod Recovery Zone (together with the North Sea and West of Scotland fishing areas) due to decades-long reductions in landings (MMO 2024). Ecologically, these species also fulfil an important role in the trophic web with cod being an opportunistic predator and flatfish converting benthic production into energy for higher predators (Du Buit 1995, Link et al. 2014).

(5) **Wintering waterbirds, including light-bellied Brent goose *Branta bernicla hrota*.** British and Irish coasts, located along the East Atlantic Flyway, host large populations of migratory waterbirds every year; for example, internationally significant populations of the light-bellied Brent goose *Branta bernicla hrota*, which winters almost entirely in Ireland (largest sites in the BBT include Dublin Bay and Rogerstown Estuary; Whelan (2017)). Considering the abundance and diversity of waterbirds and seabirds on both sides of the Irish Sea, birdwatching is a popular recreational activity in the area (Nairn 2022, Oliver 2025).

Main activities and pressures impacting biodiversity and habitats

One of the primary concerns contributing to biodiversity and habitat change in the BBT, according to the MARBEFES stakeholders, is the production of energy from offshore wind farms (OWFs), which can cause habitat loss and disturbance to several species (through removal of sediment, increased noise, presence of electromagnetic fields or collision risks; Galparsoro et al. (2022)). In the Irish Sea case study, the main pressures stemming from OWFs were identified as physical and chemical changes to the environment, to which most of the species and habitats selected for this analysis are highly susceptible (Marine Protected Area Advisory Group 2023). However, wind turbine foundations could offer some potential environmental benefits serving as artificial reefs, enhancing populations of shellfish (e.g. blue mussel *Mytilus edulis*) and their predators, though the extent to which this persists over time is uncertain. A risk associated with artificial reef creation is the input or spread of invasive species, which could compete with the native *M. edulis* (Sewell et al. 2008).

Tourism and recreational activities can result in increased littering, habitat degradation and disturbance to wildlife. A notable example comes from the North Bull Island in Dublin Bay, where high levels of dog walking off-lead negatively impacts several species of birds and seals (Lauder and Riley 2017). Dog disturbance can impact behavioural responses of birds (e.g. disrupt parental care, reduce food intake, decrease reproductive success or even cause the birds to leave the site for one with fewer feeding opportunities; Fitzpatrick and Bouchez (2010), Weston and Stankowich (2013)).

Commercial fishing, in particular bottom trawling, directly impacts the marine ecosystem through seafloor erosion, sediment re-suspension and removal of benthos (Hiddink et al. 2017). Bottom trawling catches also non-target bycatch species that are later discarded (Hilborn et al. 2023). An indirect consequence of bottom trawling is stock depletion; however, with proper regulations in place, overfishing can be prevented (Hilborn et al. 2021). Currently, most mobile bottom-contact fishing gears in the BBT are concentrated on the *Nephrops* grounds in eastern and western mud belts (ICES Area VIIa, FU 14 and FU15; ICES (2024)). Bottom trawling can adversely affect *Nephrops* fisheries by disrupting their habitats and hampering the recovery of populations (Hill and Sabatini 2008).

Lastly, the Irish Sea is affected by high pollution coming from urban and industrial uses, sewage input and agricultural runoff. It is also subject to extensive maritime transport, with three internationally significant ports in Dublin (the largest port by vessel arrivals and tonnage in Ireland; CSO (2024)), Liverpool and Belfast (respectively 5th and 10th largest ports by tonnage in the UK; DfT (2024)). Pressures from human use of the area include, but are not limited to: noise pollution and input of ballast water from the ships, potential spread of invasive species due to maritime traffic, increased litter, input of nutrients, organic contaminants and metals which might accumulate in both species and sediments (CEFAS 2005, Schéré 2024).

Consequences of ecosystem decline

Three main categories of impacts of biodiversity and habitat change as per the bow-tie methodology concern nature, economy and society. Impacts on nature might be related to either changes in ecologically significant marine processes (habitat formation, water cycling etc.), provisioning or regulating ecosystem services, modification of landscape or seascape and impacts on nature governance. In this analysis, changes in all the abundance/area and condition of selected species and habitats will have a profound impact on natural processes and ecosystem services. For instance, loss of blue carbon habitats, such as intertidal mudflats or coastal wetlands, will negatively affect carbon sequestration and storage, leading to release of significant amounts of CO_2 into the atmosphere (Cott et al. 2021). Decrease in waterbird diversity or reduction in waterbird populations in coastal wetlands, which will have an impact on several processes and services (e.g. pest control, pollination, seed consumption and dispersal; additionally for migratory birds: transfer of energy) as waterbirds usually occupy the highest trophic level in wetland ecosystems (Qiu et al. 2024). A more nuanced example would be an increase in abundance in blue mussel *Mytilus edulis*, predicted to colonise artificial structures such as wind turbines (Maar et al. 2009). While this growth could provide a secondary substrate for epifaunal colonisation and further affect ecosystem structure and function, it is important to acknowledge that this benefit comes with the trade-off of losing a certain area of natural habitat from the installation of the turbines themselves.

From an economic perspective, biodiversity loss and habitat changes impact the value of ecosystem services, with consequences that extend to the broader economy and societal well-being. For instance, reduced carbon sequestration from degraded blue carbon habitats and the depletion of fish and shellfish stocks result in lower values for carbon storage and fish provisioning services (Beaumont et al. 2014). The value losses translate to broader economic impacts, such as decreased income from activities like fisheries which may become economically unviable. This in turn affects the labour market (e.g. job losses in the fishing sector) and hampers the development of the Blue Economy, particularly in regions where fisheries are an essential economic sector. For example, a potential decline in *Nephrops* fisheries, especially in the crucial Western Irish Sea stock (which accounted for the highest percentage of landings and was worth approximately €51 million for Irish vessels in 2023; Marine Institute (2024)), could have severe socioeconomic consequences.

Sociocultural impacts refer to change in aesthetic value, sense of place, physical and mental health benefits and several activities that promote spiritual and cultural wellbeing, for example, relaxation or enjoyment. Coastal waterbirds and seabirds attract birdwatchers, tourists and artists; some species become a representation of conservation efforts of wetlands (Green and Elmberg 2013). Coastal locations and powerful landscapes/seascapes can have a significant aesthetic value and profound impact on spirituality and wellness, contributing to emergence of sense of place or attachment to the area (Jarratt 2015, Ainsworth et al. 2019, Ryfield et al. 2019). For instance, vast and dramatic landscapes of Morecambe Bay, Britain's largest intertidal area, have been identified as one of the main reasons for people's attachment to the area and have continually inspired planning and tourism marketing efforts (Jarratt et al. 2018). Deteriorating condition of culturally important areas and species could cause a sense of loss or detachment, both for the declining ecosystem and for activities and well-being benefits associated with it.

Prevention and mitigation measures

The bow-tie contains suggestions of the authors of this study for prevention (removing or reducing pressures leading to potential biodiversity/habitat change) and mitigation (limiting consequences once that change occurs) measures. These controls were selected from the harmonised vocabulary list compiled by the MARBEFES project (Franco et al. 2025). They follow the 10 tenets of adaptive and sustainable environmental management (Barnard and Elliott 2015); some of them can act as both prevention and mitigation controls. Overall, they can be divided into:

- **Nature protection measures**, for example, fishing quotas, enforcing or improving Marine Protected Areas, minimising harmful activities to match seasonality of reproduction or recruitment. For example, high underwater noise levels from construction of offshore windfarms can be harmful to marine mammals and fish (Bergström et al. 2014). Spatial (i.e. avoiding important recruitment areas) and temporal (i.e. timing construction outside of biologically sensitive periods) exclusion of piling activities could, along with technological measures, reduce the displacement of mobile species and allow them to forage and travel (Russell et al. 2016);
- **Technological solutions**. Following the above example of underwater noise emission, vibratory pile driving and acoustic barriers such as bubble curtains are an effective technique of noise abatement during OWF construction, while ship-quieting technologies and regular maintenance can reduce some of the noise pollution from shipping (Merchant 2019). Similarly, modernisation or construction of adequate coastal infrastructure can help reduce water pollution (Uisce Éireann 2023);
- **Knowledge building and monitoring measures**, for example, monitoring offshore and onshore activities or early warning systems (for Harmful Algal Blooms – HABs, jellyfish, invasive species). In recent years, there has been an increase in monitoring methods allowing quick identification of contamination or presence of

non-indigenous species in Irish and British waters (Murphy et al. 2015, Fernandez et al. 2021). Implementing low-cost methods for environmental surveillance and establishing water monitoring centres could reduce health and environmental risks (University of Bath 2025);

- **Governance tools and strategies**, ranging from legislation (international, national, local) to sectoral development or co-development plans. Importantly, simply imposing new policies is not enough – with multiple actors and legal instruments of marine management in the UK and Ireland (Boyes and Elliott 2014, O'Hagan et al. 2020), there is a clear need for good coordination and reducing conflicts in order to prevent or mitigate the negative impacts of biodiversity and habitat decline;
- **Economic controls**, such as funding incentives or disincentives (sanctions or fees). For instance, the government can subsidise private sector or citizens to support positive activities (coastal habitat maintenance, recycling) or, contrarily, place a tax on harmful activities, such as waste emissions and habitat degradation (Osborn and Datta 2006);
- **Cultural and social measures**, including citizen science and fostering awareness of nature. Citizen-science data can also contribute to the evidence base (if high-quality and used alongside other methods; Hyder et al. (2015)). For instance, Irish Coastal Environment Group – Coastwatch is a European pioneer in community-led long-term monitoring, running annual all-Ireland surveys since late 1980s and collecting data on coastal biodiversity, litter, effluent pollution, invasive species and seagrass beds (Coastwatch 2025).

Importantly, relying solely on one approach limits the potential for sustainable outcomes (e.g. MPAs will exist only in theory if they are not supported by robust monitoring); therefore, various controls should be considered for effective risk management.

Conclusions

The bow-tie analysis of the Irish Sea BBT highlights the connections between the marine environment and society and key concerns related to ecologically, economically and culturally important species and habitats. By integrating diverse stakeholder perspectives in its framework and by offering prevention and mitigation solutions, it can serve as a valuable conceptual and evidence-based tool for managers and practitioners.

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Ethics and security

Stakeholder interviews, which were the starting point for the analysis, were conducted by MARBEFES Project Partner HuFoSs. All interviewed stakeholders agreed to participate in the consultations and signed a document of informed consent, compliant with EU and national ethical and legal regulations.

Conflicts of interest

The authors have declared that no competing interests exist.

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Supplementary materials

Suppl. material 1: Supplementary file 1

Authors: BC3 (Basque Centre for Climate Change)
Data type: image
Brief description: Mindmap for the Irish Sea BBT created during the Project (driver: Recreational Activities).
Download file (77.24 kb)

Suppl. material 2: Supplementary file 2

Authors: BC3 (Basque Centre for Climate Change)
Data type: image
Brief description: Mindmap for the Irish Sea BBT created during the Project (driver: Marine Renewables).
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Suppl. material 3: Supplementary file 3

Authors: BC3 (Basque Centre for Climate Change)
Data type: image
Brief description: Mindmap for the Irish Sea BBT created during the Project (drivers: Wastewater, Agriculture, Urbanisation, Harbours).
Download file (99.28 kb)

Suppl. material 4: Supplementary file 4

Authors: Dorota Kolbuk
Data type: Excel spreadsheet (mapping tool)
Brief description: Details of bow-tie analysis for the Irish Sea case study
Tab: "ReadMe" - file metadata; explanation of bow-tie development steps
Tab: "CentralEvent" - a table explaining the selection of 5 species/habitats for the bow-tie analysis
Tab: "Matrix" - a matrix of identified drivers, pressures and species/habitats responses to these pressures
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