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Dorota Kołbuk, Julie Bremner, Ashley Cahillane, Valentina Di Gennaro, Tasman Crowe

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Author(-s), *Institution(-s)*: **Dorota Kołbuk** (*Earth Institute and School of Biology and Environmental Science, University College Dublin, Dublin, Ireland*), **Julie Bremner** (*The Centre for Environment, Fisheries and Aquaculture Science (Cefas), Cefas Laboratory, Suffolk, UK; Collaborative Centre for Sustainable use of the Seas, School of Environmental Sciences, University of East Anglia, Norwich, UK*), **Ashley Cahillane** (*School of English, Drama, and Film, University College Dublin, Dublin, Ireland*), **Valentina Di Gennaro** (*University of East Anglia, Norwich, United Kingdom*), **Tasman Crowe** (*Earth Institute and School of Biology and Environmental Science, University College Dublin, Dublin, Ireland*)

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 to identify management risks and highlights the most impactful control points for intervention to prevent or mitigate adverse biodiversity events.

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

Introduction

Coastal and marine ecosystems are experiencing worldwide rapid decline due to multiple stressors ranging from climate change to overfishing, marine litter, and eutrophication, among many others (e.g., Breitburg & Riedel, 2005; Sala & Knowlton, 2006; Worm & 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 & Kamenos, 2018; Thorne et al., 2023).

A decline in marine habitats and biota is predicted to negatively impact ecosystem services, 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. 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 this central issue.

Methodology

Overall methodology

Detailed methodology can be found in Elliott et al., in preparation. 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 studies (BBTs - Broad Belt Transects) in order to identify causes for biodiversity change in different marine settings (see Huertas-Olivares et al., 2024 for synthesis). The MARBEFES bow-tie approach uses a template and harmonized vocabulary to conceptualise the drivers, pressures, prevention measures, mitigation measures and impacts of changes in biodiversity.

Case study

In this paper, we apply the bow-tie analysis in the Irish Sea 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) (**Figure 1**). This case study is notable for its large size (~20,370 km^2) and, importantly, its position within Exclusive Economic Zones of Ireland and the United Kingdom. Another important political boundary are the limits of the territorial sea of the Isle of Man, a self-governing UK protectorate (O'Higgins et al., 2019). This shared jurisdiction can pose challenges for effective transboundary management (Abjean & Carval, 2021; Ansong et al., 2023).

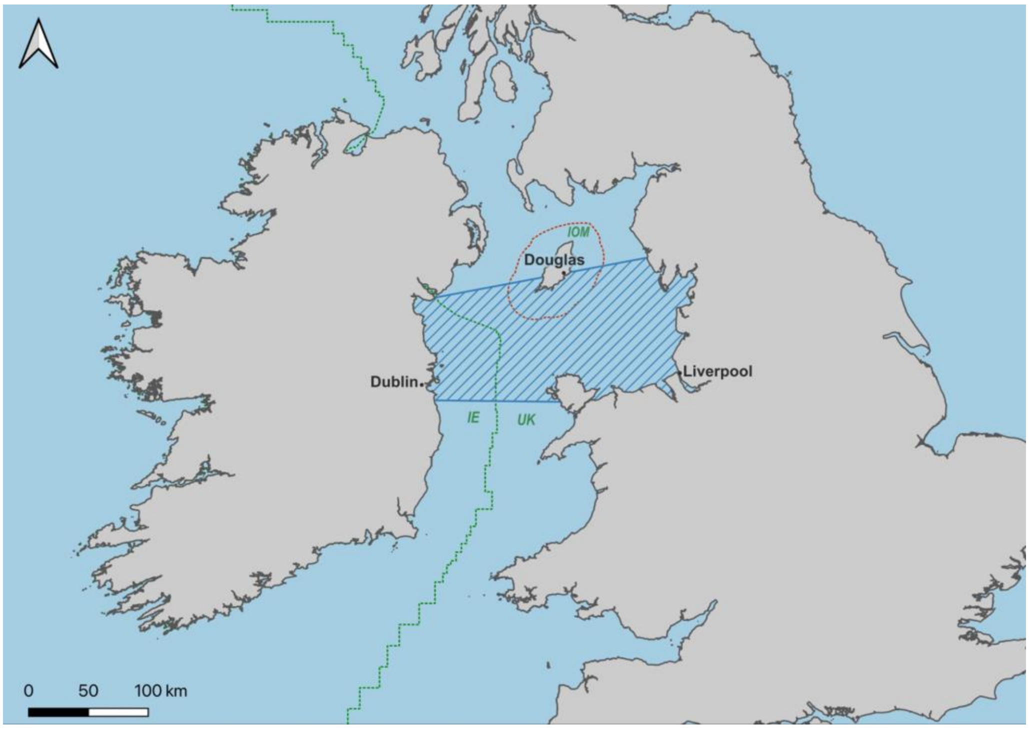

Figure 1. Study area. Irish Sea Broad Belt Transect (BBT) - blue stripes, border between Irish (IE) and United Kingdom (UK) Exclusive Economic Zones (EEZs) - green lines, the Isle of Man (IOM) territorial sea (12 NM) limits - red line.

Following the bow-tie analysis methodology (Elliott et al., in preparation), Mind Maps were created (with Xmind AI mapping tool; production by Basque Centre for Climate Change) based on (1) the outcomes of 12 stakeholder interviews conducted in Dublin and Liverpool in July 2023 (Hummel et al., 2023), and (2) expert judgement of the authors, each of whom has a background in either environmental, economic, or sociocultural studies. The Mind Maps suggest 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 Supplementary File. These drivers, re-classified according to the bow-tie method's harmonized vocabulary as "production of energy", "cultivation of living resources + transport + urban and industrial uses", and "tourism and leisure + extraction of living resources"; the latter including both recreational and professional fishing activities), were entered into the bow-tie template. Central events (i.e. specific examples of biodiversity or habitat change), their relation to the drivers (through pressures), and expected consequences were identified based on expert judgement and verified through a literature review (see Supplementary File). The specific consequences of biodiversity and habitat changes, prevention and mitigation methods were also selected from the harmonized vocabulary list. All decisions made in the process are recorded in the Supplementary File.

Results of the bow-tie analysis

The Irish Sea BBT bow-tie is a complex system with several central events and intertwined pressures stemming from different drivers (**Figure 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.

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, (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, 2014).

(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 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 UK vessels (Seafish, 2025).

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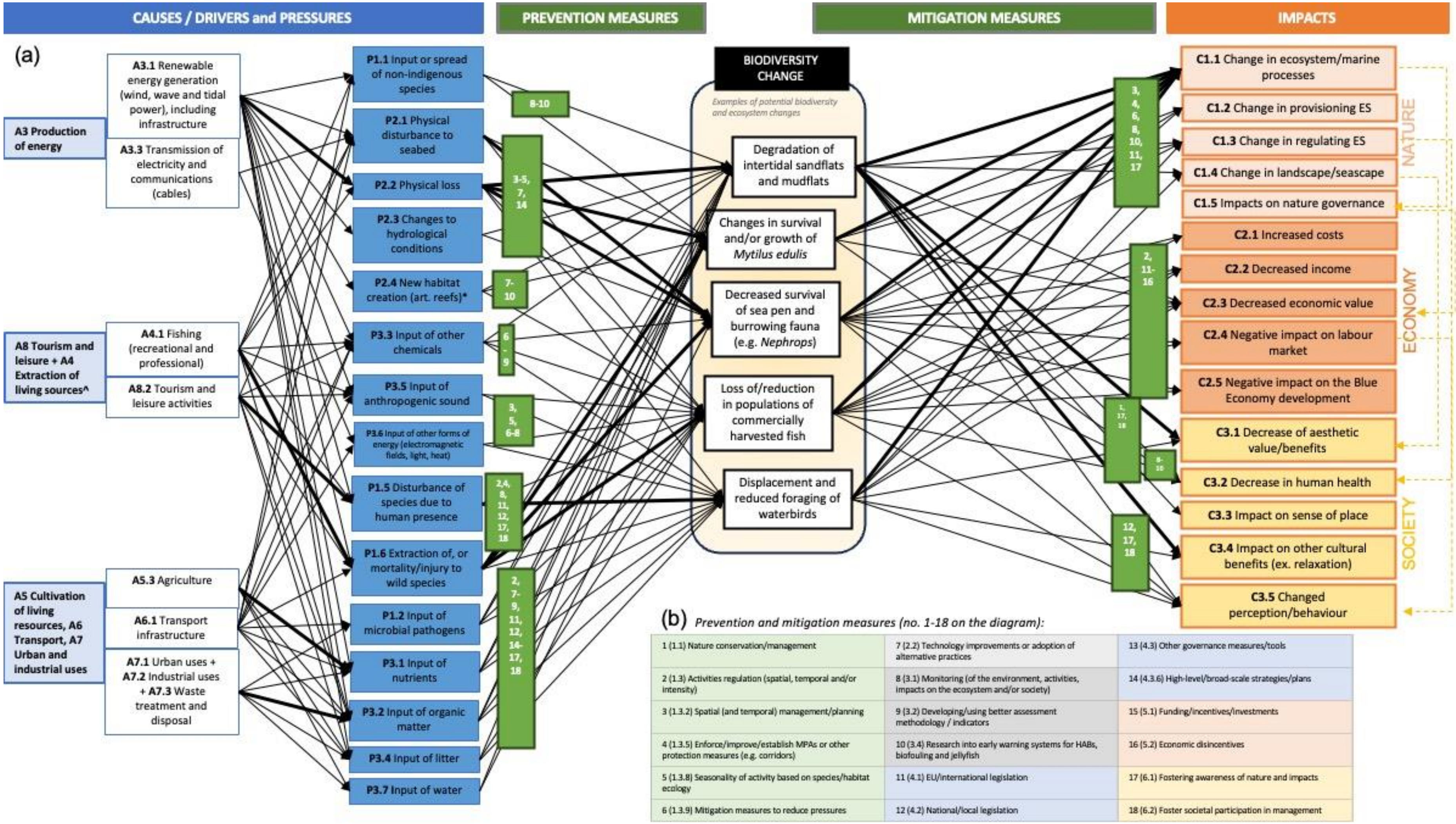

Figure 2. (a) Biodiversity and habitat change bow-tie for the Irish Sea BBT. Black arrows indicate the direction of change, thickness of arrows - magnitude of change/importance. Dashed yellow arrows indicate connections between different kinds of impacts. (b) List of suggested 18 prevention and mitigation 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 harmonized vocabulary number (Elliott et al., in preparation).

(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 & 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, M., 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, 2024).

(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, e.g., internationally significant populations of the light-bellied Brent goose *Branta bernicla hrota*, which winters almost entirely in Ireland (biggest 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 drivers 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, 2024). 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 & 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 & Bouchez, 1998; Weston & Stankowich, 2014).

Commercial fishing, in particular bottom trawling, directly impacts the marine ecosystem through seafloor erosion, sediment resuspension, 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 2021). Bottom trawling can adversely affect *Nephrops* fisheries by disrupting their habitats and hampering the recovery of populations (Hill & 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 the 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 biodiversity and habitat changes

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 in 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 colonize artificial structures such as wind turbines (Maar et al., 2009). While this growth could provide a secondary substrate for epifaunal colonization 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, e.g., relaxation or enjoyment. Coastal waterbirds and seabirds attract birdwatchers, tourists and artists; some species become a representation of conservation efforts of wetlands (Green & Elmberg, 2014). 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., 2019). 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 wellbeing benefits associated with it.

<u>Prevention and mitigation measures</u>

The bow-tie contains suggestions for prevention (removing or reducing pressures leading to potential biodiversity/habitat change) and mitigation (limiting consequences once that change occurs) measures, which follow the 10 tenets of adaptive and sustainable environmental management (Barnard and Elliott, 2015). Some measures can act as both prevention and mitigation controls. Overall, the controls can be divided into:

- **Nature protection measures**, e.g., fishing quotas, enforcing or improving Marine Protected Areas, minimizing 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, modernization or construction of adequate coastal infrastructure can help reduce water pollution (Uisce Éireann, 2023).
- **Knowledge building and monitoring measures**, e.g., 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 (e.g., 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 & 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 & 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 at 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, n.d.).

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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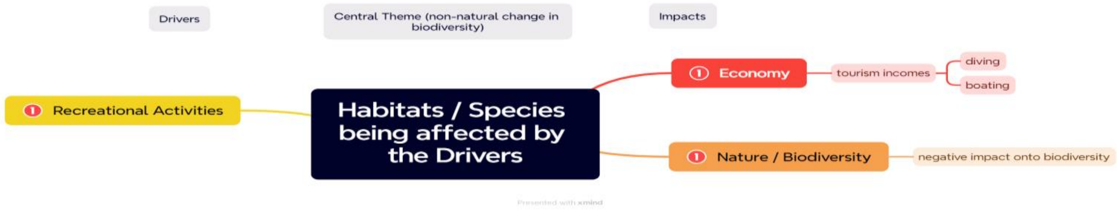
SUPPLEMENTARY FILE

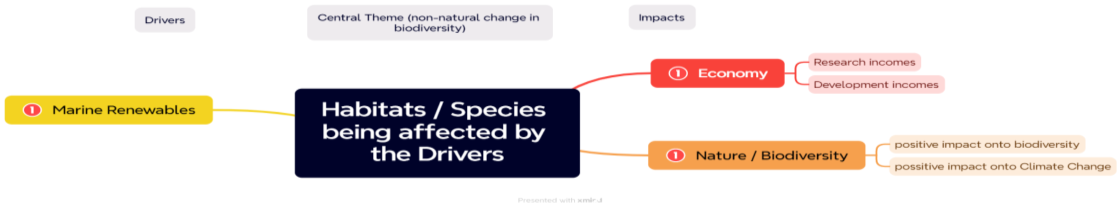
S1 - Tab 1 – ReadMe

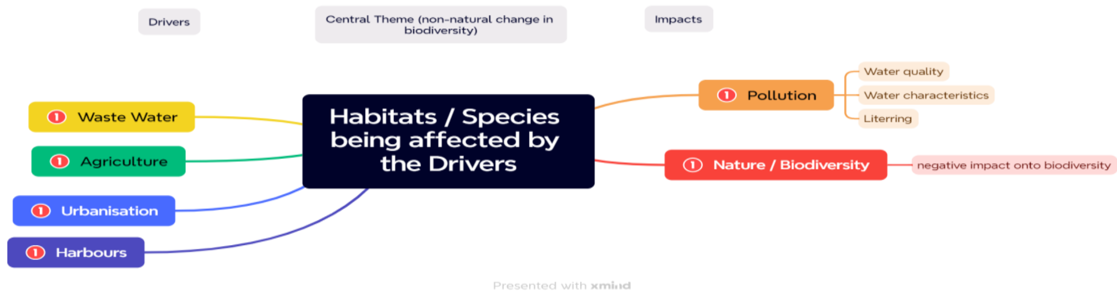
File:	**Supplementary file to manuscript "Analysis of the causes and consequences of the major concerns on biodiversity and habitat change in the Irish Sea" [doi: ....]**
Project:	MARBEFES
Content:	Tab: "ReadMe" - file metadata; explanation of bow-tie development steps Tab: "MindMaps" - mindmaps for the Irish Sea BBT created during the Project 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
Date:	22/4/2025
Contact:	dorota.kolbuk@ucd.ie, tasman.crowe@ucd.ie

Lp.	Bow-tie development steps (WP5)		References
1	Identification of main concerns of stakeholders (concerns = drivers of environmental change)	Based on 12 interviews conducted in July 2023 with stakeholders from Irish Sea BBT (Dublin-Liverpool) by Project Partner HuFoSs, concerns of the stakeholders were mapped with XMind software by Project Partner BC3 (see Tab: "MindMaps") and following that, major drivers - whose naming follows a controlled vocabulary developed by MARBEFES Project Partner IECS Ltd. - were selected: 1. ORE development, 2. tourism, leisure, and fishing (recreational and commercial), 3. agriculture, transport & shipping, urban uses, industry, wastewater treatment and disposal (first considered as "sources of pollution")	***Stakeholder interview methodology***: HuFoSs (2023) Marine SABRES Deliverable 2.1 –MARBEFES First Part of Deliverable 1.2: Stakeholders' recommendations regarding harmonization and integration of social-ecological frameworks. ***MindMaps produced by BC3 for the Irish Sea BBT:*** see Tab "MindMaps". ***MindMaps and bow-tie production guidance***: MARBEFES WP5 (2024) Deliverable 5.4 (A) Report on the synthesis reviews, including gap analysis results. https://marbefes.eu/uploads/files/13_D5.4_WP5_Report%20on%20the%20synthesis%20reviews%2C%20including%20gap%20analysis%20result...240229_.pdf ***Controlled vocabularies:*** IECS (2024) Bow-tie_CONTROLS & standardised vocabulary; Bow-tie_CONSEQUENCES & standardised vocabulary; Bow-tie_CAUSES & standardised vocabularies
2	Identification of pressures caused by those drivers	General pressures selected based on available literature of known impacts of the above on marine environment (biodiversity and habitats); all types of pressures follow a controlled vocabulary.	Which pressures are exerted by which drivers: see Tab "Matrix" (columns: Drivers, Pressures; literature sources at the bottom of these columns)
3	Selection of habitats and species of focus (=central events) of the analysis	Selection of ecologically /economically / socioculturally important species and habitats, whose change/loss or decline could impact several ecosystem services (based on expert judgement/discussions and supported by literature (Google Scholar and Scopus search [example: "intertidal	See Tab "CentralEvent" (literature sources at the bottom)
4	Connecting pressures with central events	Verification of each possible connection, e.g. MARLIN database for each species/habitat of interest, Google Scholar and Scopus search [example: "mytilus edulis" or "blue mussel" and "sensitivity" or "pollution" or "pressures"]. Rationale for inclusion of the pressure in the bow-tie along with references can be found in the Tab "Matrix".	Tab "Matrix" (columns: Central Event; literature sources at the bottom)
5	Identification of impacts of biodiversity and habitat change	Connection of central events to impacts based on ecological / economic / sociocultural relevance (return to Tab "CentralEvent").	Tab "CentralEvent" (row: Predicted main impacts of change/decline)
6	Selection of prevention and mitigation measures	Expert recommendations (suggestions), with naming convention following a vocabulary of controls developed by IECS Ltd. Main manuscript contains examples of actions supported by literature (section: "Prevention and mitigation measures")	For more comments see: IECS (2024) Bow-tie_CONTROLS & standardised vocabulary

S2 – Tab 2 – MindMaps







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S3 – Tab3 – CentralEvent

CENTRAL EVENTS: change in species or habitat. Main criteria for selection of the species or habitats: present /abundant in the Irish Sea; of ecological/economic/sociocultural importance (ideally all 3). In the end, limited to 5 "events" as to illustrate the concept and connectedness within the system rather than to capture every possibility.

Selection criteria	***Mytilus edulis***	***Burrowing fauna (e.g. Nephrops) and seapens communities***	***Economically important fish species (e.g. cod, herring, plaice, sole)***	***Sandy and muddy intertidal habitats***	***Wintering waterbirds***
Distribution in the Irish Sea BBT	Very common all around the coast of the British Isles (Tyler-Walters, 2008)	Plains of fine mud, at water depths ranging from 15- 200m or more, which are heavily bioturbated by burrowing megafauna with burrows and mounds - main grounds in the Western Irish Sea and minor in the Eastern Irish Sea (O'Sullivan et al., 2014). Biggest Irish Sea stock of burrowing *Nephrops norvegicus* present in the BBT.	Common species; spawning grounds of certain species present in the BBT. Example: The Irish Sea herring population is one of the major herring populations in Ireland and spawns in two areas: the Isle of Man and the Mourne (Dundalk Bay: (MPA Advisory Group report, 2023)	Present and common on both 'ends' of the BBT (e.g. Dundalk Bay, Malahide Estuary, Dublin Bay in Ireland, Menai Strait and Conwy Bay, Dee Estuary, and Morecambe Bay in the UK (NPWS, 2025; JNCC, n.d.)). Dundalk Bay - one of the largest mudflats in Ireland (NPWS, n.d.), Morecambe Bay - in the UK (Morecambe Bay Partnership, n.d.)	British and Irish coasts, located along the East Atlantic Flyway, host large populations of migratory waterbirds every year, e.g., internationally significant populations of the light-bellied Brent goose Branta bernicla hrota, which winters almost entirely in Ireland (biggest sites in the BBT include Dublin Bay and Rogerstown Estuary; Whelan, 2017).
Ecological relevance	Water filtration, nutrient cycling and habitat engineering (Norling & Kautsky, 2007). It also constitutes a food source for over-wintering waders (Lewis et al. 2019).	Burrowers rework soft sediments through bioturbation, which influences sediment structure and chemistry (Hill et al., 2023).	Important role in the trophic web -e.g. cod is an opportunistic predator and flatfish converts benthic production into energy for higher predators (Du Buit, 1995; Link et al. 2014)	Nursery grounds for many commercially important fish species and feeding and roosting grounds for wintering shorebirds and waders; support of invertebrate communities due to high organic material content, support of nutrient cycling and carbon sequestration (Foster et al., 2013; Paterson et al., 2019).	Waterbirds usually occupy the highest trophic level in wetland ecosystems (Qiu et al., 2024) - direct or direct role in several processes: pest control, pollination, seed consumption and dispersal, transfer of energy
Economic relevance	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.	As a community - no, but one species stands out: *Nephrops norvegicus*, which is the second most valuable species to be landed by Irish vessels (DAFM, 2022).	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), other species include herring, flounder, whiting	Mudflats are blue carbon habitats - carbon sequestration as an ecosystem service can have an economic value (Beaumont et al., 2014)	Coastal waterbirds and seabirds attract birdwatchers, tourists and artists (Green & Elmberg, 2014); ecotourism is related to some extent to birdwatching though usually works in conjunction with other attractions -- no estimates of economic contributions of birdwatching/bird-related activity in British and Irish context.
Sociocultural relevance	Historically important species; cultural impact (e.g. traditions associated with blue mussel and cockle harvesting, songs) (TCD, 2021)	Re: *Nephrops*, which constitutes an important fishery - same comment as for the commercially harvested fish: Fisheries are of huge cultural importance for coastal communities; big role in identity formation and the emotional attachment and relationships associated with the fishing industry (Urquhart et al., 2013; Bratton & Hinz, 2002).	Fisheries are of huge cultural importance for coastal communities; big role in identity formation and the emotional attachment and relationships associated with the fishing industry (Urquhart et al., 2013; Bratton & Hinz, 2002).	Aesthetic or recreational value (Foster, 2014; UCD Cultural Values of Coastline Project, 2019); profound impact on spirituality and wellness, contributing to emergence of sense of place or attachment to the area (Jarratt, 2015).	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 pressures	*see Tab "Matrix" for the drivers and pressures affecting this species/habitat*				
Predicted main impacts of change/decline	Impact on ecosystem function and regulating ecosystem services, decreased economic value and quality of the product; possible impacts on human health (if decline in quality through pollution and pathogens)	Decline in burrowing fauna will have a negative impact on ecosystem services and ecosystem function (burrowing/sediment reworking/nutrient cycling). Overfishing of *Nephrops* will have impact on the stock survival and economic consequences: decreased economic value, decreased income, negative impacts on labour market, and negative impact on Blue Economy development. Loss of fisheries jobs could also have a sociocultural impact on the community/ identity of fishers. Possible impact on human health depending on health and nutritional value of the depleted shellfish stocks.	Overfishing will have impact on the stock survival, ecosystem function (e.g.cod being a predator), ecosystem services ; decreased economic value, decreased income (e.g., from fisheries which would no longer be an economically viable activity), negative impacts on labour market (e.g., decline in jobs supported by fishing activities), and negative impact on Blue Economy development (e.g., lack of sustainable fisheries contributing to food security). Loss of fisheries jobs could also have a sociocultural impact on the community/ identity of fishers. Possible impact on human health depending on health and nutritional value of the depleted fish stocks.	Impact on ecosystem function and regulating ecosystem services; decreased economic value; impacts on aesthetic value, possible impacts on human health (if degradation is caused by pollution), fewer recreational/leisure activities	Impact on ecosystem function and ecosystem services, possibly decreased economic value, due to less birdwatching/tourism activities, decrease in aesthethic value.

Sources

Mytilus edulis	***Burrowing fauna (e.g. Nephrops) and***	***Economically important fish species***	***Sandy and muddy intertidal habitats***	***Wintering waterbirds***
Tyler-Walters, H., 2008. Mytilus edulis Common Lewis, L. J., Burke, B., Fitzgerald, N., Tierney, T. D. & Norling, P., & Kautsky, N. (2007). Structural and TCD (2021). Tully, O. (2017). Atlas of Commercial Fisheries for	Bratton, S. P., & Hinz, S. (2002). Ethical responses to Department of Agriculture, Food and the Marine Hill, J.M., Tyler-Walters, H., Garrard, S.L., & Watson, O'Sullivan, D., Lordan, C., Doyle, J., Berry, A., & Lyons, Urquhart, J., Acott, T., & Zhao, M. (2013). Introduction:	Bratton, S. P., & Hinz, S. (2002). Ethical responses to Du Buit, M. H. (1995). Food and feeding of cod (Gadus Link, J. S., Smith, B. E., Packer, D. B., Fogarty, M. J., & Marine Management Organisation (2019). Main Marine Protected Area Advisory Group (2023). Urquhart, J., Acott, T., & Zhao, M. (2013). Introduction:	Beaumont, N. J., Jones, L., Garbutt, A., Hansom, J. D., Foster, N. M. (2014). Towards understanding and Foster, N. M., Hudson, M. D., Bray, S., & Nicholls, R. J. Jarratt, D. (2015). Sense of place at a British coastal JNCC (n.d.) Intertidal mudflats and sandflats Morecambe Bay Partnership (n.d.) NPWS (n.d.). Mudflats & Sandflats not covered by Paterson, D. M., Fortune, I., Aspden, R. J., & Black, K. UCD Cultural Values of Coastline Project, 2016-	Nairn, R. (2022). Wild Shores: The Magic of Ireland's Oliver, C. (2025). 'The birds of the Bay'#: Avian Qiu, J., Zhang, Y., & Ma, J. (2024). Wetland habitats Whelan R. (2017). Species focus: Brent Goose.

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S4 – Tab4 – Matrix

Drivers - selected based on stakeholder interviews								**Pressures** - derived from harmonized list, levels 1-2 (if associated with a driver - marked by "X" in the columns A-H)		**"Central Event"** - important species and habitats affected by pressures (for criteria of selection, see Tab "CentralEvent"). Connections included in the bowtie are in green, not included in orange (lack of data or pressure from the driver not present/documented), in blue - indirect effects /also repeating in other column				
ORE	Recreation (other than fis	Fishing (commercial+recr	Agriculture	Transport/shipping	Urban uses	Industrial uses	Wastewater	Code (fi	Pressure name	*Mytilus edulis*	*Burrowing fauna (e.g. Nephrops) and seapens communities*	*Economically important fish species (e.g. cod, herring, plaice, sole)*	*Sandy and muddy intertidal habitats*	*Wintering waterbirds*
								P1	**BIOLOGICAL PRESSURES**					
x		x		x				P1.1	Input or spread of non-indigenous species	Cannot be ruled out due to high shipping	No evidence (Hill et al., 2023)	NN/NA	Coastal and estuarine areas are	NN
				x	x	x	x	P1.2	Input of microbial pathogens	Mussels have been reported to accumulate faecal and pathogenic bacteria and viruses, and toxins from toxic algal bloom. Overall susceptible, but generally recovers fast. Requires routine monitoring (Tyler-Walters, 2008).	Nephrops susceptible to some microbes, but recovers fast (Hill & Sabatini, 2008), other species - unknown (Hill et al., 2023)	Fish are a common transmitter of pathogens, potentially having consequences for the food web (Novoslavskij et al., 2015)	Parasitism and pathogens important are an important component of the food web of the mudflat ecosystems, therefore some indirect effects through communities on the habitats (Albuixech-Martí et al., 2021)	Susceptible to microbes (Szabo et al.., 2022)
								P1.3	Input of genetically modified species and translocation of native species	NN	No evidence (Hill et al., 2023)	NN/NA	NN/NA	NN
								P1.4	Loss of, or change to, natural biological communities due to cultivation of animal or plant species	NN (very common species, mussel cultivation is common but no known effects on wild population) (Tyler-Waters, 2008)	No evidence (Hill et al., 2023)	NN/NA	While aquaculture exists in a few locations around the BBT- e.g.Morecambe Bay Oysters, it is not the main activity (practiced to lesser extent than other parts of Ireland or England; Defra, 2015, Marine Atlas, n.d.). Considering small scale of aquaculture in the BBT and little known about other changes to natural communities due to cultivation of animal/plant species, this connection is not included in the bow-tie.	NN
x	x	x						P1.5	Disturbance of species (e.g. where they breed, rest and feed) due to human presence	NA	NA	Example: bottom trawling impacting herring spawning grounds (MPA Advisory Group, 2023)	There are impacts on e.g. wintering birds feeding in these habitats (Elliott et al., 1998)- marked in the "wintering waterbirds" column	Disturbance displacements, barriers to movement (OWFs; Langston & Pullan, 2003), recreation leading to displacement or change in behaviour (Borgmann, 2011; Lewis 2019)
x	x	x		x				P1.6	Extraction of, or mortality/injury to, wild species (by commercial and	Actively targeted species around the Irish	Nephrops is extracted and possibly	Extracted (targeted or	Will impact communities that are	Collision risks (with OWFs;
								P2	**PHYSICAL PRESSURES**					
x	x	x		x				P2.1	Physical disturbance to seabed (temporary or reversible)	Intermediate intolerance to physical disturbance (Tyler-Walters, 2008)	High intolerance of the community to seabed disturbance (Hill et al., 2023). Nephrops is mobile, but if disturbed it is likely to seek refuge within a burrow within the substratum and so are also likely to be removed-high intolerance (Hill & Sabatini, 2008).	Examples: Herring spawning beds are vulnerable to anthropogenic disturbance of the seabed including but not limited to dredging, sand and gravel extraction, dumping of dredge spoil and waste from fish cages (MPA Advisory Group, 2023)	Mudflats and sandflats are generally resilient and can recuperate well from isolated physical and chemical disturbances (OSPAR 2008, Elliott et al., 1998)	NN (potentially causing temporary displacements; physical loss is a bigger concern)
x		x						P2.2	Physical loss (due to permanent change of seabed substrate or	Removal of the substratum will entail the	High intolerance of the community to	Examples: Herring	Physical removal of the habitat	Depends - not a big concern
x								P2.3	Changes to hydrological conditions	Generally tolerant to turbidity and water flow changes (Tyler-Walters, 2008)	Community sensitive to some of the hydrological pressures (Hill et al., 2023)	NN (might depend on species/hard to assess in the context of climate change and range shifts)	Sensitive to changes in hydrophysical regime, water activity and concomitant sediment change, sea-level rise, exposure or dessication, climate extremes/storms (OSPAR, 2009)	NN
x								P2.4	New habitat creation	Colonizes artificial structures	NN	It is debated whether	Artificial reefs could halt sand-	NN
								P3	**SUBSTANCES, LITTER AND ENERGY**					
x	x		x	x	x	x	x	P3.1	Input of nutrients — diffuse sources, point sources, atmospheric	Intermediate intolerance (Tyler-Walters,	Exhibiting resistance to organic/nutrient	Bioaccumulation of	Highly susceptible to nutirent and	Adverse effects on waterbirds
x	x	x	x	x	x	x	x	P3.2	Input of organic matter — diffuse sources and point sources	Sensitivity to waste/organic matter	Exhibiting resistance to organic/nutrient	Sensitive to effluent	Sensitive to industrial and	Adverse effects on waterbirds
x	x	x	x	x	x	x	x	P3.3	Input of other substances (e.g. synthetic substances, non-synthetic substances, radionuclides) — diffuse sources, point sources, atmospheric deposition, acute events	NN (known to accumulate radionuclides, but little information about adverse effects; Tyler-Walters, 2008)	The effects of 'Other substances' as a pressure will vary depending on the chemical contaminant and the species studied (e.g. seapens are sensitive to cyanide; Hill et al.., 2023; Nephrops exhibits some intolerance to heavy metal contamination; Hill & Sabatini, 2008).	High capacity to bioaccumulate toxic contaminants (Fernandes et al., 2018)	High capacity to accumulate pollutants - synthetics, oil, heavy metals (Elliott et al., 1998)	Waterbirds are an indicator of heavy metal contamination (Wei Zhang & Zhang Ma, 2014)
x	x	x	x	x	x	x	x	P3.4	Input of litter (solid waste matter, including micro-sized litter)	NN (little known about adverse effects,	NN (little known about adverse effects, Hill	Macro- and	Intertidal mudflats can act as a	Sensitive to litter and plastic
x	x	x		x				P3.5	Input of anthropogenic sound (impulsive, continuous)	Tolerant to noise pollution (Tyler-Walters, 2008)	Not relevant (most of the species are infaunal and unlikely respond to a noise disturbance at the benchmark level; Hill et al., 2023)	Noise during works could cause disruption to herring spawning behaviour (MPA Adv. Group, 2023)	NN/NA	Sensitive to anthropogenic sound (Cutt et al., 2013)
x				x				P3.6	Input of other forms of energy (including electromagnetic fields, light and	No evidence of adverse effects (JNCC,	Not sensitive to light; no evidence for other	Impacts on larvae of	NN/NA	Sensitive to light (Cutt et al.,
			x		x	x	x	P3.7	Input of water — point sources (e.g. brine)	Tolerant to salinity changes (Tyler-	Decrease in salinity might cause adverse	NN/NA	E.g. polluted storm-water run-	NN/NA

Sources	Sources				
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