Methods

Author-formatted document posted on 01/08/2025

Published in a RIO article collection by decision of the collection editors.

DOI: https://doi.org/10.3897/arphapreprints.e167392

Operationalising Bow-tie analysis to assess main concerns about biodiversity change in European Seas

Anita Franco, Katie Smyth, Michael Elliott

Operationalising Bow-tie analysis to assess main concerns about biodiversity change in European Seas

Anita Franco[1*], Katie Smyth[1], Michael Elliott[1,2]

[1] International Estuarine & Coastal Specialists, Leven, HU17 5LQ, UK

[2] School of Environmental and Life Sciences, University of Hull, Hull, HU6 7RX

*Corresponding Author: Anita.Franco@iecs.ltd

Abstract

Marine biodiversity is adversely affected by many human activities and their pressures. As such, there is the need for a cause-consequence-response method to objectively address the risks associated with those adverse changes. Such a method is the ISO-accredited Bow-tie technique as an objective and structured approach giving the causes, preventative control measures, mitigation and compensation measures and consequences of changes to biodiversity. Here, the Bow-tie method underpinned by the cause-consequence-response DAPSI(W)R(M) framework was used and adapted to help managers map out risks to biodiversity requiring management of the human activities and their relevant pressures, in specific case study areas (termed Broad Belt Transects, BBTs). Instead of using restrictive proprietary software, a more-flexible template framework was developed in Microsoft PowerPoint to allow a broad user base. This employed standardised lists of elements (and further adapted during the application process) allowing the development of unique, but standardised and directly comparable Bow-ties for all BBTs. The methods of developing the template and standardised lists are described together with the techniques used to help quantify this usually qualitative approach. The successful application of the Bow-tie method in case studies from the European seas shows the adaptability of this approach in ways wider than the original policy-driven risk-assessment use. Although designed for European seas, the approach and standardised lists are sufficiently generic for adoption in wider areas worldwide.

Keywords: marine biodiversity change, marine activities, pressures, cause consequence relationships, risk assessment, risk management, standardised lists

Introduction

The coastal and marine environment is subject to many hazards, each with causes (either natural or anthropogenic) and consequences (adverse effects) (Elliott et al., 2019; Elliott and Kennish, 2024). When such consequences adversely affect something valued by humans, such as health, welfare or property (i.e., the objectives of environmental protection as in ISO 31000; Cormier et al., 2019), a risk ensues, which depends on the frequency, probability and severity of the effect. Marine environmental managers need to be aware of the hazards, their causes and consequences to assess the risks and identify and implement appropriate management responses. The management responses are summarised in the EU Water Framework Directive and Marine Strategy Framework Directive as Programmes of Measures with the aim of reducing the risk to a level that is tolerable or As Low as Reasonably Practical (ALARP) by society (Cormier et al., 2019). However, determining the individual effects of the hazards and risks may be challenging, especially for the environmental and operational managers of coastal activities due to the combined action (and interaction) of several or many hazards which generate cumulative impacts or effects (Piet et al., 2024). Considering such cumulative effects/impacts is a key principle of the ecosystem-based approach that is called for by many national and international policies for the management of the marine environment (Papadopoulou et al., 2025). The Ecosystem-Based approach (EBA) sets the policies and framework which is then operationalised through Ecosystem-Based Management (EBM).

Marine Ecosystem-Based Management fits within the overall DAPSI(W)R(M) framework (pronounced *dap-see-worm*), the cause-consequence-response framework that links Drivers, Activities, Pressures, State change, Impacts (on human Welfare) and Responses (using management Measures) (Elliott, et al., 2017). The Drivers are the basic needs required by society such as food, shelter, employment etc, which then need to be fulfilled by Activities (such as fishing for food). In turn these cause Pressures as mechanisms of change on the natural system (the S) and on the human system (I(W)). The alignment with DAPSI(W)R(M) is required to determine the risks and hazards to the marine system from natural and human causes and how those risks and hazards can be overcome using a programme of management measures (the R(M)) (Elliott et al., 2017). Such an approach can also be used to determine the opportunities in the marine system, which can be affected using a holistic management system (e.g., as carried out using a stakeholder-led approach in the EU FP7 Project CERES; Elliott et al., 2020b). This, in turn, is embedded in a systems analysis approach for integrated marine management (Elliott et al., 2020a). The latter ensures that despite the human stressors, the marine ecological structure and functioning can generate ecosystem services in the natural domain and then societal goods and benefits in the human domain after inputting human capital (Elliott, 2023). Hence, there is the need for an objective, structured approach to determine the effects of human activities and pressures on ecosystem structure, functioning and services and on societal goods and benefits.

Bow-tie analysis is an analytical approach for risk assessment and management, which can be easily adapted for opportunity assessment and management – essentially a cause-consequence-response approach (IEC/ISO, 2009). It is an ISO-31000 compliant method for producing qualitative conceptual models which can lead to quantitative assessments and hence to determine management success (Cormier et al., 2013, 2018, 2019). It addresses a risk or problem of concern and indicates the causes of that problem, ways to prevent those causes and mitigate or compensate the resulting consequences that occur because of the problem. Originally designed for use within industry sectors (e.g., the aviation industry and health and safety practices), the Bow-tie analysis is increasingly used for the ecosystem approach and mapping environmental and ecological risks and their management (e.g., Burdon et al., 2018; Elliott et al., 2020b). As an ISO-compliant and therefore a legally-defendable technique, this approach has been recommended by ICES (International Council for the Exploration of the Sea) (Cormier et al., 2018) and the Department for Fisheries & Oceans Canada as their preferred risk assessment and management methodology (Cormier et al., 2013).

This paper aims to explain the structure of the Bow-tie technique as developed in the context of marine management and marine biodiversity protection. It also, for the first time, gives the standardised lists of components in the approach in order for the technique to be adopted in a standardised manner across not only European seas but also other areas worldwide exposed to similar activities and pressures and with common management approaches. This paper also provides the methodological basis for the Bow-tie analysis implementation in twelve case study areas (termed Broad Belt Transects, BBTs) distributed across the European Seas (Arctic, Baltic, Atlantic and Mediterranean), with the results of some of these analyses being described in the other papers in this collection.

The Bow-tie Diagram Structure and Creation

Bow-tie analysis results in the creation of a bow-tie-shaped diagram which visualises the risks being considered. The DAPSI(W)R(M) framework is easily overlain onto the Bow-tie structure, making it ideal for ecological risk assessment and management (Figure 1). In this context, the central knot represents a particular risk (e.g., loss of profits for a specific fishery due to climate change, or the risk of not meeting biodiversity targets) which may pertain a state change on the natural system or an impact the human system (respectively the S and I(W) of the DAPSI(W)R(M) framework). The left side identifies pathways of potential causes (Drivers, Activities and Pressures in DAPSI(W)R(M)), whereas the right side indicate the consequences resulting from the event and affecting both the natural and human system. Controls to reduce or prevent the consequences are positioned along the pathways of risks on the left (solutions to prevent the central event) and on the right (mitigation/compensation and recovery from the central event), and account for the responses as management measures (R(W) in DAPSI(W)R(M)). The prevention measures are aimed at stopping the hazard, stopping the hazard becoming a risk or reducing the likelihood that the hazard will occur or create consequent risks. Such controls are therefore essential in achieving successful marine management (Elliott et al., 2025).

Escalation factors, which undermine the effectiveness of a given control, can also be added with additional barriers. For example, creating a new piece of legislation might be required to effect prevention but that legislation cannot be created under the prevailing governance system. Hence, the scheme can accommodate uncertainty in risk management. The performance of management controls in managing or reducing these uncertainties relies on a suite of barriers that eliminate, avoid or control the likelihood of a given risk to occur or to mitigate or recover from the consequences of a given risk (Cormier et al., 2019). Barriers implemented closest to the sources of the risk (e.g., at the site of an activity) provide the greatest assurance in reducing uncertainty in achieving environmental management objectives. At the same time, determining the prevention or response to risk allows the opportunities to be defined for the sector in question to accommodate impacts and enhance growth successfully.

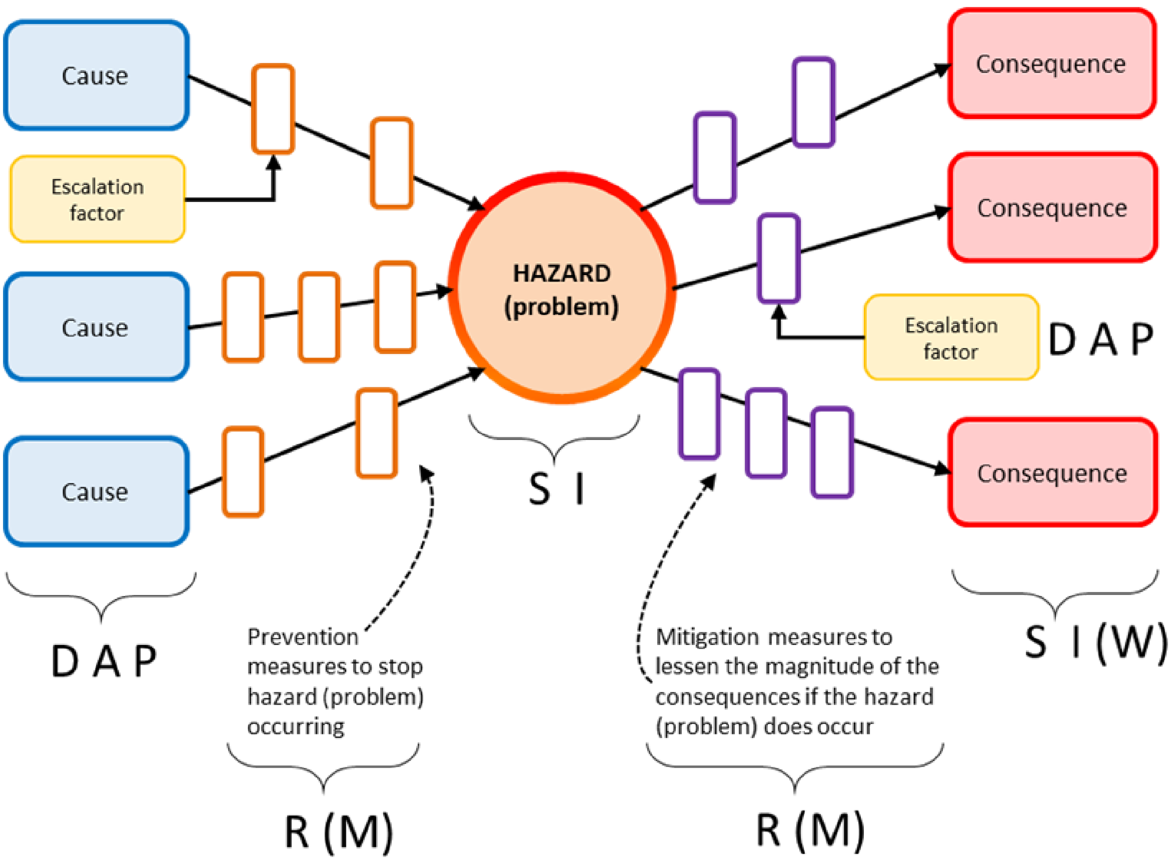

Figure 1. A simplified generic Bow-tie structure overlain by the DAPSI(W)R(M) framework (Elliott et al. 2020b).

The power of a Bow-tie analysis is that it shows a summary of numerous risk scenarios in a single, easy-to-follow picture that can be understood by all levels of an organisation, as well as the general public, thus being a powerful communication tool. While proprietary software to undertake Bow-tie analysis exists (e.g., BowTieXP – see https://www.wolterskluwer.com/en-gb/solutions/enablon/bowtie/bowtiexp), the conceptual model of a Bow-tie structure may be created using various platforms (e.g., Microsoft PowerPoint, mind-mapping software), allowing higher flexibility and wide applicability of such an approach. A similar stakeholder-led approach has previously been used in relation to the effects of climate change on fisheries and aquaculture (Elliott et al., 202b).

For the current paper, the guidance on building Bow-tie conceptual models (or diagrams) was developed for implementation in geographical case-studies (BBTs) across the European Seas, where the main problem (central knot or central event) was a biodiversity change. The Bow-tie approach was adapted with the aim of standardising its implementation across BBTs and making it fit-for-purpose, as described below.

Bow-tie method adaptation

The aim of the Bow-tie analysis as adapted to this study is to conceptually model relevant storyline(s) in a case study area (BBT), which are defined by the question "*What are the main issues/concerns in the area regarding risks to biodiversity and require management of the human activities and their relevant pressures?*". Once the storyline(s) for each BBT has/have been selected, the main question to interrogate the storyline is: "*In relation to the selected storyline, what are the causes and consequences of risks to biodiversity in the area, and how can the causes (human activities) be best managed to reduce the pressures to a level that will allow the appropriate biodiversity to be achieved and maintained?*".

The storyline may be further specified (i.e., to build the Bow-tie model) using the following questions:

- What causes this/these issue(s)/concern(s)? What pressures are caused by human activities?
- What are the consequences of the issue(s)/concern(s)?
- What opportunities (if any) come from the issue(s)/concern(s)? What are the drivers that are seeking the opportunities?
- What can be done as management measures (i) to prevent the issue(s)/concern(s) from happening, (ii) to adapt, control, mitigate and/or compensate for the consequences if the issue(s)/concern(s) does/do occur?
- How can these measures reduce the pressures and what mitigation is needed when biodiversity is adversely affected due to non-natural causes?

Further questions may be formulated regarding which escalation factors can enhance the management measures or can cause them to fail, thus contributing to the pressures and undermining biodiversity. However, these were not explored in detail the methodology developed here.

A template was created in Microsoft PowerPoint to structure the Bow-tie diagram according to the rationale above and to standardise its visual appearance. The DAPSI(W)R(M) framework was overlain to the Bow-tie structure and linked to the central knot representing the main problem of biodiversity change in a BBT, as outlined in Figure 2.

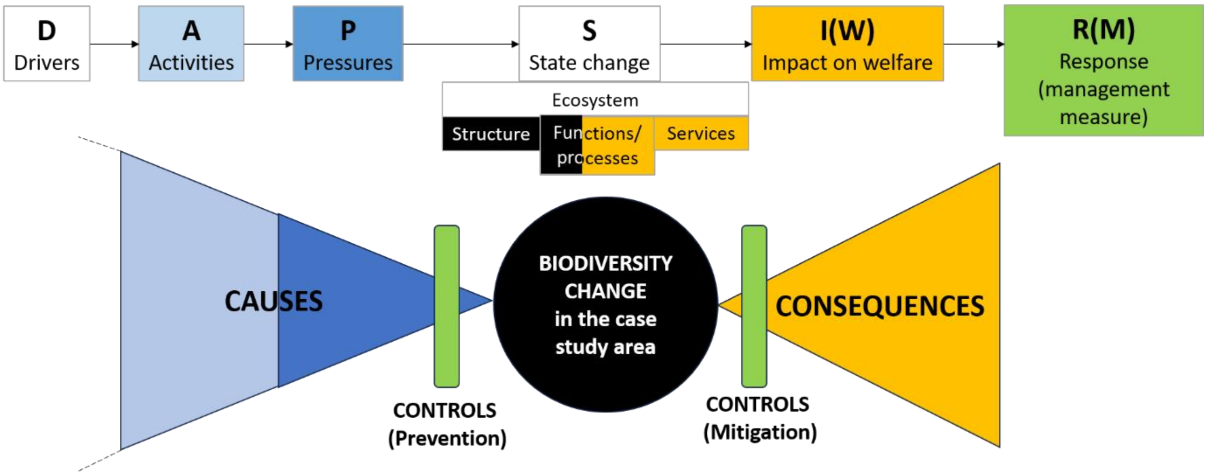

Figure 2. Outline of the broader Bow-tie structure and components (causes, consequences etc) overlain with the relevant elements of the DAPSI(W)R(M) framework.

Standardised lists (also termed controlled vocabularies) were created for the different components of the Bow-tie. For each component (causes, consequences etc), the lists provided categorisations according to a hierarchical nested classification system including multiple levels which specify the component with increasing detail. Where possible, the categorisation of the different types of elements followed existing, accepted standards and criteria, as described below in the resulting guidance.

Results: Bow-tie guidance

Bow-tie graphic template

The template for the Bow-tie structure is shown in Figure 3. Example elements and cause-effect links are shown, defined according to the standardised lists of elements. The template has the main aim to define a common structure and organisation of the content of a finalised Bow-tie diagram, while the formatting (text size, colouring etc) is indicative and may be adjusted by the user as preferred. The diagram was created in Microsoft PowerPoint, but the user has the freedom of using whichever platform they prefer, as long as the structure and content are standardised.

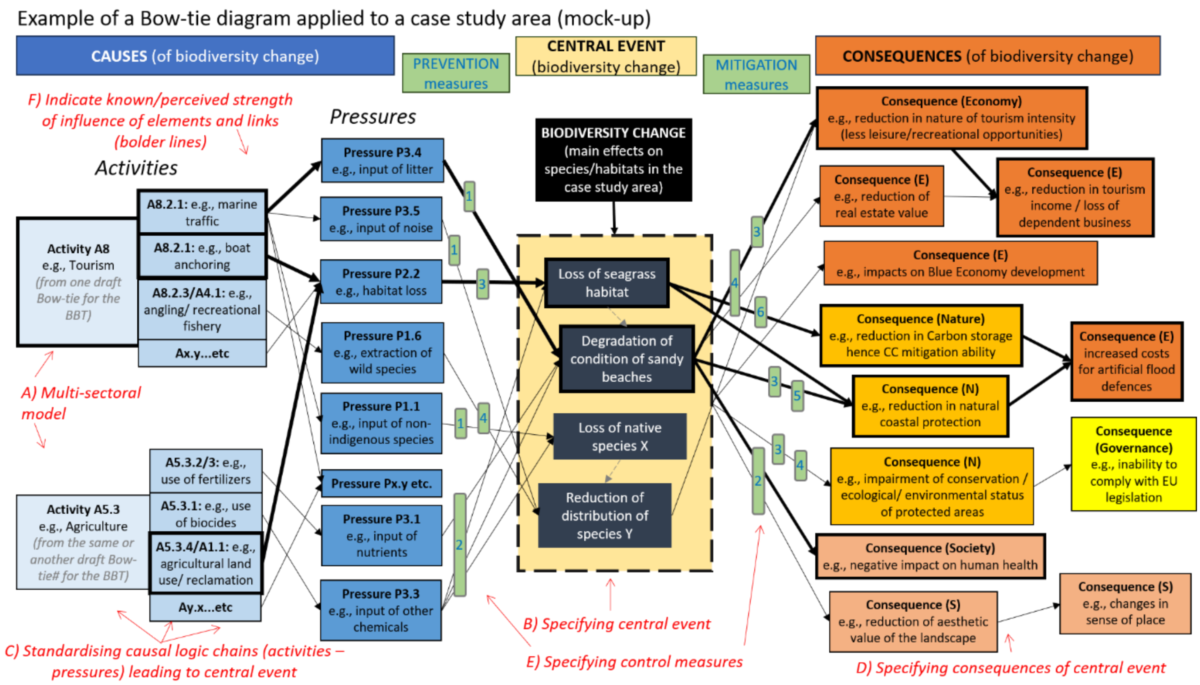

Figure 3. Bow-tie template as developed in this study. Key steps in the creation of the diagram (points A-F, in red) are as described in the text.

Key aspects and steps in the creation of the Bow-tie conceptual model according to the provided template are outlined below, following the lettering (A-F) shown in Figure 3.

A) Multi-sectoral model

When answering the main question about the main issues/concerns in a case study area in relation to changes in biodiversity, it is necessary to focus on identifying the main sectors of human activities that may create or cause the problem. Depending on the breadth of expertise and experience of those answering the question (e.g., researchers, stakeholders), this may lead to generating one (or multiple) sectoral Bow-tie diagrams (e.g., one for the problems caused by tourism, one for fisheries). As the different sectors (and activities within) do not exist in isolation and may interact generating cumulative adverse effects in an area, it is recommended that activities from multiple sectors are included in a single Bow-tie model, provided that they contribute to causing the same biodiversity changes that are at the core of the model (central event; see step B).

B) Central event – the specific problem

The central element of the Bow-tie represents the ‘undesirable event’ or ‘event to be avoided’; this represents the most fundamental and challenging part of the analysis on which the remaining analysis is dependent. This is the starting point of building the Bow-tie diagram. Here, the central element represents an unwanted change in biodiversity, which should be detailed for the case study being examined by specifying what change in biodiversity is of main importance/concern in the BBT. This relates to which habitat, species or processes of biodiversity are most affected by the main pressures in the BBT. As in the DAPSI(W)R(M) framework, pressures are defined as the mechanisms of change then this also indicates the way in which the natural and human systems are changed.

As a change in biodiversity in an area may manifest through changes concerning multiple ecosystem components (e.g., the changes for different species, habitats or processes), the traditional and proprietary (ISO compliant) structure of the Bow-tie analysis, which allows for a single central event of concern, would lead to the creation of multiple Bow-tie diagrams, one for each individual central event. The Bow-tie method adaptation developed here allows to split the central event into a group of central events to identify the different ways of biodiversity change in the study area. This allows to depict the possible links between these multiple central events, which may be indirect (e.g., being caused by the same pressure and associated activities, or generating similar consequences) or direct linkages (e.g., where a loss of a habitat affects the populations of associated species, or where a change in a species distribution affects other species via competitive or prey-predator interactions). Providing a higher detail in the specification of the central event also helps in identifying more specific consequences and control measures.

In general terms, the central event relevant to the Bow-tie model developed here would refer to a change affecting species, habitats or ecosystem processes, which may manifest in altered distribution, quantity (e.g., species abundance, habitat extent, intensity of ecosystem processes) or condition of the ecosystem components affected. The detailed specifications of the central event for an area (e.g., which species, which habitat, which change) would relate to the question posed by the user with local knowledge, may be varied and are specific to the BBT and the storyline of interest. Therefore, there no standardised lists could be defined for the possible central events. However, the generic questions of concern indicated above lead to examples of how the central event may be specified such as: reduction in seagrass cover, reduction in herring population, or loss of mud for carbon sequestration. A higher detail may even be provided, for example by specifying an amount of change (e.g., 50% reduction in northern shrimp population).

It should be noted that the causes of biodiversity changes may differ due to their different spatial occurrence. For example, activities and their pressures that mainly occur in the coastal area would affect elements of its biodiversity (e.g., anchoring of tourist ships may lead to physical disturbance and loss of seagrass) but are unlikely to directly affect other biodiversity components offshore. The latter, in turn, may be affected by offshore activities and associated pressures (e.g., the physical impact of offshore wind farm turbine operation might lead to distribution change of migratory birds, due to collision impacts, avoidance and changes in migratory routes). As the Bow-tie diagram represents an area as a whole and needs to account for the dynamic nature of the environment and its biodiversity, this differentiation is not explicit in the model, although notes accompanying the diagram might help in correctly interpreting it. If the spatial differentiation within the BBT is essential to assess risk and define management (e.g., independent management units under the remit of different authorities or even different countries, where the BBT is trans-border), separate Bow-tie models could be developed for different parts of the study area.

The changes in biodiversity that are specified as central event(s) are likely to represent broad scale changes (at the higher levels of ecological organisation, e.g., population or habitat) that may result from smaller scale changes (e.g., physiological effects due or leading to reduced tolerance or survival, increased mortality, impaired reproduction). These latter changes are effectively part of the central biodiversity concern in the Bow-tie, although they might be only implicitly included in the diagram; however, if specified, they should be part of the central event.

C) Causes: activities and pressures

The causes directly leading to the changes in biodiversity specified in the central knot of the Bow-tie diagram are the left-hand side pressures exerted on the environment as the result of human activities. However, it is of value to further detail causes by creating logic chains linking activities and pressures and then pressures and the central event. To create greater discrimination, activities may be expressed at different levels, e.g., at a higher level (sectors such as tourism/recreation, fisheries, navigation), and with more detailed specification (operations such as, anchoring of tourism vessels). Therefore, making explicit logic chains will make it easier to identify the main pressures affecting biodiversity.

As a minimum, the Bow-tie should therefore include the main relevant causal logic chains for the problem of interest/concern in the area and the most important pressures. Any link between an activity and a change in biodiversity should always be mediated (pass through) a pressure, the mechanism of change, so that only pressures are directly linked to the central events in the Bow-tie diagram.

In order to link the Bow-tie analysis to current European marine policy and management, the standardised lists of causes are primarily based on the categorisation of activities and pressures given in the Marine Strategy Framework Directive (EU, 2017). According to this, two main category levels are identified for each type of cause: the broader categorisation (here defined as Level 1) identifying themes and the more detailed categorisation (Level 2) identifying types of activities or pressures within (Tables 1 and 2). However, as the MSFD list of pressures does not include climate change, this was added as broad pressure category (theme, Level 1; Table 2), with the physico-chemical changes to the aquatic environment indicated as specific pressures (Level 2) for the change in biodiversity.

The provided standardised lists may be further populated by specifying activities or pressures to a higher detail (Level 3 or higher in the hierarchical nested classification system) as relevant to and needed by the specific application (case study). For example, activities pertaining coastal defence and flood protection (A1.3 in Table 1) could be differentiated into flood defence achieved by either hard engineering (e.g., seawalls) or soft engineering (e.g., beach nourishment, managed realignment), leading to further coding of such activities in more detail (e.g., as A1.3.1 and A1.3.2). Similarly, the extraction of minerals (rock, metal ores, gravel, sand, shell) (A2.1) could be further specified as coastal mining (A2.1.1), or the activity broadly defined as agriculture (A5.3) could be differentiated in a set of operations such as use of biocides, use of Nitrogen-based fertilisers, use of Phosphorus-based fertilisers, irrigation, agricultural land use, etc (A5.3.1, A5.3.2, A5.3.3 etc). In a similar way, the pressure types defined at Level 2 could be further specified, e.g., by differentiating input and spread of non-indigenous species from P1.1 (Table 2), specifying which hydrological conditions are affected by change (from P2.3), or indicating which types of substances are introduced into the system (from P3.3). Given the large number of possible permutations, for both activity operations and detailed pressures (defined at lever higher than Level 2 in the hierarchy), where such defined levels are required, these are left to the user to specify down to the level of detail needed. Indicating the specific cause of the biodiversity change of concern in the case study will make it easier to identify targeted control measures to manage the specific activity or pressure.

Table 1. Standardised list for activities with standardised coding (modified from: EU, 2017).

Theme - Level1		**Activity type - Level 2**	
ID	**Name**	**ID**	**Name**
A1	PHYSICAL RESTRUCTURING OF RIVERS, COASTLINE OR SEABED (WATER MANAGEMENT)	A1.1	Land claim
		A1.2	Canalisation and other watercourse modifications
		A1.3	Coastal defence and flood protection
		A1.4	Offshore structures (other than for oil/gas/renewables)
		A1.5	Restructuring of seabed morphology, including dredging and depositing of materials
A2	EXTRACTION OF NON-LIVING RESOURCES	A2.1	Extraction of minerals (rock, metal ores, gravel, sand, shell)
		A2.2	Extraction of oil and gas, including infrastructure
		A2.3	Extraction of salt
		A2.4	Extraction of water

Theme - Level1		Activity type - Level 2	
ID	**Name**	**ID**	**Name**
A3	PRODUCTION OF ENERGY	A3.1	Renewable energy generation (wind, wave and tidal power), including infrastructure
		A3.2	Non-renewable energy generation
		A3.3	Transmission of electricity and communications (cables)
A4	EXTRACTION LIVING RESOURCES	A4.1	Fish and shellfish harvesting (professional) (*for recreational fishing please see A8)*
		A4.2	Fish and shellfish processing
		A4.3	Marine plant harvesting
		A4.4	Hunting and collecting for other purposes
A5	CULTIVATION OF LIVING RESOURCES	A5.1	Aquaculture — marine, including infrastructure
		A5.2	Aquaculture — freshwater
		A5.3	Agriculture
		A5.4	Forestry
A6	TRANSPORT	A6.1	Transport infrastructure
		A6.2	Transport — shipping
		A6.3	Transport — air
		A6.4	Transport — land
A7	URBAN AND INDUSTRIAL USES	A7.1	Urban uses
		A7.2	Industrial uses
		A7.3	Waste treatment and disposal
A8	TOURISM AND LEISURE	A8.1	Tourism and leisure infrastructure
		A8.2	Tourism and leisure activities
		A8.2	Local recreation (angling, walking, canoeing, …)
A9	SECURITY/DEFENCE	A9.1	Military operations
		A9.2	Research, survey and educational activities

Table 2. Standardised list for pressures with standardised coding (modified from: EU, 2017).

Theme - Level1		Pressure type - Level 2	
ID	**Name**	**ID**	**Name**
P1	BIOLOGICAL PRESSURE	P1.1	Input or spread of non-indigenous species
		P1.2	Input of microbial pathogens
		P1.3	Input of genetically modified species and translocation of native species
		P1.4	Loss of, or change to, natural biological communities due to cultivation of animal or plant species
		P1.5	Disturbance of species (e.g. where they breed, rest and feed) due to human presence
		P1.6	Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities)

Theme - Level1		Pressure type - Level 2	
ID	**Name**	**ID**	**Name**
P2	PHYSICAL PRESSURE	P2.1	Physical disturbance to seabed (temporary or reversible)
		P2.2	Physical loss (due to permanent change of seabed substrate or morphology and to extraction of seabed substrate)
		P2.3	Changes to hydrological conditions
		P2.4	New habitat creation
P3	SUBSTANCES, LITTER AND ENERGY	P3.1	Input of nutrients — diffuse sources, point sources, atmospheric deposition
		P3.2	Input of organic matter — diffuse sources and point sources
		P3.3	Input of other substances (e.g. synthetic substances, non-synthetic substances, radionuclides) — diffuse sources, point sources, atmospheric deposition, acute events
		P3.4	Input of litter (solid waste matter, including micro-sized litter)
		P3.5	Input of anthropogenic sound (impulsive, continuous)
		P3.6	Input of other forms of energy (including electromagnetic fields, light and heat)
		P3.7	Input of water — point sources (e.g. brine)
P4	CLIMATE CHANGE	P4.1	Change in temperature
		P4.2	Change in precipitation
		P4.3	Change in sea level
		P4.4	Change in storminess
		P4.5	Change in water pH

It is of note that the causes of interest in the Bow-tie model are solely those directly creating the central concern. Some activities may have other effects (directly affecting the local economy, society etc) but these may not be the consequence of changes in biodiversity and therefore are not relevant to the Bow-tie model. Hence, in this model, while possibly important for other reasons not connected with biodiversity, links that do not pass through the central event to connect cause and consequence are not included. Similarly, activities and pressures not affecting biodiversity are also not included in the context here.

As the Bow-tie in the current case focusses on the ecological (biodiversity) state change influencing, then physico-chemical alterations (e.g., temperature increase, turbidity increase) are considered as pressures created by activities and so are in the logic chains on the left-hand side (as causes).

D) Consequences of biodiversity change

The elements on the far right of the Bow-tie represent the consequences of the changes in biodiversity in the case study area and which affect other parts of the ecosystem or on human welfare (economy, society, nature, governance etc).

There should be logic chains also on the right-hand side of the Bow-tie linking a central event (aspect of change in biodiversity in the BBT) to primary (direct) consequences, and the latter to secondary consequences (and tertiary if needed). These logic chains may involve consequences defined within the same domain or between domains. For example, the primary and secondary consequences could be all within the economic domain if the change in biodiversity in an area leads to a reduction in tourism intensity (primary consequence) which causes an economic loss (secondary consequence). Alternatively, when the biodiversity change leads to a decrease in the environmental status in the region (primary consequence for nature), this may lead to the inability of the Member State to comply with EU MSFD requirements (secondary consequence for governance) which would then may lead to infraction proceedings and a fine by the European Court of Justice (hence a tertiary economic consequence).

To our knowledge, there is no comprehensive list of all possible consequences as these are varied and site-specific. Therefore, a categorisation of the types of consequences has been defined in this study to promote standardisation of their identification between Bow-tie models in different areas. The categorisation has been refined by discussion with stakeholders from twelve case study areas (BBTs) across the European seas (Arctic, Baltic, Atlantic and Mediterranean) (see specific results in the other papers in this collection), and also considering the types of consequences identified from other Bow-tie analyses in Elliott et al. (2020b). The resulting standardised list identifies three main domains for consequences (impacts to nature, economy and society; 'Themes' in Table 3) and the typologies within these (Table 3).

The impacts on nature (C1) include specific consequences of the change in biodiversity (central event) on marine processes (including the ability to deliver provisioning and regulating ecosystem services (ES); e.g., change in carbon sequestration which may affect climate regulation) and on the ability to deliver other ESs, as specified in the associated typologies. The consequence types defined in relation to the supply of ESs are grouped by type of ES (at Level 2 classification) and further detailed (Level 3) in relation to specific ecosystem services relevant to the Bow-tie model. The impact on governance has been included under C1 as changes in nature that are related to requirements of nature conservation policies (and which may lead to inability to comply with them; this may also have secondary economic consequences as indicated before).

The impacts on economy (C2) include consequences such as: increasing costs to undertake/increase additional specific activities (e.g., beach cleaning, monitoring etc) or due to price increase (C2.1); decreased income (e.g., from reduction of business sales, activities using the area, or in relation to a specific sector such as for example tourism or a fishery) (C2.2); decreased economic value of assets (C2.3; e.g., real estate devaluation); impacts affecting the labour market (C2.4; e.g., increase of unemployment), Blue economy development (C2.5), or other types of economic impacts (C2.6; e.g., fragmentation of the uses of the marine environment, development of the black market).

The impacts on society (C3) include consequences affecting the cultural benefits humans extract from the marine system (e.g., decrease in activities leading to spiritual and cultural wellbeing, including relaxation, amusement, enjoyment, leisure) as well as human health (both physical and mental) and behaviour.

In the context of risk assessment and management, the consequences to be included in the Bow-tie model have been specified as negative impacts (e.g., decrease in provision of a particular resource, increase in cost). However, it is recognised that opportunities may also arise from changes in biodiversity (e.g., potential new/alternative resources) and therefore the consequences listed in Table 3 may alternatively be expressed as positive changes/impacts (e.g., decrease in cost) should this be relevant to the specific Bow-tie model.

It is emphasised that the list of consequences provided in Table 3 is not exhaustive and may be updated and integrated by the user should additional types become relevant or further specification (to classification Level 3 or above) be needed for the specific implementation.

Table 3. Standardised list for consequences with associated ID codes. Negative impacts are indicated in the context of risk assessment and management, but these may be changed into positive impacts instead in case of arising opportunities as consequences.

Theme - Level1		**Consequence type - Level 2**		**Consequence - Level 3**	
ID	**Name**	**ID**	**Name**	**ID**	**Name**
C1	Impacts on NATURE	C1.1	Change in ecosystem /marine processes		
		C1.2	Decrease in provisioning ecosystem services	C1.2.1	Decrease in provision of fish & shellfish
				C1.2.2	Decrease in provision of algae & seaweed
				C1.2.3	Decrease in provision of genetic resources
				C1.2.4	Decrease in provision of water supply
		C1.3	Decrease in regulating ecosystem services	C1.3.1	Decrease in Climate regulation
				C1.3.2	Decrease in Natural Hazard Protection
				C1.3.3	Decrease in Waste breakdown and detoxification
		C1.4	Change in landscape/seascape		
		C1.5	Impacts on nature governance		
		C1.6	Other impact on nature		
C2	Impacts on ECONOMY	C2.1	Increased costs		
		C2.2	Decreased income		
		C2.3	Decreased economic value		
		C2.4	Negative impact on labour market		
		C2.5	Negative impact on the Blue Economy development		
		C2.6	Other economic impact		
C3	Impacts on SOCIETY	C3.1	Decrease of aesthetic value/benefits		
		C3.2	Decrease in human health (and benefits for it)		
		C3.3	Impact on sense of place		
		C3.4	Decrease in other cultural benefits		
		C3.5	Changed perception/behaviour		
		C3.6	Other impact on society		

E) Control measures (PREVENTION / MITIGATION)

The control measures should be those included in the Programmes of Measures necessary to manage areas and prevent, recover or mitigate deterioration which would ensure that, for example, the Good Environmental Status under EU Directives is not met. They are differentiated into:

- PREVENTION measures, i.e., management measures that are implemented with the aim of reducing or possibly avoiding the pressures in order to reduce or possibly avoid the changes in biodiversity. As such, these controls apply to elements and links on the left of the central event. Examples are: technological measures that, applied to the equipment used in certain activities, may reduce or eliminate the resulting pressure; regulatory/governance measures, e.g., monitoring also to inform marine spatial planning, or restricting certain activities outside the area or the period of the year that may be more sensitive for the species/habitats of concern.

- MITIGATION measures, i.e. management measures that are implemented with the aim of reducing the magnitude of the impacts (consequences) of biodiversity change on economy, society or nature, after the biodiversity changes have happened. In this case, the mitigation measures have no effect on the magnitude of the biodiversity changes, but rather on their consequences. As such, these controls apply to elements and links on the right of the central event. These also include compensatory measures which may be of three types: compensating the users (economically), compensating the resource (such as by restocking or replanting) or compensating the environment (such as by creating new habitats). Examples are: economic measures such as compensation or subsidies; regulatory measures such as legislation and monitoring; raising awareness and knowledge, e.g., towards changes in behaviour to promote the use of alternative resources to obtain the same benefits.

Some types of management measures may be implemented as both Prevention and Mitigation controls, for example governance methods such as fishing quotas can be used as a preventative measure to attempt to stop a decline in the population of a species, but can also be used as a mitigation measure to try to halt further reduction if the population has already declined thus mitigating its effects on society, economy or other nature components.

To avoid excessive text in the Bow-tie diagram, it is suggested that the control measures selected for the specific Bow-tie model are identified and numbered in a separate list (legend) and their numbers reported on the diagram. As the control measures may apply to individual elements or links of the Bow-tie, they should be included in the Bow-tie diagram in a clear position as to indicate the specific element or link to which they are relevant (to the left or right of the Bow-tie). Hence, they may be inserted within the logic chains one either side of the central event.

It is of note that prevention measures may apply to the link between a pressure and the central biodiversity change (where the management measure is applied to the pressure itself to reduce/remove it; e.g., invasive species control/eradication) but also to the link between an activity and a pressure (where the measure is applied to the activity that generates the pressure to reduce/remove the latter; e.g., regulation of activities that are the main source/pathways of introduction of invasive species). Similarly, mitigation and compensation control measures may apply to the link between the biodiversity change and a primary consequence, but also to the link between a primary and a secondary consequence. If needed, control measures for these different links may be indicated, but there is a minimum requirement to indicate those controls that apply to the links between central event and primary consequences, where identified.

To our knowledge, there is not a comprehensive list defined for all the possible types of controls as these are varied and site-specific. Therefore, a categorisation of the types of controls is defined here to promote standardisation of control measures between Bow-tie models in the different areas. The categorisation was refined by discussion with stakeholders for the different case study areas (BBTs) across the European seas and also considering the types of controls identified from other Bow-tie analyses in Elliott et al. (2020b). The characteristics defining the 10-tenets of adaptive management and sustainability (Elliott, 2013; Elliott et al., 2025) were also used to establish the control categories, especially at the broader level (theme, Level 1) in order to consider all environmental and societal aspects of marine management.

The resulting standardised list identifies six broad categories of controls based on the types of instruments used for management and the part of the socio-economic-environmental system where they operate (nature/activities management measures; economic measures, legal/administrative measures etc.) (themes, Level 1 classification in Table 4). These include: the control measures managing the ecosystem through the protection, maintenance or improvement of nature (habitats, species, connectivity, ecological structure, functioning, carrying capacity) and the causes of their degradation (regulating/reducing activities/pressures, including spatial planning) (Ctrl1); the use/application of technological improvements and/or better practices for sustainable use of the environment (Ctrl2); the measures towards improving, building or sharing knowledge of the socio-ecological system towards its better understanding, use and management (Ctrl3); legal and administrative measures (Ctrl4); controls using economic instruments/tools/measures (Ctrl5), and measures to change behaviour, habits and societal perception (acceptance, tolerance, value, societal carrying capacity) (Ctrl6).

Within these themes, control measures have been further specified into two additional classification levels, with Level 2 often (but not always) corresponding to the strategy adopted or vision driving the implementation of management measures, rather than the implementing measures/tools themselves, which are more likely to be represented in Level 3 of the classification (Table 4).

It is emphasised that the list of controls provided in Table 4 is not exhaustive and may be updated and integrated by the user should additional types become relevant or further specification (to classification Level 3 or above) be needed for the specific implementation.

Table 4. Standardised list for controls with associated ID codes.

Theme - Level1		Control type - Level 2		Control - Level 3	
ID	**Name**	**ID**	**Name**	**ID**	**Name**
Ctrl1	NATURE PROTECTION	Ctrl1.1	Nature conservation/ management		
		Ctrl1.2	Nature restoration/ enhancement	Ctrl1.2.1	Habitat/Ecosystem restoration/remediation/enhancement
				Ctrl1.2.2	Species populations restocking (incl. of threatened and declining species)
				Ctrl1.2.3	Habitat creation or offsetting (compensation)
		Ctrl1.3	Activities regulation (spatial, temporal and/or intensity)	Ctrl1.3.1	Setting limits and restrictions (e.g. fishing quotas, number of visitors per season) to control impacts
				Ctrl1.3.2	Spatial (and temporal) management/planning
				Ctrl1.3.3	Relocate activities
				Ctrl1.3.4	Promote co-development of activities
				Ctrl1.3.5	Enforce/improve/establish MPAs or other protection measures (e.g. corridors)
				Ctrl1.3.6	Flexible spatial limits for management to improve habitats and productivity, including offsetting and No-take/No-activity Zones
				Ctrl1.3.7	Protect essential habitats, including temporal closure/dynamic MPAs
				Ctrl1.3.8	Adapt seasonality of activity based on species/habitat ecology (e.g., reproduction migrations, recruitment)
				Ctrl1.3.9	Implement mitigation measures to reduce pressures
Ctrl2	INNOVATION: TECHNOLOGY/ PRACTICES TOWARDS HIGHER SUSTAINABILITY	Ctrl2.1	Reduce fossil fuel consumption (and CO2 emissions) or increase alternative energy use		
		Ctrl2.2	Technology improvements or adoption of alternative practices towards reduction/ mitigation of the impact	Ctrl2.2.1	Building with nature-based solutions
				Ctrl2.2.2	Organic farming
				Ctrl2.2.3	Sustainable meat production
				Ctrl2.2.4	Arable land for crops
				Ctrl2.2.5	Crop rotation
				Ctrl2.2.6	Regionalised agriculture

Theme - Level1		Control type - Level 2		Control - Level 3	
ID	**Name**	**ID**	**Name**	**ID**	**Name**
				Ctrl2.2.7	Growth of non-native plantations
				Ctrl2.2.8	Controlled drainage
				Ctrl2.2.9	Erosion control on fields
				Ctrl2.2.10	Environmentally friendly energy generation
				Ctrl2.2.11	Technical improvements of waste water treatment plants related to aspects other than nutrients
				Ctrl2.2.12	Riparian zones
				Ctrl2.2.13	Flood defence - hard engineering methods
				Ctrl2.2.14	Coastal erosion defence (sand dunes, wetlands)
Ctrl3	KNOWLEDGE BUILDING (MONITORING & RESEARCH)	Ctrl3.1	Monitoring (of the environment, activities, impacts on the ecosystem and/or society)		
		Ctrl3.2	Developing/ using better assessment methodology / indicators to provide more robust management measures		
		Ctrl3.3	Research to fight new diseases		
		Ctrl3.4	Research into early warning systems for HABs, biofouling and jellyfish		
		Ctrl3.5	Promoting knowledge transfer (e.g. data sharing, digitalisation, communication, co-working)		
Ctrl4	GOVERNANCE (LEGAL & ADMINISTRATIVE MEASURES)	Ctrl4.1	EU/international legislation (enforcement, new adoption)	Ctrl4.1.1	New EU/international legislation to control climate change (e.g. limiting greenhouse gas emissions)
				Ctrl4.1.2	Adaptive legislation which can react to unexpected positive or negative changes, allow innovation development
				Ctrl4.1.3	New EU Invasive Alien Species Regulation
				Ctrl4.1.4	EU legislation needed for the adaptation for monitoring and support

Theme - Level1		**Control type - Level 2**		**Control - Level 3**	
ID	**Name**	**ID**	**Name**	**ID**	**Name**
				Ctrl4.1.5	EU legislation to promote co-development (e.g., to build up offshore big polygons with common facilities)
		Ctrl4.2	National/ local legislation (enforcement, new adoption)	Ctrl4.2.1	Local legislation to reduce [XYZ] pressure by controlling activities
				Ctrl4.2.2	Adopt legislation according to changes in presence and/or distribution of the species/habitat (allow/ban activities, regulate use of new/alternative resources)
		Ctrl4.3	Other governance measures/ tools	Ctrl4.3.1	Set/adopt targets, standards, norms
				Ctrl4.3.2	Establish access rights (to a resource, area etc)
				Ctrl4.3.3	Clustering and risk assessment
				Ctrl4.3.4	Well-designed ecosystem management
				Ctrl4.3.5	Pluri-annual management plan
				Ctrl4.3.6	Developing/implementing high-level/broad-scale strategies/plans (incl. development plans)
Ctrl5	ECONOMIC CONTROLS	Ctrl5.1	Funding, incentives, investments	Ctrl5.1.1	Government compensation payments to [SECTOR XYZ] (e.g. to mitigate the loss of revenues)
				Ctrl5.1.2	Economic incentives to improve/promote/support alternative activities with lower impact on biodiversity (innovation)
				Ctrl5.1.3	Enhancing incentives/subsidies to support adaptation to new technologies
				Ctrl5.1.4	Invest in improving revenue in the mid-term (technology, security in price, staff recruitment and retention, equipment)
				Ctrl5.1.5	Invest in reducing costs in the mid-term (technology, staff recruitment and retention, vessels)
				Ctrl5.1.6	Investment/subsidies to allow/promote alternative species
		Ctrl5.2	Economic disincentives (e.g., taxation, fees, sanctions)		
		Ctrl5.3	Other economic measures		

Theme - Level1		Control type - Level 2		Control - Level 3	
ID	**Name**	**ID**	**Name**	**ID**	**Name**
Ctrl6	CULTURAL & SOCIAL MEASURES (BEHAVIOUR / EDUCATION / MARKETING)	Ctrl6.1	Fostering awareness of nature and impacts		
		Ctrl6.2	Foster societal participation in management (e.g. stakeholder engagement, citizen participation in monitoring)		
		Ctrl6.3	Changing societal perception of values		
		Ctrl6.4	Educating society (e.g., consumers on changing species and origin of products, including ecolabelling)		
		Ctrl6.5	Explore and promote alternative resources, species or stocks (including invasive thermophilic ones) to provide the benefit and/or to conserve the impacted species		
		Ctrl6.6	Explore alternative markets and consumers		
		Ctrl6.7	Explore and promote alternative ways (activities etc)		

F) Strength of influence

Once the Bow-tie structure has been defined, a further step may be undertaken to include additional information regarding the variability in the known/perceived strength of influence of the different elements and links in the specific case study. The weighting may be indicated graphically in the Bow-tie diagram by using thicker shape outlines for those elements (causes, central events, consequences) and links that are considered more important to define the case study (e.g., more intense activities or pressures, stronger changes, consequences of major relevance). The weighting system (e.g., score or weight class assigned to the links and correspondence with the line thickness in the Bow-tie diagram) should be clearly defined by the user to aid interpretation of the resulting Bow-tie model. It is recommended that, as a minimum, a three-class categorisation (namely, Low, Medium and High strength) is used.

This approach may be used to identify priorities for the control measures (i.e., where they act on more influential links or elements) and may also be used in further developments of the Bow-tie analysis, e.g., for scenario exploration. In fact, the relative amounts/intensities of the different activities and the relative strengths of pressures may change under different scenarios, thus possibly leading to changes in which are the most important pathways (logic chains) within a Bow-tie model and therefore in which are the most relevant control/management measures.

Concluding Remarks

The guidance for Bow-tie analysis (including templates for the graphical output and standardised lists) as developed in this study represents the first attempt to consolidate the elements within Bow-tie analysis as it can be applied to stressors on marine biodiversity. The approach builds on earlier work (e.g., Elliott et al., 2020b) in the harmonisation and standardisation of the use of this approach to identify cause-effect relationships (logic chains) relevant to the risk to marine biodiversity and explore the possible measures that may be used to manage this risk. It is emphasised that the Bow-tie approach as described here gives an objective and standardised framework for addressing marine environment problems. The use of Bow-tie analysis as described here is also evidence that the method can be successfully adapted to wider functions than the policy-driven, regulatory-focused Bow-ties seen elsewhere in ecological settings (e.g., Cormier et al 2018).

The standardisation of the approach and of the terminology used to categorise the Bow-tie elements (standardised lists) is essential to allow a harmonised implementation across multiple case studies hence comparability across multiple models, as for example those implemented for the BBT case studies, as shown in this collection of papers. This has the advantage to allow straightforward integration of information compiled from multiple Bow-tie models into a comparative analysis, for example using multivariate classification or ordination techniques, thus exploring common patterns and differences, e.g., across geographic regions (as in Elliott et al., 2020b).

Despite the standardisation, the approach provided still has some flexibility, both in terms of the platform used to implement it and the building blocks used to build and adapt the Bow-tie model to the specific case study, which are seen both as advantages for an easier usability. In fact, the graphic model (Bow-tie diagram) may be created using free and user-friendly platforms (e.g., Microsoft PowerPoint or any mind mapping software) without the constraints that are inherent in the original proprietary software (e.g., those mentioned before and pertaining the central event). For ecological settings where there may be multiple but linked central events, this less restrictive approach allows users to map the “big picture” without the need for numerous or nested Bow-ties. It also increases the ability of lay-users or the public to understand the big picture presented by environmental managers and the interconnectedness of its components. In addition, while the higher-level categories defined for the model elements (themes and types) are harmonised through the standardised lists provided, the user has the freedom to refine these lists, for example by specifying some categories with higher detail. A variability in the level of detail may be needed, depending on the knowledge and information available to the user, and their expertise (e.g., leading to the ability to specify parts of the Bow-tie model more than others). The best use of this characteristic would be made by developing the Bow-tie model as a collaborative exercise involving the contribution of multiple stakeholders, to capture and integrate knowledge and expertise from multiple and varied sources.

Although the Bow-tie diagram for which guidance is given here is essentially a conceptual model providing a qualitative framework for the problem of concern, it can be further developed to undertake a quantitative analysis of the risks and opportunities arising from the case study if the relative magnitudes of the different elements are known or at least can be obtained by expert judgement. For example, Bayesian Belief Network Analysis can be employed to indicate the probabilities along the various logic chains (Rambo et al., 2019). A first step towards this is taken in this guidance by introducing the possibility of rating the importance of certain elements of the Bow-tie model and their links and representing this graphically in the diagram. A similar approach was trialled in Elliott et al. (2020b), where causes and consequences were ranked according to importance thus allowing to inform on priorities in the adoption of management measures (controls). Even when the Bow-tie model is purely qualitative, additional metadata may be attached to the elements of the diagram to provide the user with information for example on the possible data sources available to quantify the different elements or the indicators that may be used for this. For example, for the pressure related to input of nutrients (P3.1), indicators to measure the intensity of this pressure may include total Nitrogen (or Phosphorus) load from agricultural land into rivers and coastal waters or their concentration in effluents from water treatment plants. Similarly, measurements of mean or extreme values, and or differences from a given baseline, for air or water temperature, annual precipitations, sea water levels etc. may be used as indicators for climate-change related pressures (within P4). Such an approach (adding metadata to the bow-tie diagram) may be applied by developing the bow-tie into a Knowledge Graph model, as applied by the Environment Agency of Abu Dhabi (Barnard et al., 2023).

Acknowledgments

This article is based on work from the project MARBEFES (MARine Biodiversity and Ecosystem Functioning leading to Ecosystem Services), funded by the European Union under the Horizon Europe research and innovation program (grant agreement no. 101060937) and UK Research and Innovation (grant agreement no. 10048815). We wish to thank the many experts from the case study areas for the discussions that helped shaping the methodology presented in this paper.

References

Barnard, S., Elliott, M. (2015) The 10-tenets of adaptive management and sustainability - applying an holistic framework for understanding and managing the socio-ecological system. Environmental Science & Policy, 51: 181-191. https://doi.org/10.1016/j.envsci.2015.04.008

Barnard S., Franco A., Burdon D., Atkins J.P. and Elliott M. (2023) EAD Knowledge Engineering. A Knowledge Management Platform for the Environment Agency – Abu Dhabi Research Agenda. A report of International Estuarine and Coastal Specialists (IECS) Ltd to the Environment Agency of Aby Dhabi, 15 July 2023

Burdon, D., Boyes, S.J., Elliott, M., Smyth, K., Atkins, J.P., Barnes, R.A., Wurzel, R.K. (2018) Integrating natural and social marine science to sustainably manage vectors of change: Dogger Bank transnational case study. Estuarine, Coastal and Shelf Science 201: 234-247, http://dx.doi.org/10.1016/j.ecss.2015.09.012.

Cormier, R., Kannen, A., Elliott, M., Hall, P., Davies, I.M, (Eds) (2013) Marine and Coastal Ecosystem-based Risk Management Handbook. ICES Cooperative Research Report, No. 317, March 2013, International Council for the Exploration of the Sea, Copenhagen, 60pp, ISBN 978-87-7472-115-1.

Cormier, R., Elliott, M., Kannen, A. (2018) IEC/ISO Bow-tie analysis of marine legislation: A case study of the Marine Strategy Framework Directive. ICES Cooperative Research Report No. 342. 70 pp. https://doi.org/10.17895/ices.pub.4504 http://www.ices.dk/sites/pub/Publication%20Reports/Cooperative%20Research%20Report%20(CRR)/CRR342/CRR342.pdf

Cormier, R., Elliott, M., Rice, J. (2019) Putting on a Bow-tie to sort out who does what and why in the complex arena of marine policy and management. Science of the Total Environment, 648: 293-305. https://doi.org/10.1016/j.scitotenv.2018.08.168

Elliott, M. (2013) The 10-tenets for integrated, successful and sustainable marine management. Marine Pollution Bulletin 74(1): 1-5. http://dx.doi.org/10.1016/j.marpolbul.2013.08.001

Elliott, M. (2023) Marine Ecosystem Services and Integrated Management: "There's a crack, a crack in everything, that's how the light gets in"! Marine Pollution Bulletin, 193. https://doi.org/10.1016/j.marpolbul.2023.115177

Elliott, M., Kennish, M.J. (2024) A synthesis of anthropogenic impacts and solutions in estuarine and coastal environments. In: M. J. Kennish and M. Elliott (eds.), Anthropogenic Uses, Effects, and Solutions on Estuarine and Coastal Systems, Volume 6 of the Treatise on Estuarine and Coastal Science, 2nd Edition, pp. 1-58. Elsevier, London. https://doi.org/10.1016/b978-0-323-90798-9.00126-8

Elliott, M., Burdon, D., Atkins, J.P., Borja, A., Cormier, R., de Jonge, V.N., Turner, R.K. (2017) "And DPSIR begat DAPSI(W)R(M)!" - a unifying framework for marine environmental management. Mar. Pollut. Bull. 118 (1–2), 27–40. https://doi.org/10.1016/j.marpolbul.2017.03.049

Elliott. M., Day, J.W., Ramachandran, R., Wolanski, E. (2019) Chapter 1 - A Synthesis: What Future for Coasts, Estuaries, Deltas, and other Transitional Habitats in 2050 and Beyond? In: Wolanski, E., Day, J.W., Elliott, M., Ramachandran, R. (Eds.), Coasts and Estuaries: The Future. Elsevier, Amsterdam, ISBN 978-0-12-814003-1, p1-28.

Elliott, M., Borja, Á., Cormier, R. (2020a) Managing marine resources sustainably: a proposed integrated systems analysis approach. Ocean & Coastal Management, 197, 105315. https://doi.org/10.1016/j.ocecoaman.2020.105315

Elliott M, Franco A, Smyth, K. (2020b) CERES Deliverable Report 5.1: Industry- and policy-driven conceptual frameworks of climate change impacts. CERES (Climate change and European aquatic RESources) Project (EU, Horizon 2020 - BG-02-2015 Forecasting and anticipating effects of climate change on fisheries and aquaculture). February 2020. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cc9ce83a&appId=PPGMS

Elliott, M., Borja, Á., Cormier, R. (2025) Managing marine resources sustainably – But how do we know when marine management has been successful? Ocean & Coastal Management, 265: 107623; https://doi.org/10.1016/j.ocecoaman.2025.107623

European Union (2017). Commission Decision (EU) 2017/845 of 17 May 2017 amending Directive 2008/56/EC of the European Parliament and of the Council as regards the indicative lists of elements to be taken into account for the preparation of marine strategies. Official Journal of the European Union L 125/27

IEC/ISO 2009. Risk Management - Risk Assessment Techniques. International Organization for Standardization. IEC/ISO 31010:2009. 176 pp.

Papadopoulou, N., Smith, C. J., Franco, A., Elliott, M., Borja, A., Andersen, J.H., Amorim, E., Atkins, J.P., Barnard, S., Berg, T., Birchenough, S., Burdon, D., Claudet, J., Cormier, R., Galparsoro, I., Judd, A., Katsanevakis, S., Korpinen, S., Lazar, L., Loiseau, C., Lynam, C., Menchaca, I., O'Toole, C., Pedreschi, D., Piet, G., Reid, D., Salinas-Akhmadeeva, I. A., Stelzenmüller, V., Tamis, J., Uusitalo, L., Uyarra, M. C. (2025) 'Horses for courses' – an interrogation of tools for marine Ecosystem-Based Management. Frontiers in Marine Science, Marine Ecosystem Ecology, 12, 1426971. https://doi.org/10.3389/fmars.2025.1426971

Piet, G., Bentley, J., Jongbloed, R., Grundlehner, A., Tamis, J., de Vries, P. (2024) A cumulative impact assessment on the marine capacity to supply ecosystem services. Science of The Total Environment 948: 174149. https://doi.org/10.1016/j.scitotenv.2024.174149

Rambo, H., Stelzenmüller, V., Catalan, I., Icely, J., Maynou, F., Fragoso, B., Ospina-Alvarez, A. (2019) CERES Deliverable Report 5.2: Risks and opportunities as quantified using BBN models. CERES (Climate change and European aquatic RESources) Project (EU, Horizon 2020 - BG-02-2015 Forecasting and anticipating effects of climate change on fisheries and aquaculture). November 2019. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c9e74380&appId=PPGMS