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An integrated risk-based assessment of the North Sea to guide ecosystem-based management

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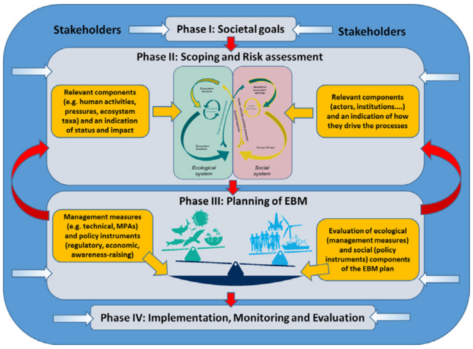
HIGHLIGHTS

- A risk-assessment identifies the main threats to societal goals.
- The effectiveness of EBM was evaluated using a risk-based approach.
- The exercise suggests improvements to the current knowledge base.

GRAPHICAL ABSTRACT



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ABSTRACT

This study provides an integrated perspective to ecosystem based management (EBM) by considering a diverse array of societal goals, i.e. sustainable food supply, clean energy and a healthy marine ecosystem, and a selection of management measures to achieve them. The primary aim of this exercise is to provide guidance for (more) integrated EBM in the North Sea based on an evaluation of the effectiveness of those management measures in contributing to the conservation of marine biodiversity. A secondary aim is to identify the requirements of the knowledge base to guide such future EBM initiatives.

Starting from the societal goals we performed a scoping exercise to identify a “focal social-ecological system” which is a subset of the full social-ecological system but considered adequate to guide EBM towards the achievement of those societal goals. A semi-quantitative risk assessment including all the relevant human activities, their pressures and the impacted ecosystem components was then applied to identify the main threats to the North Sea biodiversity and evaluate the effectiveness of the management measures to mitigate those threats.

This exercise revealed the need for such risk-based approaches in providing a more integrated perspective but also the trade-off between being comprehensive but qualitative versus quantitative but limited in terms of the “focal” part of the SES that can be covered. The findings in this paper provide direction to the (further) development of EBM and its knowledge base that should ultimately allow an integrated perspective while maintaining its capacity to deliver the accuracy and detail needed for decision-making.

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1. Introduction

Human use of marine environments is increasing, resulting in the degradation of habitats and losses in biodiversity (EEA, 2015c; EEA, 2015a; Halpern et al., 2015). At the same time, society is becoming more dependent on the ecosystem services that seas can sustainably provide, e.g. seafood, and the exploitation of one service may compromise that of another (Thilsted et al., 2016; EEA, 2015a). Thus, management of often multiple competing interests is required for marine environments. However, this is complex and requires an approach that can consider the entire social-ecological system and the synergies and trade-offs that come with management decisions. Integrated Ecosystem Assessments (IEAs) (Levin et al., 2009; Samhouri et al., 2014), Maritime Spatial Planning (MSP) (Ansong et al., 2017) and Ecosystem-based Management (EBM) (Long et al., 2015; Piet et al. this issue) are approaches used to deal with complex management in marine ecosystems. Yet, the current scientific knowledge base often constrains more informed decision-making. In order to reveal the limitations of the current North Sea knowledge base this study presents a first attempt to provide guidance into the EBM decision-making process towards achieving different societal goals as the means to assess the suitability of the knowledge base.

One of the main points of consensus on the requirements for more holistic management approaches such as EBM (Long et al., 2015) is to better acknowledge the complexity of social-ecological systems (SES) (De Lange et al., 2010). A comprehensive SES combines an understanding of environmental processes, as well as socio-economic (including ethical and cultural) processes (Christie, 2011) and is already used to guide the implementation of EBM towards the achievement of societal goals (Cormier et al., 2017). However, extending the knowledge base in order to cover a wide(r) array of human activities or include socio-economic considerations should not result in inaction from overwhelming complexity (DeFries and Nagendra, 2017). Therefore (Piet et al. this issue) propose the adoption of the concept of a “focal SES” (Ostrom, 2009), a subset of the full SES which is assumed adequate for salient knowledge production (Rockmann et al., 2015) while maintaining simplicity to avoid inertia.

We explore the application of such an approach here, focusing on the North Sea, which is one of the busiest seas with many (often growing or newly emerging) sectors laying claim to a limited amount of space (Halpern et al., 2015). Human activities in the region include fishing, shipping, oil and gas, as well as newly emerging activities such as the renewable energy sector. Every sector introduces additional pressures on the marine environment. These combined human activities and their pressures have compromised the achievement of the ecological goals for the North Sea (Knights et al., 2011; OSPAR, 2010; EEA, 2015c). In Europe, the long-term Blue Growth Strategy supports sustainable growth in the marine and maritime sectors (Johnson et al., 2018). Thus, many activities, such as offshore wind farms (OWFs), are expected to increase and potentially further compromise marine biodiversity and the ecosystem services it provides. At the same time, the Blue Growth Strategy as well as all existing management initiatives have been developed traditionally to meet sectoral goals, rather than integrated sets of societal goals including social, economic and ecological objectives. In this study, we consider the competing interests of two sectors and the trade-offs that may apply when balancing sectoral demands with the ecological goals set out for the system. We explicitly apply an integrated, interdisciplinary perspective and consider the requirements of EBM when developing our knowledge base, in order to show how an integrated management approach can help to balance trade-offs in decision making.

Societal goals are often reflected in (inter)national policy documents. Society's goals for the North Sea ecosystem are stated in the EU Biodiversity Strategy (EC, 2011) and the Marine Strategy Framework Directive (MSFD) (EC, 2008) and include a healthy marine ecosystem and the protection of biodiversity. This has resulted in the creation of a network of Natura 2000 (N2000) Special Areas of Conservation and other Marine Protected Areas (MPAs). At the same time, there are goals related to specific sectors. The Common Fisheries Policy (EC, 2009b; EC, 2013) aims for a sustainable supply of seafood from fisheries; and the Renewable Energy Directive (EC, 2009a) requires the EU to fulfil at least 20% of its total energy needs with renewables (including offshore wind farms OWF) by 2020. All three of these societal goals, i.e. healthy ecosystem, sustainable seafood and renewable energy, are known to take up considerable space in the North Sea (and hence the extent of seabed habitats involved) and are thus among the main players in MSP (EC, 2014). As the amount of space in the North Sea is limited, there is tension in achieving all these goals simultaneously and trade-offs will need to be considered. This is the basis for the North Sea application of the EBM approach developed by Piet et al. (this issue) intended to guide decision-making towards the (balanced) achievement of different societal goals and involving important societal actors, i.e. fishing industry, offshore wind energy sector and non-governmental organisations (NGOs). The sectoral management initiatives we consider are usually developed and implemented in isolation with the aim to mitigate a specific sector but in this study we will consider them together and evaluate their performance in terms of their contribution to conserve marine biodiversity. As such we will also compare them to the principal conservation measure, i.e. MPAs (EEA, 2015b). This EBM approach distinguishes four phases, some with multiple steps, each described in more detail below:

I. Societal goals: define what is to be achieved
II. Integrated Ecosystem Assessment: establish the knowledge base and identify the main threats to the achievement of the societal goals
  - Scoping
  - Risk Assessment

III. Planning of EBM: select management options likely to perform best at achieving the societal goals
  - Design
  - Evaluation

IV. Implementation, monitoring and evaluation: this occurs outside the science domain and is therefore not considered further in this study.

2. Results

2.1. Phase I: societal goals

In order to demonstrate an integrated perspective to EBM we considered three societal goals for our focal SES: sustainable food supply, clean energy and a healthy marine ecosystem, which we define in detail for the North Sea context below. These were selected because achievement of any one of these goals may be at odds with that of the others. For example, achievement of each of these goals requires use of space for different outcomes, and space is becoming increasingly more limited in this busy sea. Also the human activities required to achieve the first two goals produce (often undesired) pressures, of which the cumulative effects may impact biodiversity and compromise achieving a healthy marine ecosystem (EEA, 2015c). For each of those goals we present the current state of affairs in relation to existing relevant policy frameworks.

Sustainable (sea)food supply

Societal goal: The principal aim of fisheries management under the Common Fisheries Policy (CFP) is to ensure high, long-term fishing yields for all stocks by 2015 where possible, and at the latest by 2020.

This is referred to as Maximum Sustainable Yield (MSY) (EC, 2009b; EC, 2013).

Catches of (shell)fish in the North Sea have dropped from a peak level of 3–4 million tonnes taken per year starting in the late 1960s up to the mid-1990s, after which it declined to a low of 1.4 million tonnes in 2012, and a slight increase since (ICES, 2017). This decline is attributed to overfishing and decreased productivity of important stocks such as cod and herring, but also to the successful reduction of fishing mortality to more sustainable levels after 2000 (ICES, 2017). There are two key policy instruments in Europe that regulate fishing commercial species. The first of these is the EU Common Fisheries Policy (CFP), which is targeted specifically on managing fisheries, while the MSFD is an environmental directive that aims to achieve good environmental status (GES) for the commercial fish species (EC, 2008). Regarding the impact of fishing on commercial fish species the CFP and MSFD are aligned but the MSFD also considers other pressures as well as the wider ecosystem which may result in conflicting elements. For example, the MSFD addresses the impacts of commercial fishing on the seafloor through Descriptor 6 for determining GES, while the CFP appeals to an ecosystem-based approach to fisheries management to limit environmental impacts of fishing activities in general, without offering specifics on the dimensions of environmental impact. More importantly, the CFP is not only concerned with environmental goals such as the status of commercial (shell)fish species but also aims to ensure that fishing and aquaculture activities contribute to long-term economic and social sustainability. The CFP is directly funded by the European Maritime and Fisheries Fund (EMFF, 2014–2020), one of the five complementary European Structural and Investment (ESI) funds that aim to promote economic growth and job-based recovery within the EU. Clearly this aim for socio-economic sustainability may be at odds with the environmental goals and ecological sustainability. In contrast, the MSFD states that fishing for the current generation is not the only public interest, but that the regeneration and maintenance of marine biodiversity for use of current and future generations should also be accounted for.

Clean energy

Societal goal: The Renewable Energy Directive establishes an overall policy for the production and promotion of energy from renewable sources in the EU. It requires the EU to fulfil at least 20% of its total energy needs with renewables by 2020 (EC, 2009a). In its most recent progress report, the European Commission reports that a continued effort will be needed to meet the 2020 targets with the latest data on final energy consumption showing that the EU as a whole achieved a 16.4% share of renewable energy in 2015 (EC, 2017). Currently only 10% of total wind energy in Europe is produced in offshore wind farms (OWFs), most of which are located in the North-East Atlantic (EEA, 2015a). Offshore wind employs 35,000 (full-time equivalent) and accounts for a GVA of 2.4 billion EUR (EEA, 2015a, 2015b, 2015c). Offshore wind is a significant part of the EU's future renewable energy mix as a sustainable way of producing energy. However, the development and operation of OWFs can pose a threat to aquatic biodiversity (e.g. seabirds, bats, marine mammals) but also interfere with several marine economic activities such as fisheries (Stelzenmüller et al., 2016; Gray et al., 2016) and transport (MarCom, 2018).

Healthy marine ecosystem

Societal goal: for this we refer to the European Union Biodiversity Strategy, which translates the Aichi Targets at the EU level stating an aim to "halt the loss of biodiversity and the degradation of ecosystem services in the EU by 2020, restore them in so far as feasible, while stepping up the EU contribution to averting global biodiversity loss". The Biodiversity Strategy is aligned to several marine policy frameworks, e.g. Birds and Habitat Directive (BHD), Marine Strategy framework Directive (MSFD) and Common Fisheries Policy (CFP).

The BHD aims to implement protected areas in which human activities are restricted, and effectively decrease species extraction and enhance the status of the environment and related biodiversity. The MSFD requires Member States to draw up a programme of measures for each marine (sub-)region to achieve or maintain GES. This includes spatial protection measures contributing to coherent and representative networks of MPAs, adequately covering the diversity of the constituent ecosystems, such as protected areas required under BHD, as well as other types of Marine Protected Area set up under international or regional agreements (Art.13(4), MSFD). The BHD explicitly supports the MSFD through Art. 40(f) but while the BHD requires implementation of protected areas, the MSFD promotes the incorporation of MPAs in a country's programme of management measures, including specific protective measures, as a means to achieve GES. The MSFD therefore does not necessarily demand MPAs if GES can be achieved with other measures. Thus, MPAs are not necessarily an addition to the N2000 network, but N2000 areas can be an element of the member states' programs of measures.

In addition to the implementation of N2000 areas or other types of MPAs specifically aimed at achieving conservation goals, there is the option to manage the OWFs, e.g. through a ban on specific activities such as trawl fisheries, so that these OWFs de facto become MPAs.

Integration of societal goals

The EU Integrated Maritime Policy (EC, 2007) aims to provide a coherent policy approach with increased coordination between different policy areas and with a focus on cross-sectoral and regionally cross-cutting maritime issues. The policy takes the interaction between different sectors into account and is therefore relevant for issues such as OWFs occupying historical fishing areas. The Maritime Spatial Planning Directive (EC, 2014) aims to ensure cooperation, harmonisation and coherent action across a range of policy areas, such as the BHD, MSFD, CFP and the Renewable Energy Directive. It does not set any environmental targets and, at the same time, does not set out targets for economic activities. Instead, it provides a framework for setting targets and measures to, for example, maximise economic output (e.g. from fishing, OWFs) while meeting environmental requirements (e.g. MPAs). Environmental targets are embedded in other legislation such as the BHD and MSFD. The MSFD is possibly the clearest on the need to consider a range of pressures arising from renewable energy development, for example including sealing of the seafloor or collision mortality of seabirds.

2.2. Phase II: Integrated Ecosystem Assessment (IEA) – scoping

This phase of the EBM approach, and identical to the first step of an IEA process, is intended to focus the scientific knowledge base towards the identified societal goals, while ascertaining that the elements in the knowledge base resonate with stakeholders. This step results in the focal SES, which should be suited to guide EBM towards achievement of these specific societal goals and to that end, needs to be adequately covered by the available knowledge. Here we adopted the linkage framework developed by Borgwardt et al. (this issue) but taking just those linkages that consist of the specific nodes representing human activities, their pressures and the ecosystem components impacted by those pressures that were reported for the North Sea, and then identified which of these specific and clearly defined nodes and their linkages are relevant to our focal SES (Table 1). The ratio of the (weighted) number of linkages in the focal SES relative to those in the comprehensive SES is an indication of how representative the analysis is. The aim is to increase this ratio over time.

In this scoping phase we can match the three societal goals to specific human activities. For example, in terms of the selection of relevant human activities the "Sustainable food supply" goal would require the

Table 1
The human activities, pressures and ecosystem components that make up the nodes of the North Sea “comprehensive SES” and the subset (in bold) that make up the “focal SES”.

Human activities	Pressures		Ecosystem components		
Agriculture	Biological	**Extraction of flora and/or fauna**	**Fish & Cephalopods**		
Forestry		Introduction of genetically modified species	**Mammals**		
Aquaculture		Introduction of Microbial pathogens	Reptiles		
Coastline management		Introduction of non-indigenous species	**Birds**		
Dredging		Translocations of species (native or non-native)	Habitats	**Habitats**	
Land claim or conversion	Chemical	Changes in input of organic matter		Coastal-Terrestrial	Coastal dunes and sandy shores (B1)
Watercourse management		Introduction of Non-synthetic compounds		Coastal-Terrestrial	Coastal shingle (B2)
Fishing - benthic towed gears		Introduction of Radionuclides		Coastal-Terrestrial	Rock cliffs, ledges and shores, including the supralittoral (B3)
Fishing - fixed gears		Introduction of Synthetic compounds		Inlets Transitional	Littoral rock and other hard substrata (A1)
Fishing - pelagic towed gears		**Litter**		Inlets Transitional	Littoral sediment (A2)
Land -based manufacturing		N&P Enrichment		Inlets Transitional	Infralittoral rock and other hard substrata (A3)
Mining - other non-renewable		pH changes		Inlets Transitional	Circalittoral rock and other hard substrata (A4)
Oil and Gas - offshore		Salinity changes		Inlets Transitional	Sublittoral sediment (A5)
Power stations	Physical	**Abrasion/Damage**		Inlets Transitional	Pelagic water column (A7)
Tidal and wave energy		**Artificialisation of habitat**		Inlets Transitional	Deep-sea bed (A6)
Wind energy		Barrier to species movement		Coastal	Littoral rock and other hard substrata (A1)
Research		Change of habitat structure/morphology		Coastal	Littoral sediment (A2)
Ports and marinas		**Changes in Siltation**		Coastal	Infralittoral rock and other hard substrata (A3)
Urban developments		Changes in wave exposure		**Coastal**	**Circalittoral rock and other hard substrata** (**A4**)
Military		**Death or Injury by Collision**		**Coastal**	**Sublittoral sediment** (**A5**)
Shipping		**Disturbance** (**visual**) **of species**		Coastal	Pelagic water column (A7)
Telecoms and Electricity		Emergence Regime Changes		Coastal	Deep-sea bed (A6)
Transport		**Selective Extraction of non-living resources: substrate e.g. gravel**		**Shelf**	**Circalittoral rock and other hard substrata** (**A4**)
Cruise ships and ferries (large)		**Smothering**		**Shelf**	**Sublittoral sediment** (**A5**)
Recreational boating and watersports		**Total Habitat Loss**		Shelf	Pelagic water column (A7)
Recreational hunting, fishing and angling		Water abstraction		Oceanic	Deep-sea bed (A6)
Shore-based recreation and tourism		Water flow rate changes		Oceanic	Pelagic water column (A7)
Waste management	Energy	Electromagnetic changes			
		Input of light			
		Noise (Underwater and Other)			
		Thermal changes			

inclusion of all fisheries activities (aquaculture was not considered in this exercise), “Clean energy” goal requires the inclusion of OWFs (we ignored tidal and wave energy) while for “Healthy ecosystem” we included all extractive activities. In terms of selecting ecosystem components the “Healthy marine ecosystems” goal would allow the selection of any ecosystem component deemed at risk, but our prior selection of fisheries and OWFs provided further focus towards those ecosystem components primarily impacted by those activities. This, then, resulted in the selection of fish & cephalopods as the ecosystem component on which the “Sustainable food supply” depends (focus of the CFP), specific offshore seabed habitats (focus of the HD and MSFD policy frameworks), seabirds and marine mammals.

EBM is a cyclical adaptive process where each new cycle should be advanced in terms of becoming more ecosystem-based, compared to the previous cycles (Piet et al. this issue). This progress towards more ecosystem-based management can be assessed using the system- and process-oriented criteria proposed by Piet et al. (this issue) showing that it primarily advances management practices in the following ways:

- It considers ecological integrity and biodiversity. With its focus on many different ecosystem components, including both species and habitats, this is a clear improvement to conventional management focussing on a single species or component.
- It considers ecosystem connections. This integrated perspective also requires a full consideration of all potential ecosystem connections. Even though our focal SES covers only a subset of the comprehensive SES, it is a major improvement as it includes many more ecosystem connections than existing single-sector or single-species approaches. For example typical fisheries management consists of only a single impact chain in this linkage framework, e.g. Fishing (benthic towed gears) - Extraction of flora and/or fauna - Fish & Cephalopods (see Table 1).
- It considers cumulative impacts. This approach applies an integrated perspective in that it explicitly considers different societal goals and how their achievement is potentially compromised by several human activities and their pressures. Current management in the North Sea is usually focussed on a single sector (e.g. fisheries management).

This shows that this study presents a major advancement to existing management approaches in that it provides a (more) integrated perspective by simultaneously considering different ecosystem components and human activities. However, it is still restricted to the ecological system. Further integration would involve the application of a coupled SES where the performance of the EBM plan is assessed both in relation to the ecological system as well as the social system.

Phase II: Integrated Ecosystem Assessment – risk assessment

This is based on the conceptual framework for ecosystem risk assessment (ERA) (Holsman et al., 2017). This distinguishes different levels of risk analyses and classes of system complexity, varying from qualitative to semi-quantitative approaches that cover extensive SESs with high complexity, to quantitative approaches that cover only a small subset of the SES. In this study we apply a semi-quantitative risk assessment (Knights et al., 2015; Piet et al., 2017; Borgwardt et al., this issue; Culhane et al., this issue) covering all the human activities and their pressures occurring in the comprehensive (hence including focal) SES, to assess the risk that the policy objectives are not achieved. For the purposes of this risk assessment, the impact risk (IR) scores were aggregated for each human activity and its pressures, as well as for each ecosystem component (consisting of specific mobile biotic groups and habitats), to indicate which ecosystem components are most at risk and which human activities and pressures contribute to that risk. Following (Piet et al., 2015; Piet et al., 2017) we used summation as the preferred aggregation method when using risk assessment to evaluate management measures.

The assessment of the comprehensive SES in relation to the societal goals that apply to the offshore North Sea (hence excluding the realms: Terrestrial/Coastal and Inlets-Transitional) shows (see Fig. 1) that all fishing activities together would be, by far, the main source of risk with one single type of fishing, i.e. trawl fisheries (fishing - benthic towed gears), almost equally important as the single human activity that introduces the most impact risk (IR), Offshore Oil and Gas. Both are contributing approximately 7% to the total IR. OWFs are among the lesser important human activities contributing almost 4% to the total IR. This risk assessment, however, is based on the recent status and therefore does not take into account the expected increase of OWFs while, for example, offshore oil and gas is expected to decrease. For trawl fisheries, the pressures Habitat disturbance (which include: Abrasion/Damage, Changes in Siltation and Smothering), Extraction of biota and Litter are about equally important. For OWFs most of the IR involves the seabed habitat with the main pressures: Habitat loss and modification (which includes Total Habitat Loss and Artificialisation of habitat) and Habitat disturbance (mostly Changes in Siltation).

The scoping phase also includes an overview of what should be considered the main ecosystem components in terms of risk from the two selected human activities, i.e. trawl fisheries and OWFs. Fig. 2 shows a ranking of all ecosystem components in the comprehensive SES based on their calculated IR including the ecosystem components selected for the focal SES. In terms of total IR covered by ecosystem components the focal SES represents 32% of the comprehensive SES.

The outcome of this risk assessment, in terms of the relative contribution of the different human activities and their pressures to the risk of not achieving the societal goals (this phase II), as well as the evaluation of the potential performance of the management measures (phase III), should then be the basis to develop and apply one or more dedicated quantitative risk assessments covering only one or more specific impact chains. These impact chains emerge from the semi-quantitative risk assessment as the main threats. Only the results of the semi-quantitative risk assessment are presented in this study.

2.3. Phase III: Planning of EBM – design

In this step we only consider the programme of measures consisting of different management measures as this is how the EBM plan interacts with the ecological system. Table 2 presents the management measures in the EBM plan in relation to the identified societal goals.

Phase III: Planning of EBM – evaluation

In this planning phase we evaluate the performance of the EBM plan to contribute to the achievement of the societal goals, i.e. the effectiveness criterion in Piet et al. (this issue), ignoring any socio-economic criteria. This evaluation is conducted on what is considered the focal SES consisting of a specific subset of the activities, pressures and ecosystem components, deemed most relevant for this evaluation. The evaluation of the performance of the management measures is based on their potential contribution to reduce total IR (see Borgwardt et al., this issue). The proportion of total IR reduced by a specific management measure compared to the baseline situation (or business as usual) is used as the indicator of effectiveness. We assume the baseline situation

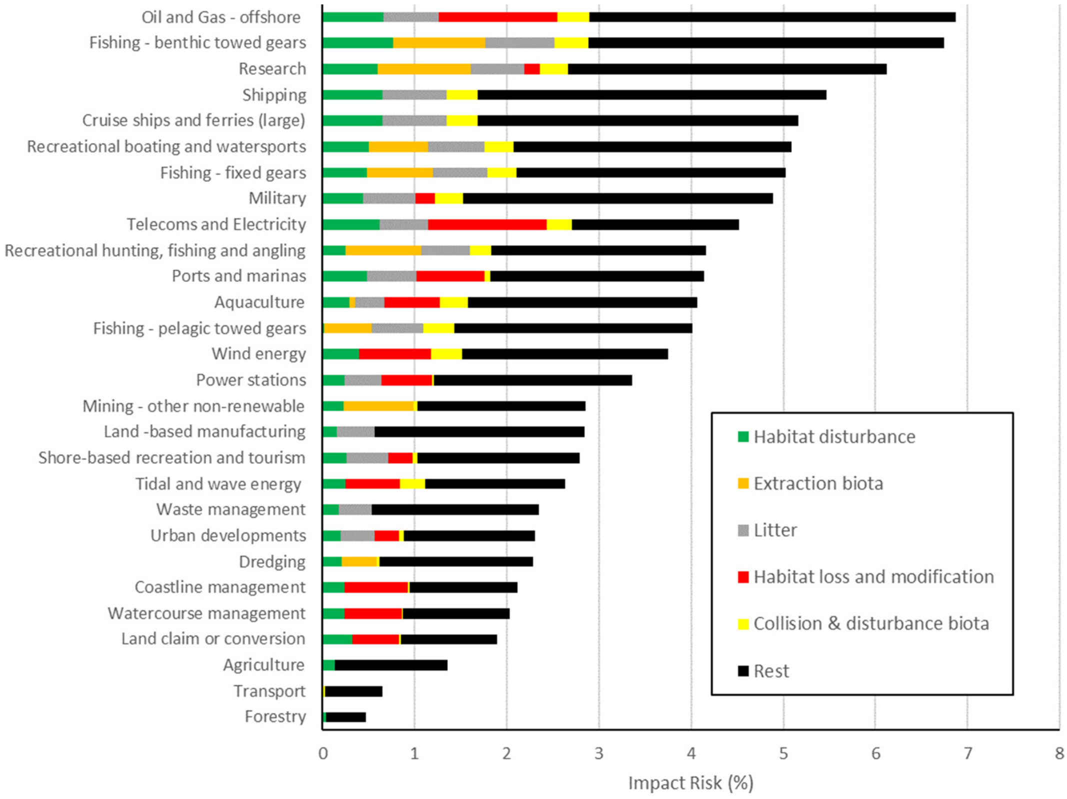

Fig. 1. Scoping of the relative importance of the human activities and some selected pressures in terms of their contribution to the total impact risk.

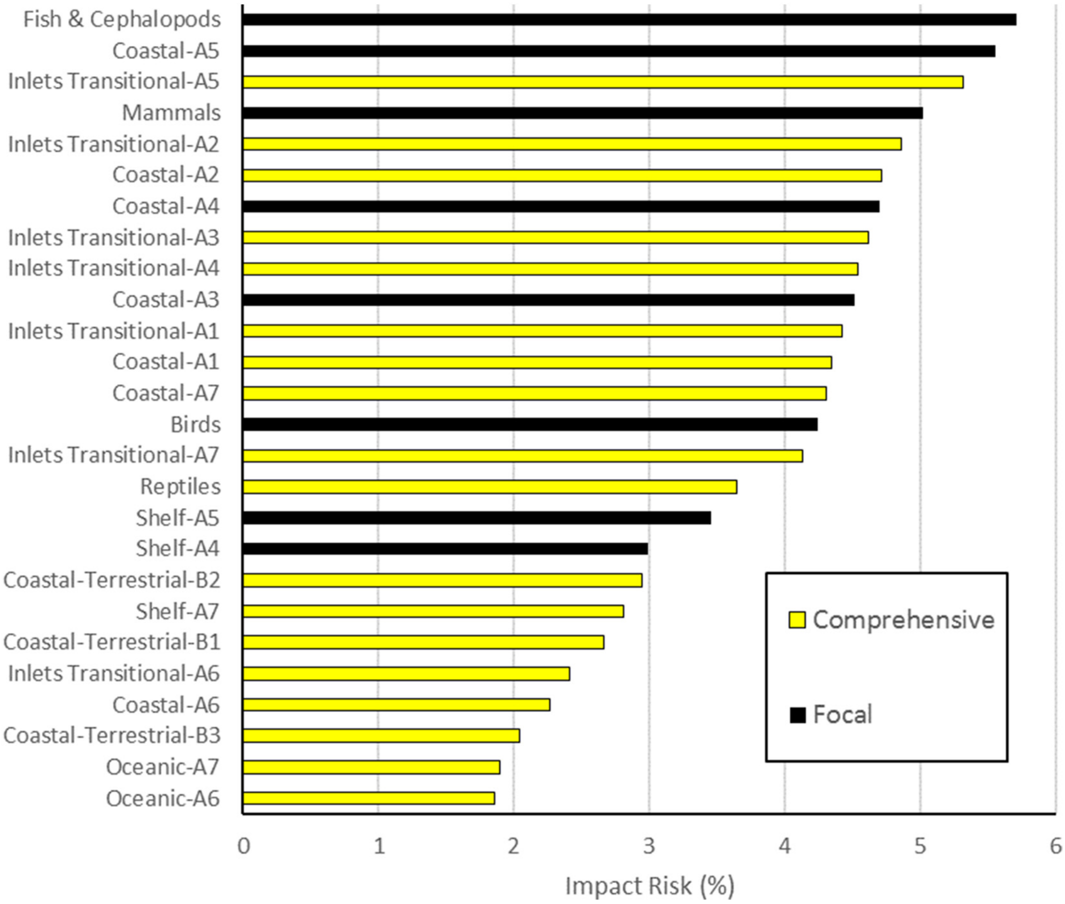

Fig. 2. Scoping of the relative importance of the ecosystem components in the comprehensive SES in terms of the risk of the cumulative effects of the human activities and their pressures in Fig. 1.

for any management measure is represented by the risk scores of the selected (suite of) impact chain(s) without any consideration of any other management measures that are being considered. For example the effects of management measures involving OWFs or MPAs assume that in the baseline situation the risk of fishing impact was estimated without any consideration of the OWFs or MPAs already in place. A management measure that eliminates fishing from 10% of the North Sea is therefore expected to reduce 10% of the IR caused by fishing without any consideration of the extent by which fishing is already affected by other (spatial) management measures. Below we will describe the application of the risk assessment to evaluate three broad categories of management measures each aimed at a specific societal goal, i.e. (1) Sustainable food supply, (2) Healthy marine ecosystems and (3) Clean energy (see Tables 2 and 3).

A sustainable food supply is the main aim of fisheries management and the aim to achieve MSY for all the main fish stocks already exists in the baseline situation. In the EBM plan we consider an extension of (some of) the conventional fisheries management measures, i.e. reduction of fishing effort (or capacity) or adopting more precautionary mixed fisheries advice, as well as the implementation of novel and more ecosystem-based fisheries management (EBFM), i.e. a technological innovation replacing the beam trawl with a pulse trawl or using a credit system to incentivize fishers to avoid sensitive habitats. One major distinction between the (extended) conventional measures and the novel EBFM measures is that we assumed the former result in an overall reduction of fishing (i.e. effort or capacity), which affects all the fishing-induced pressures, as opposed to the novel EBFM measures targeting a specific pressure, i.e. physical disturbance of the seabed

Table 2
Specific aim of the management measures (MM) in the EBM plan and the societal goals and human activities they are related to.

Societal goals	MM#	Specific aim of the management measure (MM)	Human activities
Sustainable food supply	1.1	Extension of regular fisheries management to achieve MSY through a reduction in fishing effort or capacity	Fisheries with benthic trawls
	1.2	More precautionary fisheries management that results in bigger reduction of fishing effort or capacity than 1.1 and results in less than the maximum sustainable food supply.	
	1.3	Using incentives to change fishers behaviour in order to reduce physical disturbance of the seabed habitats.	
	1.4	Applying new technology, i.e. gear substitution of conventional beam trawl to pulse trawl, to reduce the impact of fishing on the ecosystem.	
Healthy marine ecosystem	2.1	A ban on all extractive human activities in the existing MPAs.	All extractive human activities, i.e. fisheries, dredging and mining
Clean energy	3.1	Using turbines that reduce bird mortality in the OWFs	OWFs and fisheries with benthic trawls
	3.2	Planning the OWFs in locations where bird mortality is lower	
	3.3	Banning fishing with benthic trawls in the OWFs	
	3.4	Building OWFs such that their additional hard substrate enhances marine biodiversity	

Table 3

Knowledge base applied to determine for each societal goal the extent to which the management measures implemented to achieve that goal are expected to reduce impact risk for the impact chains (human activity-pressure-ecosystem component) involved. The management measures to achieve the sustainable food supply all target the fishing sector as the main human activity, those aimed to achieve the clean energy goal target OWFs. The pressure "Physical disturbance" represents three pressures as they occur in the focal SES (Table 1), i.e. Abrasion/Damage, Smothering and Changes in Siltation.

Societal goa	MM#	Pressure(s)	Ecosystem component(s)	Estimated degree to which specific impact chains are reduced in terms of impact risk
Sustainable food supply	1.1	Physical disturbance Changes in input of organic matter Death or Injury by Collision Litter	Mammals Birds Coastal (A1, A5) Shelf (A4, A5)	Several of the main commercial fish stocks are still overexploited suggesting that a (further) reduction in effort (or capacity) of the fishing fleet, and hence all its main pressures, could contribute to the long-term goal of a sustainable food supply. Based on ICES (2017) we found that several stocks, i.e. cod, haddock, whiting and megrim, caught using otter trawl and seine fisheries are still exploited above MSY levels. For these we assumed a 10% reduction in effort or capacity is possible. Also several sole stocks caught using beam trawl were exploited only just above MSY levels. For this type of fishery we therefore assumed a 5% reduction was feasible. Based on ICES (2017) showing beam trawls make up approximately half of the nominal effort deploying benthic trawls we assume an average reduction of 7.5% for all fishing-induced pressures other than catch.
		Extraction of flora and/or fauna	Fish & Cephalopods Coastal (A5) Shelf (A5)	We assume the impact risk caused by the extraction of fish and benthic invertebrates is reduced by 40% as this management measure should achieve the societal goal of a sustainable food supply (i.e. a "good" status of the commercial fish species) but not for a healthy marine ecosystem as several of the sensitive non-target species will not achieve a "good" status.
	1.2	Extraction of flora and/or fauna	Fish & Cephalopods Coastal (A5) Shelf (A5)	This alternative represents more precautionary fisheries management which sacrifices the achievement of a sustainable maximum food supply in order to achieve more of a healthy ecosystem. In addition to the conventional single species advice ICES (2018a) provides a more precautionary management mixed fisheries advice where fishing stops if the most limiting of the stock shares of a fleet has been caught up (i.e. the "Minimum" scenario determined by choke species). This causes underutilization of the single-stock advice possibilities of all other stocks. This scenario shows a reduction in total fish catch of 50% while benthic invertebrate catch (i.e. Norway lobster) was reduced by 73%. As fishing grounds of Norway lobster only make up a relatively small part of the habitat we assume for all these ecosystem components a reduction in impact risk of 50%
		Physical disturbance Changes in input of organic matter Death or Injury by Collision Litter	Mammals Birds Coastal (A1, A5) Shelf (A4, A5)	For all other fishing-induced pressures we assume a reduction in impact risk equal to that of the fish catch, i.e. 50%.
	1.3	Physical disturbance	Fish & Cephalopods Coastal (A5) Shelf (A5)	Habitat credits provide an incentive to fishermen to avoid sensitive seabed habitats thereby contributing to the conservation of the seabed habitats. A study by Batsleer et al. (2018) shows a shift from coarse (high credits) to soft (low credits). Assuming the credits are representative of the quality of the habitat and that the total amount of credits does not result in a reduction of effort and catch quota can still be fished, a reduction of 37% in physical damage was achieved.
	1.4	Physical disturbance	Coastal (A5) Shelf (A5)	The implementation of the pulse trawls results in a decreased physical disturbance of the sublittoral sediment. ICES (2018b) considered several aspects of the trawling impact on the seabed habitats. An average disturbance depth of an experimentally trawled study site was reduced from 4.0 cm with the traditional beam trawl to 1.8 cm in the pulse trawl. Together with a lower trawling footprint the total reduction of the mechanical impact on seafloor and benthos was estimated at 50%.
		Death or Injury by Collision	Mammals	Pulse trawls are deployed at a lower towing speed than traditional beam trawls which should result in a reduced chance of death or injury by collision of marine mammals. ICES (2018b) shows that average towing speed is reduced by 22% from 6.3 to 4.9 knots in large vessels and by 15% from 5.4 to 4.6 in small vessels. Death or injury by collision for marine mammals is based on: 1) probability of encounter (Martin et al., 2016) and 2) probability of lethal injury from a vessel strike (Vanderlaan and Taggart, 2007). The above reduction of speed will reduce this pressure by an average of 46%
		Changes in input of organic matter	Fish & Cephalopods Coastal (A5) Shelf (A5)	The pulse trawl results in less unwanted bycatch and should thus result in a lower input of organic matter affecting sublittoral sediment, fish and cephalopods. ICES (2018b) shows improved species selectivity when deploying a pulse trawl as opposed to the conventional beam trawl. An improved selectivity should result in less discarding and hence a lower input of organic matter. The discards negatively impact on the benthic community and scavenger fish species. A lower catch rate of 16% (small vessels) and 24% (large vessels) discarded fish in the pulse trawl was observed from discard monitoring programme. This was translated to a decrease of 20% of the organic matter input.
Healthy marine ecosystem	2.1	Physical disturbance Disturbance (visual) of species Extraction of flora and/or fauna Selective Extraction of non-living resources: substrate e.g. gravel	Fish & Cephalopods Mammals Birds Coastal (A1, A2, A3, A4, A5) Shelf (A4, A5)	The assumption is that all extractive activities are banned from the MPAs. The reduction in impact risk is assumed equal to the proportion surface area of the North Sea covered by the MPAs. Currently 18% of EU waters area in the North Sea within 200 nm is covered by MPAs (https://www.eea.europa.eu/data-and-maps/figures/regional-seas-surrounding-europe-and-2).
Clean energy	3.1	Death or Injury by Collision	Birds	Planning the OWFs in areas selected to minimize bird casualties. Moving from average bird casualties OWF areas to low bird casualties areas achieves a 90% reduction of death or injury by collision for the 5 most sensitive bird species (Leopold et al., 2014).
		Barrier to species movement Total Habitat Loss	Birds	Planning the OWFs in appropriate areas achieves a 91% reduction of Habitat loss and Barrier to species movement (Leopold et al., 2014).
	3.2	Barrier to species movement Death or Injury by Collision Total Habitat Loss	Birds	Optimising the turbines and wind park design to minimize casualties results in a reduction of bird collision rate. Using data from land based turbines where the death rate of birds was studied for different type of turbines, the collision rate is reduced by approx. 40% by doubling the capacity of wind turbines (Thaxter et al., 2017). Assuming collision chance at sea is similar to land based

Table 3 (*continued*)

Societal goa	MM#	Pressure(s)	Ecosystem component(s)	Estimated degree to which specific impact chains are reduced in terms of impact risk
				turbines (chosen due to lack of knowledge). The sensitivity for increasing windturbine capacity among seabird species varies.
	3.3	Physical disturbance Extraction of flora and/or fauna	Fish & Cephalopods Coastal (A5) Shelf (A5)	A ban on fishing (benthic trawling) inside the OWFs results in an assumed 25% decrease in impact risk (roughly the equivalent of a decrease in the exposure categories used in Culhane et al. (this issue) from widespread-even to widespread patchy) of all relevant fishing-induced pressures.
	3.4	Total Habitat Loss	Coastal (A5) Shelf (A5)	This represents a potential benefit of OWFs based on the assumption that the foundations, scour protection and other structures of the wind turbines provide additional hard substrate, i.e. habitat type A4, which is assumed to compensate 0.1% of the total impact risk experienced by this habitat. The assumed 0.1% is an arbitrary value but based on a recent estimate that OWFs make up 0.02% of natural substrate (Hyder et al., 2017). Further increases can be achieved by planning artificial reefs within the OWFs.

habitats. While many potential pressures that are part of the comprehensive SES, e.g. noise or the introduction of (non-)synthetics, were not considered as part of the focal SES, we did include litter. This because fishing is considered the major source of marine litter in the North-east Atlantic (Veiga et al., 2016) with “dolly” rope (ropes attached to the cod-end of nets to protect them from abrasion) and derelict fishing gear (the cause of ghost fishing) as the major items. In this evaluation, litter is used to distinguish between measures aimed at an overall reduction of fishing, or measures aimed at mitigating one specific pressure. Another distinction is that measures 1.1–1.3 target the whole fishing fleet using benthic trawl, whereas measure 1.4 only targets the part of the fishing fleet using beam trawl, as opposed to otter trawl or seine (Table 3). ICES (2017) shows beam trawls make up approximately half of the nominal effort deploying benthic trawls.

The aim for a healthy marine ecosystem is represented here by the implementation of MPAs, as these are considered a key conservation measure for halting biodiversity loss (EEA, 2015b). MPAs cover a broad range of protection levels: their scope may include reserves as well as multiple use areas. In the North Sea there are special areas of conservation pursuant to the Habitats Directive and special protection areas pursuant to the Birds Directive. For this evaluation of the implementation of MPAs (2.1, Table 3) we assume that, compared to the baseline, in the MPAs all activities are banned that impact the seafloor because they extract either flora and fauna or non-living resources. In practice this is probably an overestimation as several of the MPAs were not intended as pursuant to the Habitats Directive. In addition to both those extraction pressures we include in this evaluation only the pressures causing physical disturbance or loss of the habitat, as well as visual disturbance.

In the marine domain clean energy is achieved through the implementation of tidal barrages, the exploitation of wave energy or OWFs of which only the latter is considered in this evaluation. In the baseline situation the total installed capacity of OWFs was approximately 5 GW (WindEurope, 2018). With approximately 50 GW of installed capacity anticipated in the North Sea, this implies a future increase by factor 10. Extrapolating this to (changes in) risk scores proved difficult as there were too many unknowns. An inventory of existing OWFs in the southern North Sea shows marked differences between the different OWFs depending on the foundation type. For example the area occupied per installed capacity differs by approximately factor 10 (24 MW/km^2 for Monopile as opposed to only 2 MW/km^2 if floating) (Table 4). Also, considering that the proportion of seabed area that is lost due to sealing differs considerably, (between 0.002% for floating turbines versus 0.726% for the concrete Gravity Based Foundations (GBF)), we find for the OWFs considered here, a loss of seabed per capacity installed that differs by a factor 300. Based on this it was not possible to come up with any realistic extrapolation of the current (baseline) IR towards some future IR that can then be mitigated by the measures in our EBM plan and we assumed the 10-fold increase in capacity results in an assumed increase of 50% in IR, which is approximately the equivalent of an increase in the exposure categories used in Borgwardt et al. (this issue) from site or local to widespread-patchy. In this evaluation we then considered different decisions involving the planning phase of new OWFs or the management of the operational OWFs. For those involving the planning phase either the location (3.1) or the applied technology, i.e. type of turbines, is changed to reduce the impact on seabirds once operational (3.2). For the management of the operational OWFs, the decision involved a ban of the fishing activities inside the OWFs (3.3) (Table 3).

In addition we consider a potential management measure (3.4) that can only be evaluated if the risk assessment framework also includes potential positive impacts (or benefits) as opposed to only the negative impacts. This management measure involves a potential benefit of OWFs because the foundations, scour protection and other structures of the wind turbines provide additional hard substrate which is known to be a suitable habitat for a diverse fouling community (Krone et al., 2013) and associated fish species (Bohnsack, 1989; Reubens et al., 2013), and hence contributes to biodiversity and a healthy marine ecosystem. Habitat loss is considered as one of the pressures that contribute to the IR of OWFs. However, to balance the loss of the, in the North Sea, most common, soft-sediment seabed habitats, man-made structures may also contribute to the quality, productivity and biodiversity of the North Sea ecosystem through the additional hard substrate they provide. A first inventory of the importance of such man-made structures in relation to natural hard substrate shows that man-made structures already provide an additional 14% substrate to the existing rocks and boulders habitat (Hyder et al., 2017). As much of the North Sea seabed is mud and sand, with sometimes rocky shores and occasional rocks and boulders or reefs, these man-made structures may also increase the connectedness of the network of hard substrate,

Table 4
Overview of relevant parameters that determine the potential impact risk of future OWFs.

Foundation type	Example	Wind farm Area (in km^2)	Number of turbines	Total installed capacity (in MW)	Sealed area per turbine (in m^2)	Proportion sealed/total area (in %)
Monopile	Northwind, Be	9	72	216	573	0.458
Jacket	C-Power Phase 2 & 3, Be	16.1	48	295	10	0.003
GBF	C-Power Phase 1, Be	2	6	30	2419	0.726
Jacket (suction bucket)	Aberdeen Offshore wind farm, UK	19	11	93,2	2796	0.162
Floating	Hywind, UK	15	5	30	60	0.002

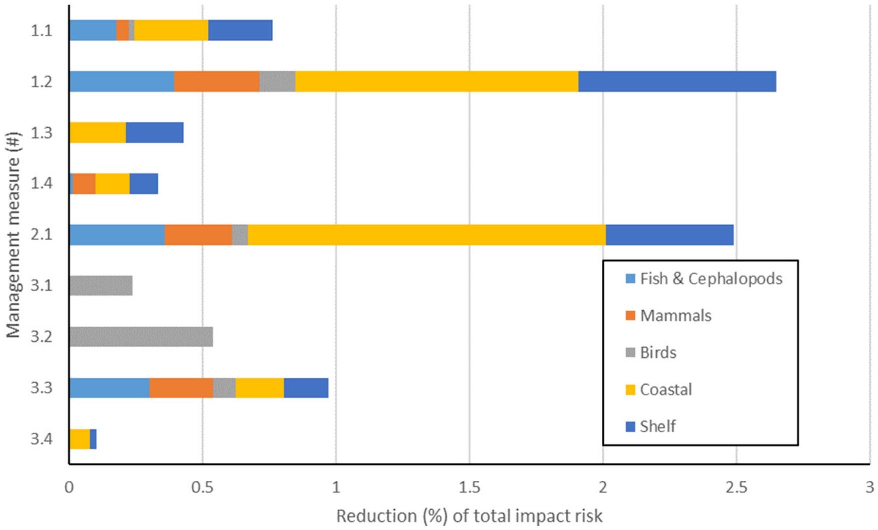

Fig. 3. The effectiveness per management measure (see Table 2) expressed as the potential reduction (%) of total impact risk in the focal SES, compared to the baseline situation.

thereby improving the resilience of the ecosystem. As the current set-up of the risk assessment does not allow any positive impacts to be considered and the available information does not allow any realistic estimation of those impacts, we assume that the baseline 5GW of OWF offset 0.1% of the total impact risk on the coastal Infra- and Circalittoral rock and other hard substrata (A3, A4). The future 50GW scenario with OWFs moving further offshore is then assumed to offset another 0.1% of the total impact risk on both the coastal and shelf hard substrata.

The effectiveness of the management measures is calculated as the aggregated risk across all impact chains affected by the management measure (defined by the human activities in Table 2 and the pressures and ecosystem components in Table 3) multiplied with the estimated degree to which IR of those specific impact chains is reduced (Table 3). Effectiveness reflects the potential degree to which the implementation of the measure contributes to biodiversity conservation compared to the baseline situation and is calculated as the cumulative reduction (%) of impact risk on the combined biodiversity components in the focal SES.

This evaluation shows that the precautionary fisheries management measure (1.2) is most effective to conserve overall biodiversity (Fig. 3). This is because the way the measure is defined in the risk assessment, where we assume that all fishing stops once these estimated lower catch quota are achieved. This essentially implies a 50% (or for some fisheries even 73%) reduction in fishing effort (or capacity), which would compromise the viability of the fishing fleet and economic sustainability, as well as the societal goal of sustainable (maximum) food supply. More sophisticated quantitative models would be required to explore the trade-offs between food supply and conservation goals. What this evaluation did show, and what is not considered in the existing quantitative models, is that several other pressures, notably physical disturbance affecting the seabed habitats and marine litter affecting all ecosystem components are also potentially affected by such measures and contribute even more to the cumulative effects on biodiversity than the one ecosystem component, fish, these models do include.

The second best management measure (2.1) in terms of effectiveness performs well because it includes several sectors, i.e. all types of fishing, dredging and mining and assumes all their activities are banned equivalent to the current extent of all MPAs. In reality not all MPAs require a total ban of all these activities and often the actual planning of the MPAs is such that economically important areas, e.g. with high fisheries catch per unit of effort, are avoided. A more detailed evaluation of the current and future MPA network would require detailed spatial maps of both the MPAs and all relevant human activities. At least in the case of fishing, it is known that fishing patterns may change over time and that any extrapolations of future reductions in catch opportunities based on maps of past exploitation patterns are at best only indicative of what can be expected.

For the measures involving OWFs, the most effective measure, again, involves a ban of all fishing with benthic trawls within the OWF area. This implied assumption is that these fishing activities then disappear, so that it essentially implies a significant reduction in fishing effort. This is not realistic for the economic reasons given before and in reality will result in the fishing activities reallocating to other areas outside the OWF area, which would require additional management to be implemented to prevent a net negative impact. Also, the estimated reduction in fishing-induced impact risk is based on an assumed 25% decrease for which considerable uncertainty applies, as it depends, similar to the evaluation of the MPAs, on an assumed overlap between future fishing activities and the future position of the OWF, both of which are not considered in this exercise and currently unknown. The next best performing measures involving OWFs suggests a considerable potential reduction in impact risk on only one component, i.e. birds, depending on the design of the wind turbines (3.2) or their location (3.1). This, again, illustrates that more detailed information is required but that this can considerably reduce the impact risk on a component which could prevent the development of any further anthropogenic impacts such as OWFs that cause additional mortality.

2.4. Phase IV: Implementation, monitoring and evaluation

Several of these management measures and policy instruments have already been implemented but in slightly different shape or form (e.g. extent of MPAs, amount of fishing effort or catch quota, size of OWFs). Many monitoring programs already exist and have provided the knowledge base for this EBM cycle. Much of this phase occurs outside the science domain with managers and decision-makers as the main actors but where science fulfils a distinct role in providing guidance for the implementation, designing the monitoring programs and conducting or contributing to the evaluation. Rockmann et al. (2015) provided some recommendations regarding the role of science as part of the EBM process, which should be adhered to, but are not further considered in this paper.

3. Discussion and conclusions

EBM should be considered an incremental, piecemeal process (Piet et al., this issue) where each EBM cycle advances the process to provide salient and credible advice to the decision-makers and other actors

(Rockmann et al., 2015). Compared to prior cycles of (ecosystem-based) management advice, the EBM cycle described in this study is novel in that it presents a first attempt to provide a more integrated, ecosystem-based approach, which considers diverse societal goals, includes several sectors and considers their impacts on the entire ecological system (but not the social system). This is also a first attempt to apply a risk assessment in order to assess the effectiveness of a suite of management measures that are part of an EBM plan. Even though only the application of a semi-quantitative risk assessment framework (see (Holsman et al., 2017)), is presented in this paper, it is appropriate to identify the main threats to a healthy marine ecosystem and the most effective management measures to mitigate those threats. As such this risk assessment framework that covers the focal SES provides the basis for more quantitative modelling tools that only cover a subset of the focal SES but can forecast specific scenarios in the detail required by decision-makers. Thus, the outcome of this semi-quantitative risk assessment should guide the selection and, if needed, further development of those quantitative modelling tools that cover the main threats (represented by specific impact chains) and/or most promising management measures.

The evaluation of the EBM plan was based on the comparison of an alternative situation where a specific measure was implemented, with the baseline (or business as usual) situation. An unambiguous definition of the baseline is a key requirement but also a major challenge for several reasons.

Firstly the EBM plan is, as stated, not entirely new and builds on other existing management measures and policy instruments. This is reflected in the evaluation where some of the management measures were also included in the baseline situation but modified/expanded in the alternative EBM plan. A clear distinction of how the alternative management measures differ from those already in place is therefore required.

Secondly, and related to the first point, the risk assessment should reflect this baseline situation but may, to some extent, reflect a status already affected by the management measures being considered. Considering the time the North Sea risk assessment was completed and the sources of information that were explicitly or implicitly used, our assumption was that it reflects a situation during the period 2010–2015 in which huge changes in terms of marine spatial planning occurred, specifically involving the sectors considered in this study, e.g. the implementation of N2000 areas and the planning and building of OWFs. It was unclear to what extent the most recent information was considered in the risk assessment. For a sector developing and expanding as fast as the renewables it makes a huge difference how the OWFs are defined in the baseline and management scenarios, both in terms of extent and location as well as the techniques deployed. At any point in time there are OWFs already operational as well as in varying development/planning stages. Moreover, our brief inventory of existing OWFs already shows that the techniques deployed may have considerable consequences for their impact on (specific parts of) the ecosystem. For several of the novel techniques even the most basic parameters to estimate the ecological impact risk are not available making it difficult to evaluate the effectiveness of any management decisions.

This first attempt to apply a semi-quantitative risk assessment in order to assess the effectiveness of a suite of management measures showed that this approach is a useful first step in identifying the critical activities, pressures and ecosystem components that need to be targeted by management measures. As we have shown, one advantage of the risk assessment approach is the ability to define the focal SES in relation to the full SES which is an indication of how representative the applied knowledge base is, and hence the quality of that knowledge base. The choice of a more integrated perspective required the application of this risk assessment framework based on expert judgement to weight the impacts of the activities and pressures on the ecosystem. The problem of data availability is widely recognised in such assessments, and expert judgement is seen as a useful way to move forward despite this (e.g. Mace et al., 2015). However, considering a (more) comprehensive set of elements is often prohibitive to detailed, quantitative analysis of the interactions of those elements (Holsman et al., 2017) and the often fairly crude categories may not provide the accuracy that allows an evaluation of the relatively small changes that occur in real-world management. For example the combined MPAs now make up approximately 18% of the North Sea surface area and are expected to increase by only few percent in the coming years. Similarly, even a sector expanding as fast as OWFs is only expected to increase its extent with, at best, a few percent each year. At the scale of the North Sea, this small degree of change in MPAs or sectors would not be captured by the rather coarse categories of risk, for example, spatial extent of activities are measured as: Exogenous = 1, Site = 3, Local = 37, Widespread-patchy = 67 and Widespread-even = 100% (Borgwardt et al. this issue), representing much larger intervals. On the other hand, it could be argued that at the scale of the North Sea, a relatively small increase or decrease in MPA or OWF size would not have a significant impact on the overall risk, unless specific locations or habitats were disproportionately targeted. Should this be the case, the risk assessment and focal SES could be adapted to focus on these areas. If the management measures used in this study were realistic options that could actually be implemented, it indicates that managers should be considering the effects of their measures at the appropriate scale of Regional Seas (sensu the MSFD), as opposed to their national perspectives focussing only on their respective Exclusive Economic Zones. This mismatch between the precision required for the management strategy evaluations considered here and the broad qualitative categories in the risk assessment framework compelled us to work from the assumption that the reduction in impact risk is linear to the reduction in expected population- or community-level mortality of that particular ecosystem component. Or, put differently, to weight the literature-based reduction in mortality with the impact risk of the impact chains expected to cause this mortality.

This initial evaluation of all the management measures is based on a semi-quantitative risk assessment framework. As the above discussion shows this does allow an integrated perspective covering the full breadth of all the relevant human activities, their pressures and how their cumulative effects impact all the different components in the ecosystem but often lacks the accuracy to provide the detail that decision-makers probably require at the scale considered here. It does succeed, however, in providing guidance to the next step in developing the knowledge base, i.e. the selection and further elaboration of quantitative models. For example all of the most effective management measures involved the mitigation of fishing. However practically all the quantitative models used for fisheries management only include what is considered the main pressure, i.e. catch, and how this affects a single ecosystem component, i.e. fish, without any consideration of the impacts of several of the other pressures, such as physical disturbance, on the other components, such as seabed habitats. These fisheries models therefore need to be improved/expanded so they can include such pressures and ecosystem components while recognizing this may involve trade-offs affecting their accuracy to provide information on the catches. We also worked from the assumption that the areas closed for fishing translate to a total removal of the activity. This is suitable to assess the potential (maximum) effect of the measure but is not realistic and could be improved by including knowledge on fleet dynamics (Rijnsdorp et al., 2011; Poos and Rijnsdorp, 2007). As a final point, it is clear that in order to evaluate specific management measures, the risk assessment also needs to be based on the actual spatial distributions of the human activities, their pressures and the ecosystem components as opposed to an exposure category. A knowledge base suitable to guide EBM therefore needs to acquire sufficiently detailed spatial maps of the distribution of all these elements of the SES.

This exercise aimed at providing guidance for (more) integrated EBM has shown how risk-based frameworks can be used to provide such guidance. This revealed their use in providing a more integrated perspective including several human activities and their pressures impacting all the main components in the marine ecosystem but also their limitations in terms of the required accuracy and detail required by decision-makers. The findings in this paper provide direction to the (further) improvement of the North Sea knowledge base and the type of risk assessments it can support while acknowledging the trade-offs between being comprehensive but qualitative versus quantitative but limited in terms of the part of the SES that can be covered. This will apply even more if the next step in integration is to be made, i.e. the consideration of a coupled social-ecological system allowing the application of inter-disciplinary science.

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References

Ansong, J., Gissi, E., Calado, H., 2017. An approach to ecosystem-based management in maritime spatial planning process. Ocean Coast. Manag. 141, 65–81.

Batsleer, J., Marchal, P., Vaz, S., Vermard, V., Rijnsdorp, A.D., Poos, J.J., 2018. Exploring habitat credits to manage the benthic impact in a mixed fishery. Mar. Ecol. Prog. Ser. 586, 167–179.

Bohnsack, J.A., 1989. Are high densities of fishes at artificial reefs the result of habitat limitation or behavioral preference? Bull. Mar. Sci. 44, 631–645.

Christie, P., 2011. Creating space for interdisciplinary marine and coastal research: five dilemmas and suggested resolutions. Environ. Conserv. 38, 172–186.

Cormier, R., Kelble, C.R., Anderson, M.R., Allen, J.I., Grehan, A., Gregersen, O., 2017. Moving from ecosystem-based policy objectives to operational implementation of ecosystem-based management measures. ICES J. Mar. Sci. 74, 406–413.

De Lange, H.J., Sala, S., Vighi, M., Faber, J.H., 2010. Ecological vulnerability in risk assessment - a review and perspectives. Sci. Total Environ. 408, 3871–3879.

DeFries, R., Nagendra, H., 2017. Ecosystem management as a wicked problem. Science 356, 265.

EC, 2007. Communication from the Commission to the European Parliament, the council, the European economic and social committee and the committee of the regions. An Integrated Maritime Policy for the European Union (COM(2007) 575 final).

EC, 2008. Establishing a Framework for Community Action in the Field of Marine Environmental Policy (Marine Strategy Framework Directive). 2008/56/EC (40 pp.).

EC, 2009a. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy From Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC.

EC, 2009b. Reform of the Common Fisheries Policy: Green Paper. European Commission (24 pp.).

EC, 2011. Communication from the commission to the european parliament, the council, the economic and social committee and the committee of the regions. Our Life Insurance, our Natural Capital: An EU Biodiversity Strategy to 2020 (COM(2011) 244 final. 17 pp.).

EC, 2013. Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, Amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and Repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC.

EC, 2014. Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 Establishing a Framework for Maritime Spatial Planning.

EC, 2017. Report from the commission to the European Parliament, the council, the European economic and social committee and the committee of the regions. Renewable Energy Progress Report 18 pp.

EEA, 2015a. The European Environment—State and Outlook 2015: Synthesis Report. European Environment Agency, Copenhagen.

EEA, 2015b. Marine protected areas in Europe's seas. An Overview and Perspectives for the Future (35 pp.).

EEA, 2015c. State of Europe's Seas (216 pp.).

Gray, M., Stromberg, P-L., Rodmell, D., 2016. Changes to fishing practices around the UK as a result of the development of offshore windfarms–Phase 1(Revised). The Crown Estate. ISBN: 978-1-906410-64-3 121 pages.

Halpern, B.S., Frazier, M., Potapenko, J., Casey, K.S., Koenig, K., Longo, C., Lowndes, J.S., et al., 2015. Spatial and Temporal Changes in Cumulative Human Impacts on the World's Ocean. 6 p. 7615.

Holsman, K., Samhouri, J., Cook, G., Hazen, E., Olsen, E., Dillard, M., Kasperski, S., Gaichas, S., Kelble, C.R., Fogarty, M., Andrews, K., 2017. An ecosystem-based approach to marine risk assessment. Ecosyst. Health Sustain. 3 (1), e01256. https://doi.org/10.1002/ehs2.1256.

Hyder, K., van der Molen, J., Garcia, L., Callaway, A., Posen, P., Wright, S., Taylor, N., Tidbury, H., Lincoln, S., Kirby, M., 2017. Assessing the Ecological Connectivity Between Man-made Structures in the North Sea (EcoConnect) (31 pp.).

ICES, 2017. ICES fisheries overviews. Greater North Sea Ecoregion. Ed. by. http://www.ices.dk/community/advisory-process/Pages/fisheries-overviews.aspx.

ICES, 2018a. ICES advice on fishing opportunities, catch, and effort, Greater North Sea Ecoregion. Mixed-fisheries Advice for Subarea 4, Division 7.d, and Subdivision 3.a.20 (North Sea, eastern English Channel, Skagerrak) https://doi.org/10.17895/ices.pub.4469 (15 pp.).

ICES, 2018b. Report of the Working Group on Electric Trawling (WGELECTRA). ICES Report WGELECTRA 2018 17–19 April 2018 (IJmuiden, the Netherlands. 155 pp.).

Johnson, K., Dalton, G., Masters, I. (Eds.), 2018. Building Industries at Sea: 'Blue Growth' and the New Maritime Economy.

Knights, A.M., Koss, R.S., Papadopoulou, N., Cooper, L.H., Robinson, L.A., 2011. Sustainable use of European regional seas and the role of the Marine Strategy Framework Directive. Deliverable 1, EC FP7 Project (244273) 'Options for Delivering Ecosystem-based Marine Management'. University of Liverpool (ISBN: 978-970-906370-906363-906376: 906165 pp.).

Knights, A.M., Piet, G.J., Jongbloed, R., Tamis, J.E., Robinson, L.A., et al., 2015. An exposure-effect approach for evaluating ecosystem-wide risks from human activities. ICES J. Mar. Sci. 72, 1105–1115. https://doi.org/10.1093/icesjms/fsu245.

Krone, R., Gutow, L., Joschko, T.J., Schröder, A., 2013. Epifauna dynamics at an offshore foundation – implications of future wind power farming in the North Sea. Mar. Environ. Res. 85, 1–12.

Leopold, M.F., Boonman, M., Collier, M.P., Davaasuren, N., Fijn, R.C., Gyimesi, A., de Jong, J., Jongbloed, R.H., Jonge Poerink, B., Kleyheeg-Hartman, J.C., Krijgsveld, K.L., Lagerveld, S., Lensink, R., Poot, M.J.M., van der Wal, J.T., Scholl, M., 2014. A First Approach to Deal With Cumulative Effects on Birds and Bats of Offshore Wind Farms and Other Human Activities in the Southern North Sea. IMARES Report C166/14.

Levin, P.S., Fogarty, M.J., Murawski, S.A., Fluharty, D., 2009. Integrated ecosystem assessments: developing the Scientific Basis for Ecosystem-Based Management of the Ocean (perspective). PLoS Biol. 7, e1000014.

Long, R.D., Charles, A., Stephenson, R.L., 2015. Key principles of marine ecosystem-based management. Mar. Policy 57, 53–60.

Mace, G.M., Hails, R.S., Cryle, P., Harlow, J., Clarke, S.J., 2015. REVIEW: towards a risk register for natural capital. J. Appl. Ecol. 52, 641–653.

MarCom, 2018. Interaction Between Offshore Wind Farms and Maritime Navigation. Working Group Report 161.

Martin, J., Sabatier, Q., Gowan, T.A., Giraud, C., Gurarie, E., Calleson, C.S., Ortega-Ortiz, J.G., Deutsch, C.J., Rycyk, A., Koslovsky, S.M., 2016. A quantitative framework for investigating risk of deadly collisions between marine wildlife and boats. Methods Ecol. Evol. 7 (1), 42–50. https://doi.org/10.1111/2041-210X.12447.

OSPAR, 2010. Quality Status Report 2010 (176 pp.).

Ostrom, E., 2009. A general framework for analyzing sustainability of social-ecological systems. Science 325, 419–422.

Piet, G.J., Jongbloed, R.H., Knights, A.M., Tamis, J.E., Paijmans, A.J., van der Sluis, M.T., de Vries, P., et al., 2015. Evaluation of ecosystem-based marine management strategies based on risk assessment. Biol. Conserv. 186, 158–166.

Piet, G.J., Knights, A.M., Jongbloed, R.H., Tamis, J.E., de Vries, P., Robinson, L.A., 2017. Ecological risk assessments to guide decision-making: methodology matters. Environ. Sci. Pol. 68, 1–9.

Poos, J.J., Rijnsdorp, A.D., 2007. An "experiment" on effort allocation of fishing vessels: the role of interference competition and area specialization. Can. J. Fish. Aquat. Sci. 64, 304–313.

Reubens, J., Braeckman, U., Vanaverbeke, J., Van Colen, C., Degraer, S., Vincx, M., 2013. Aggregation at windmill artificial reefs: CPUE of Atlantic cod (Gadus morhua) and pouting (*Trisopterus luscus*) at different habitats in the Belgian part of the North Sea. Fish. Res. 139, 28–34.

Rijnsdorp, A.D., Poos, J.J., Quirijns, F.J., 2011. Spatial dimension and exploitation dynamics of local fishing grounds by fishers targeting several flatfish species. Can. J. Fish. Aquat. Sci. 68, 1064–1076.

Rockmann, C., van Leeuwen, J., Goldsborough, D., Kraan, M., Piet, G., 2015. The interaction triangle as a tool for understanding stakeholder interactions in marine ecosystem based management. Mar. Policy 52, 155–162.

Samhouri, J.F., Haupt, A.J., Levin, P.S., Link, J.S., Shuford, R., 2014. Lessons learned from developing integrated ecosystem assessments to inform marine ecosystem-based management in the USA. ICES J. Mar. Sci. 71, 1205–1215.

Stelzenmüller, V., Diekmann, R., Bastardie, F., Schulze, T., Berkenhagen, J., Kloppmann, M., Krause, G., et al., 2016. Co-location of passive gear fisheries in offshore wind farms in the German EEZ of the North Sea: a first socio-economic scoping.

Thaxter, C.B., Buchanan, G.M., Carr, J., Butchart, S.H., Newbold, T., Green, R.E., Tobias, J.A., Foden, W.B., O'Brien, S., Pearce-Higgins, J.W., 2017. Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. Proc. R. Soc. B 284 (1862).

Thilsted, S.H., Thorne-Lyman, A., Webb, P., Bogard, J.R., Subasinghe, R., Phillips, M.J., Allison, E.H., 2016. Sustaining healthy diets: the role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. Food Policy 61, 126–131.

Vanderlaan, A.S.M., Taggart, C.T., 2007. Vessel collisions with whales: the probability of lethal injury based on vessel speed. Mar. Mamm. Sci. 23, 144–156. https://doi.org/10.1111/j.1748-7692.2006.00098.

Veiga, J.M., Fleet, D., Kinsey, S., Nilsson, P., Vlachogianni, T., Werner, S., Galgani, F., Thompson, R.C., Dagevos, J., Gago, J., Sobral, P., Cronin, R., 2016. Identifying Sources of Marine Litter. MSFD GES TG Marine Litter Thematic Report; JRC Technical Report; EUR 28309. https://doi.org/10.2788/018068.

WindEurope, 2018. Offshore Wind in Europe - Key Trends and Statistics 2017 (37 pp.).