CRANFIELD UNIVERSITY

Charles Edward Allan Willsteed

Developing a novel approach to assess the cumulative effects of human activities to support contemporary marine management and planning

School of Water, Energy and Environment

PhD Thesis
Academic Year: 2018 - 2019

Supervisor: Dr. Simon Jude
Associate Supervisor: Dr. Andrew B. Gill
Industrial CASE Sponsor Supervisor: Dr. Silvana N. R. Birchenough

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ABSTRACT

The challenges of assessing and managing the cumulative impacts of human activities on the environment remain major obstacles to sustainable development. This challenge is highlighted by the worldwide expansion of marine renewable energy developments (MREDs) in areas already subject to multiple activities and where climate change is rapidly changing the environment. Cumulative effects assessments (CEAs) in theory provide decision makers with adequate information about how the environment will respond to the incremental effects of licensed activities and are a legal requirement in many nations. In practise, however, such assessments are beset by uncertainties that, in context of MREDs, resulting in substantial delays during the licensing process that limit progress towards meeting carbon emission reduction targets. At a broader level, poor CEA practice risks developments and activities being permitted that contribute to environmental degradation with negative implications for connected human societies. This thesis investigates the origins of CEA to understand why improved practice remains challenging and to identify key CEA considerations that need to be addressed to improve CEA. Shortcomings in current practice were evaluated to refine the key CEA considerations. A conceptual analysis of the underpinnings of CEA was completed that resulted in a tiered conception of CEA being proposed to support regional coherence between CEAs, and the elaboration of principles and a CEA pathway to support consistent CEA practice. The CEA pathway was tested by defining and collating evidence to populate the steps of the pathway, which was then applied to a case-study to investigate the potential for novel approaches to support improved CEA. Insights and directions for future research were discussed to contribute to the evidence base required to improve CEA and to advocate for a change in CEA, from being a sub-discipline of project- and plan-level assessments, to becoming the overarching purpose of such assessments.

Keywords: Cumulative effects assessment; environmental assessment; social-ecological systems; marine renewable energy; environmental impact assessment; ecosystem approach; marine management; marine spatial planning

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When we try to pick out anything by itself, we find it hitched to everything else in the Universe (John Muir)

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LIST OF ABBREVIATIONS

CEA	Cumulative Effects Assessment
CIA	Cumulative Impacts Assessment
CLD	Causal Loop Diagram
EBFM	Ecosystem Based Fisheries Management
EIA	Environmental Impact Assessment
GEnS	Good Environmental Status
MRED	Marine Renewable Energy Development
OWF	Offshore Wind Farm
SCEA	Strategic Cumulative Effects Assessment
SEA	Strategic Environmental Assessment
VEC	Valued Ecosystem Component

1 Introduction

Human activities in the 21st Century are one of the principal forces shaping social-ecological systems (Folke et al., 2016). These activities strongly influence the continuance or loss of ecosystem services and the resources that support societies and economies (Wu, 2013). How resilient services and resources are to further disturbance, extraction or other human activities is influenced by the range of cumulative effects, the cumulative effects load, acting on those services and resources. Hence, there is growing interest in cumulative effects assessment.

Cumulative effects assessments or cumulative impact assessments (hereafter CEA; see Table 1 for definitions) are a specific form of environmental assessment designed to provide information about how the effects of human activities contribute to environmental change (Spaling, 1994). The term CEA covers many forms of assessment over many temporal and spatial scales, but CEAs used in marine management and planning are typically initiated in response to legal obligations to assess cumulative effects (Jones, 2016; Judd et al., 2015). Shortcomings of such CEAs have long been cited (e.g. Beanlands and Duinker, 1984) and continue to be cited (e.g. Clark et al., 2019). Practice needs to improve urgently to fulfil legal obligations to assess cumulative effects and to support marine management and planning where social-ecological systems are being degraded by existing human activities and climate change, and are earmarked for further development to support blue growth objectives.

This thesis seeks to advance knowledge of how to improve cumulative effects assessment and thereby to contribute better management of cumulative effects. The thesis seeks to generate greater recognition of the role cumulative effects have in shaping the environment and to draw attention to lack of weight cumulative effects assessments have in decision-making. The thesis is grounded in 3 assumptions: Sustainable development *sensu* Bruntland report (WCED, 1987) is desirable; management of cumulative effects is essential to transition to sustainable development; cumulative effects assessment is essential to manage cumulative effects. The thesis argues that cumulative effects assessment is an important, worthwhile expenditure but one that is underutilised and where there are significant opportunities to deliver improved practice.

MacDonald (2000) wrote that conceiving of cumulative effects is straightforward, but defining cumulative effects assessment is not. Duinker et al (2012) and Judd et al (2015) discuss the plurality of definitions of CEA and call for researchers to define what interpretation of CEA is applied. The starting point, then, is to define cumulative effects. Cumulative effects are not a distinct category of effect, rather it is a collective term that refers to the interaction of effects that accumulate to effect change of an additive, interactive, synergistic or irregular nature in receptors. Cumulative effects can accumulate over broad temporal and spatial scales depending on the nature of sensitive receptors. The effects contributing to the net cumulative effects load acting on a receptor can be individually minor but collectively significant.

Defining Cumulative Effects Assessment is, by contrast, not straightforward. The number of systems that interact at different levels of organisation make it challenging to be accurate when assessing how human activities will effect change in social-ecological systems. Human activities and the effects that are produced by those activities are nested at multiple scales within a landscape or seascape (Hagstrom and Levin, 2017; Levin et al., 2013). The effects overlap at different scales, meaning a CEA of the stressors generated by a development is very different from a CEA of the range of effects acting on a receptor. The former is what is typically completed for project-level environmental assessment to fulfil obligations to provide an assessment of cumulative effects of a proposed development. This is not what most scientists perceive cumulative effects assessment to be, as is discussed in Chapter 2, yet this form of CEA is the dominant source of information about cumulative effects used in marine management and planning (Judd et al., 2015; OSPAR Commission, 2008).

The research presented in this thesis focusses on the need to improve project-level CEA practice, although as is explored in Chapter 4, there is an intimate connection between local and regional CEA; improving one requires improving the other. To guide the research, the research concentrates on cumulative effects uncertainties associated with marine renewable energy development (MRED) in the United Kingdom (UK). MREDs are widely recognised as a key component of a future low carbon energy generation section (Gasparatos et al., 2017; Sithole et al., 2016). Upscaling MRED infrastructure is critical for MREDs to contribute meaningfully to the ‘green’ transformation of the energy generation sector and for economies of scale to take effect (Sithole et al., 2016). The UK has been at the forefront of the expansion of MREDs, particularly offshore wind, and provides a useful case-study that has relevance to coastal states where there are national targets to produce energy from renewable sources, and where there are legal obligations to protect the integrity and wellbeing of social-ecological systems.

The scale and pace of MRED development in the UK have outpaced knowledge of MRED effects, particularly cumulative effects, resulting in substantial delays during the consenting process (Hawkins et al., 2014). General uncertainties about cumulative effects are amplified in context of MREDs, which contribute additional and novel stressors to marine ecosystems that are typically already degraded (Alexander et al., 2015). The expansion of MREDs has also coincided with the implementation of legislation that requires that the ecosystem is managed, rather than individual sectors. As a result, the information needs of regulators have changed and the uncertainties about how to discharge legal obligations to assess cumulative effects have increased (Judd et al., 2015).

The nature of cumulative effects requires CEAs to have a broader perspective than is typically found in project-level assessments, and prominent authors have questioned whether project-level assessments could ever deliver fit for purpose CEAs (e.g. Duinker and Greig, 2006; Greig and Duinker, 2014). There is, however, a strong case for seeking to improve project-level CEA, as the legal and procedural infrastructure is robust, and the project-level investigations tend to result in higher resolution environmental data than is available at the regional level (discussed in Chapters 2, 3 and 7). The aim of the research therefore was to investigate whether project-level CEA could be improved to support contemporary marine management and planning.

Table 1. Definitions of concepts and terms used in this thesis.

Term	Definition	Note/References
Activity	A human activity that introduces stressors into the environment. Activities may be one-off events such as a development project, or be continuous/sporadic, such as commercial fishing.	(Judd et al., 2015)
Cumulative effects	An interaction of effects that accumulate to effect change of an additive, interactive, synergistic or irregular nature in receptors. Cumulative effects can accumulate over broad temporal and spatial scales depending on the nature of sensitive receptors. The effects contributing to the net effects can be individually minor but collectively significant. Cumulative effects are not a distinct category of effect.	Definition adapted from Harriman and Noble (2008). There are multiple definitions of cumulative effect (see Duinker et al., 2012), but the definition proposed here reflects the contention that cumulative effects are not a distinct category of effect or impact; rather, that cumulative effects are the result of the accumulation of effects over space and time acting on a receptor.

Term	Definition	Note/References
Cumulative effects assessment (CEA)	In this thesis, CEA is defined as an assessment of the consequences of human activities on receptors within social-ecological systems. The definition is revisited and revised in Chapter 7, section 7.1 to reflect the evolved thinking of CEA as a practice and a process.	Own definition
Cumulative effects load	A term introduced in this thesis to represent the range of effects experienced by a receptor that are generated by human activities over the receptor's temporal and spatial range, which collectively influence the condition of the receptor.	Own definition
Cumulative impact assessment	An assessment of potential cumulative impacts arising from a proposed development or activity, usually completed as part of an EIA	(RenewableUK, 2013)
Ecosystem Approach	Recognising the connection between ecosystems and social systems, the Ecosystem Approach requires management that protects and maintains ecological characteristics while delivering the services and benefits required by society	(Elliott, 2011)
Effect	A change that is the consequence of an action, stressor or other cause	(Boehlert and Gill, 2010)
Environmental Impact Assessment	A written statement about the effects of a project or activity on the environment that are likely to be significant, which is intended to enable sustainable development.	(Glasson et al., 2012)
Impact	An effect of sufficient intensity, duration and/or severity to cause significant change within a receptor.	(Boehlert and Gill, 2010)

Term	Definition	Note/References
Receptors	This thesis defines receptors as entities or systems within a social-ecological system that are included in an assessment and which receive and respond to stressors. Sensitivity, recovery and resilience are determined by the traits and properties of the receptor (Segner et al., 2014).	Definition adapted from (Ball et al., 2012) and (Beanlands and Duinker, 1984) to reflect equal weighting assumed in this thesis between social and ecological components of social ecological systems.
Resilience	A dynamic concept that refers to the persistence of relationships within a system, the capacity of systems to absorb disturbance and reorganise while undergoing change, i.e. to retain the same functions, structure and feedbacks to sustain identity.	(Folke, 2016; Holling, 1973)
Social-ecological system	Coupled systems of people and nature embedded in the biosphere, recognising humans as an intrinsic part of nature.	(Folke, 2016)
Strategic Cumulative Effects Assessment (SCEA)	An ongoing process to which coherent, tractable CEAs contribute data and knowledge about the effects of human activities on the persistence of relationships between components of social-ecological systems to support adaptive management and governance.	Own definition
Stressor	External abiotic or biotic factor introduced by an activity or other source that move receptors out of normal operating ranges.	Judd et al., 2015; Segner et al., 2014

Term	Definition	Note/References
Sustainability	Meeting “human needs now and in the future by continuously improving and balancing environmental integrity, economic vitality, and social equity”	(Wu, 2013)
Sustainable Development	Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. The concept of sustainable development does imply limits - not absolute limits but limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities.	(WCED, 1987)

1.1 Research aim and objectives

The aim of the research was to integrate CEA science with social-ecological systems thinking to design a pathway to can guide the process of structuring evidence to improve project-level CEA practice. The hypothesis tested was that project-level CEA can meaningfully support contemporary marine management and planning.

To test the hypothesis, the following research objectives were established:

1. To clarify what is CEA broadly and in context of MREDs, to identify key considerations and challenges for improved practice (Chapter 2);
2. To establish what the short-comings in current CEA practice are relative to MREDs and to contemporary marine management (Chapter 3);
3. To develop a strong conceptual foundation of CEA from which to identify principles to aid consistency and a CEA pathway to improve project-level CEA (Chapter 4);
4. To define a case-study to guide the identification of evidence that could be used to populate the CEA pathway as a first test of how practical is the CEA pathway (Chapter 5);
5. To apply the evidence gathered to test novel approaches identified as having potential to support CEA (Chapter 6).

1.2 Structure of the thesis

Following this introduction, Chapter 2 reviews the literature on CEA and of CEAs of MREDs to develop a conception of what is CEA based on a review of where CEA originated from and how it has evolved. This provides the context for the thesis and presents a set of key considerations that ‘good’ CEA should address.

Chapter 3 investigates the state of current practice of CEAs within Environmental Statements of offshore wind farms in UK waters and evaluates how well recent CEAs perform relative to the critical features of ‘good’ CEA. A novel evaluation framework was developed and applied to evaluate the Environmental Statements submitted during the consenting process for the world's largest offshore wind farms.

Chapter 4 builds on the literature review in Chapter 2 and the specification of the problem in Chapter 3 to investigate the conceptual underpinnings of CEA. Systems thinking is introduced as a means to assist structuring CEAs to aid contemporary decision-making. A tiered approach to coordinating CEA to achieve regional coherence is proposed, along with principles to aid consistent practice and a CEA pathway for improved project-level CEA.

Chapters 5 and 6 test how practical the proposed CEA pathway. Chapter 5 specifies a case-study to provide context for data gathering, to define and collate evidence to test which steps of the CEA pathway are supported by appropriate existing evidence and methodologies. Chapter 6 then applies the evidence to investigate the more ambiguous steps in the CEA pathway, by testing how appropriate are approaches identified as having potential to aid CEA.

Chapter 7 brings the research together to reflect on CEA in general and on the CEA pathway in particular, as a means of improving project-level CEA, to reach a conclusion about the hypothesis, whether project level CEA can meaningfully support contemporary marine management and planning.

Chapter 8 summarises research needs and recommendations for improved CEA, before the conclusions of the research are presented in Chapter 9.

Figure 1 illustrates the progression and links between the chapters and the research objectives.

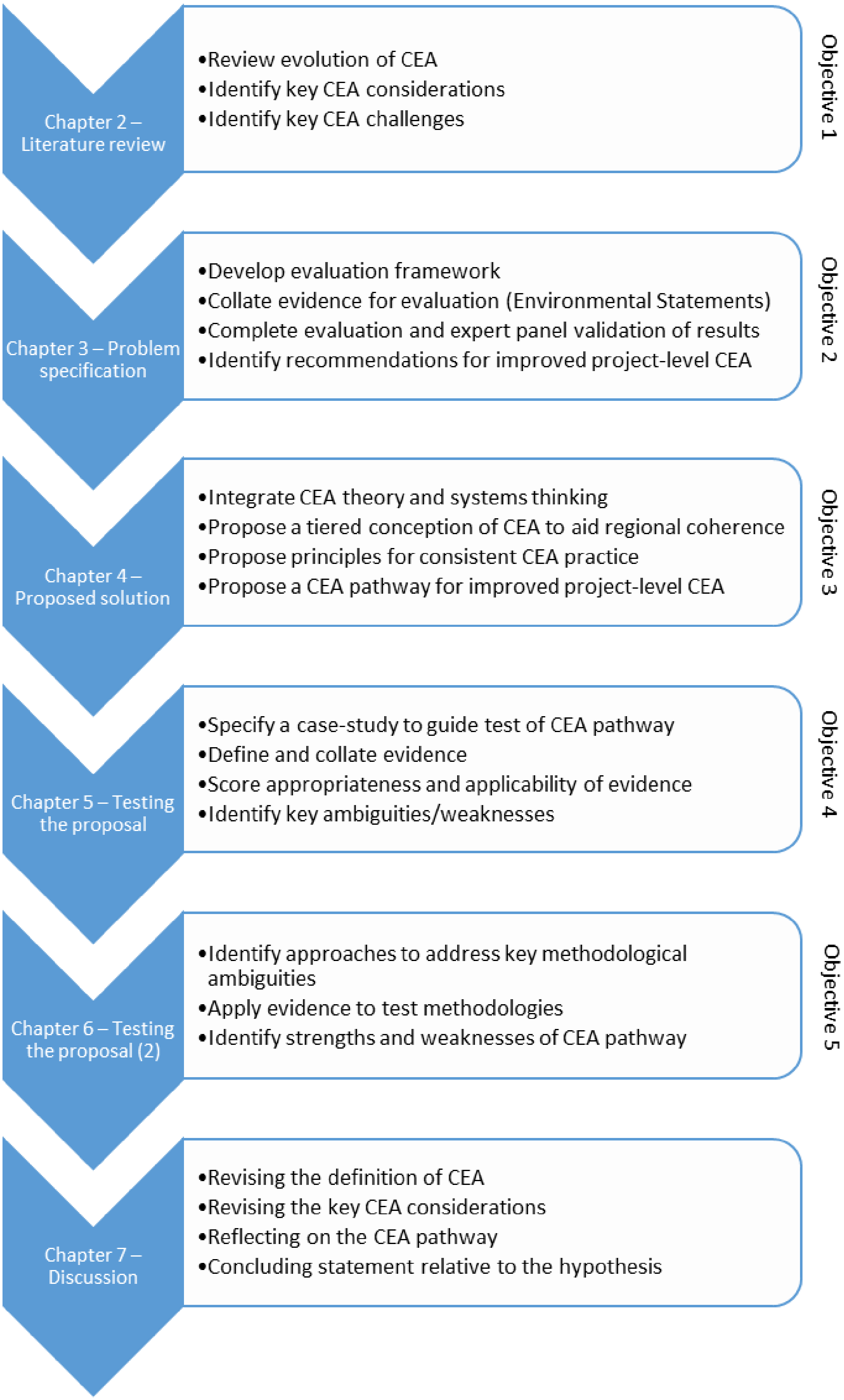

Figure 1. The flow from chapter to chapter indicating the research methodology applied to progress the research and to achieve the research objectives.

1.3 Dissemination from PhD thesis

Edward Willsteed designed and completed the research presented in this thesis with the guidance of three supervisors, Dr. Simon Jude, Dr. Andrew Gill and Dr. Silvana Birchenough. The research has resulted in three papers being accepted for publication in international peer-reviewed journals, which stem from Chapters 2, 3 and 4.

> Willsteed, E.A., Gill, A.B., Birchenough, S.N.R., Jude, S., 2017. Assessing the cumulative environmental effects of marine renewable energy developments: Establishing common ground. Sci. Total Environ. 577, 19–32
>
> Willsteed, E. A., Jude, S., Gill, A. B. & Birchenough, S. N. R. Obligations and aspirations: A critical evaluation of offshore wind farm cumulative impact assessments. *Renewable and Sustainable Energy Reviews* **82,** 2332–2345 (2018)
>
> Willsteed, E. A., Birchenough, S. N. R., Gill, A. B. & Jude, S. Structuring cumulative effects assessments to support regional and local marine management and planning obligations. Mar. Policy **98**, 23–32 (2018)

Results from the research have been presented at three international conferences over the course of the PhD:

- North Sea Open Science Conference 2016, Ostend, Belgium
- Environmental Interactions of Marine Renewable Energy 2018, Orkney, UK
- ICES Annual Science Conference 2018, Hamburg, Germany

In addition the research was presented to the Kent & Essex Inshore Fisheries and Conservation Authority committee meeting in November 2018. The work has been well received and has contributed to further development of concepts and applications with international experts working on this topic.

2 Defining cumulative effects assessment [1]

2.1 Introduction

This chapter provides a review and critique of literature on cumulative effects assessment and of cumulative effects assessment in context of marine renewable energy developments (MREDs). MREDs, defined as infrastructure developments that generate electricity from wind, wave, tidal and current resources, sit at a cross-section between economic growth, climate change adaptation and environmental protection. Governments worldwide are looking to secure future energy supplies and to mitigate climate change through generating electricity from renewable energy (Gasparatos et al., 2017). For MREDs to meaningfully contribute to decarbonisation of the energy generation sector requires significant upscaling of MRED infrastructure (Sithole et al., 2016). This industrialisation is widely perceived to be a source of economic growth, of ‘blue growth’ (Eikeset et al., 2018). Counterbalancing the drive for expansion is the requirement to safeguard long-term ecological sustainability. Most national governments have ratified conventions and enacted laws that require development to proceed only if the social and environmental costs of development are assessed as being acceptable (Glasson et al., 2012). Yet the ecological consequences of MREDs are uncertain (Bailey et al., 2014; Boehlert and Gill, 2010; Klain et al., 2018; Tabassum et al., 2014), as are the social-ecological consequences that have not been studied.

This chapter argues that defining the impacts and acceptability of one development or several developments requires meaningful assessment of the cumulative effects of development. Defining precisely what cumulative effects are and, hence, what meaningful cumulative effects assessment (CEA) is, is not straightforward, as there are multiple interpretations of cumulative effects and various drivers behind CEAs. Tackling the research aim thus requires a

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[1] Chapter adapted from: Willsteed, E.A., Gill, A.B., Birchenough, S.N.R., Jude, S., 2017. Assessing the cumulative environmental effects of marine renewable energy developments: Establishing common ground. Sci. Total Environ. 577, 19–32. Paper included in appendices.

grounding in the theory, origins and drivers of CEA, of the uncertainties associated with the environmental effects of MRED lifecycles, and insight into the confluence of the two. This chapter first revisits the origins and evolution of CEA to identify where the lack of clarity about what CEA is stems from. The chapter then reviews the knowledge gaps about cause-effect relationships between MREDs and marine ecosystems before identifying key considerations and challenges pertinent to improving CEA. The chapter concludes by presenting a working definition of what meaningful CEA is.

2.2 A brief history of Cumulative Effects Assessment

The origins of CEA are closely linked to the formation and rise of environmental impact assessment (EIA). EIA was formalised following the enactment of the National Environmental Policy Act of 1969 (NEPA) in the USA, established in the wake of popular concern and political action linked to environmental degradation caused by rapid industrial and agricultural progress in the 20th century (Du Pisani, 2006; Glasson et al., 2012). EIA is premised on sustainable development, *sensu* WCED (1987), being desirable, hence the consequences of activities should be accounted for in decision-making before they happen (Glasson et al., 2012; International Association of Impact Assessment (IAIA), 2009). In the late 1970s, it was realised that for EIA to fulfil its potential, approvals for activities needed to consider other activities in close spatial and temporal proximity (Canter and Ross, 2010). NEPA was thus revised in 1978 to explicitly require the assessment of cumulative effects and, over time (1995 in Canada and 1997 in the European Union, for example), environmental legislation in numerous regions of the world has followed suit (Canter and Ross, 2010; Connelly, 2011).

The practice of CEAs received greater attention in the 1980s and 1990s, as litigation was successfully brought against environmental agencies in the USA deemed not to be meeting their responsibility to assess and manage cumulative effects (Canter and Ross, 2010; Schultz, 2012). Scientists working in different fields increasingly realised the fundamental importance of managing cumulative environmental change, leading to transboundary research initiatives resulting in important conceptual and methodological advances (Beanlands and Duinker, 1984; Cocklin et al., 1992; Preston and Bedford, 1988). Ecological principles began to play a role in EIA, for example the focus on a limited set of valued ecosystem components, or receptors (Beanlands and Duinker, 1984). While interpretation of the principle remains problematic (see Ball et al. 2012), the focus on receptors that experience the effects of development over temporal and spatial scales greater than those typically considered by EIAs for individual projects inevitably led to a spotlight on cumulative effects (Duinker et al., 2012; Therivel and Ross, 2007).

Increasing recognition of the importance of cumulative effects in shaping marine and terrestrial ecosystems is evidenced by the growing legislation aimed at protecting the environment that requires cumulative effects to be assessed (Judd et al., 2015). In the European Union, for example, the implicit or explicit requirement to assess cumulative effects can be found in Directives 2014/52/EU (EIA Directive), 2001/42/EC (SEA Directive), 92/43/EEC (Habitats Directive), 2009/147/EC (Birds Directive), 2000/60/EC (Water Framework Directive) and 2008/56/EC (Marine Strategy Framework Directive). While the language stipulating CEA and the impetus behind the legislative drivers varies, the intent is consistent; to enable effective protection and management of the environment (Judd et al., 2015).

Growing awareness of how an increasing range and intensity of anthropogenic stressors is altering the condition and resilience of ecosystems has also led to a proliferation of CEAs driven by scientific inquiry, as opposed to responding to legal drivers. The bulk of information about the cumulative effects of anthropogenic activities used in decision-making continues, however, to stem from one source; EIAs completed for individual developments (Duinker et al., 2012; OSPAR Commission, 2008). This is problematic, as CEAs completed as subcomponents of EIAs have long been recognised as being inadequate for the task (Burris and Canter, 1997; Canter and Ross, 2010; Cooper and Canter, 1997; Foley et al., 2017). This shortcoming stems from the narrow boundaries applied by EIAs, by the lack of consideration of the range of pressures acting on receptors, the use of inadequate baselines and the difficulty of identifying if a seemingly minor impact will accumulate to have a significant impact on a receptor (Duinker and Greig, 2006; Squires and Dubé, 2013; Therivel and Ross, 2007). There are multiple definitions of cumulative effects (see Chapter 1, Table 1), but typically cumulative effects are defined as effects of an additive, interactive, synergistic or irregular nature that are caused by individually minor but collectively significant activities, accumulate over broad temporal and spatial scales (Harriman and Noble, 2008). This definition has been revised in this thesis to reflect the importance of recognising cumulative effects not as a distinct category of effect, but as a natural occurrence where receptors overlap with the effects of multiple human activities.

The term CEA (including cumulative impact assessments) has thus become an umbrella term that today encompasses a plurality of interpretations and approaches that seek to address a broadly similar problem, that of cumulative environmental change, *sensu* Spaling & Smit (1993). In the marine environment, where the crux of management is the protection of natural ecological characteristics while delivering services and benefits to society (Elliott, 2011), CEA, as a source of information about the effects of multiple activities on the environment, could provide strategic support to marine managers and planners (Stelzenmüller et al., 2013). However, the present variability between CEAs, whether conceptual or methodological, is problematic, as outputs are frequently incomparable, preventing assessments of the cumulative effects of, for example, MREDs, at scales appropriate to the identification, mitigation and management of cumulative effects (Judd et al., 2015).

This literature review seeks to establish why there are multiple definitions of and approaches to CEA, why this is problematic for MRED development today, and how this is problematic in terms of the broader objective to implement ecosystem approach management of marine waters. The review includes examination of the key considerations of CEA and why these continue to pose a challenge for marine managers and decision-makers given the current lack of consistency between CEA methods. Finally, recommendations are put forward, which seek to provide tangible considerations to enable improved CEA, supported by the presentation of a conceptual structure to coordinate CEA and pertinent research in a given area.

2.3 Cumulative environmental change and MREDs

Marine renewable energy developments have shone a spotlight on CEA, as the number of applications for development licenses increase while uncertainty about MRED cumulative effects remains (Masden et al., 2015). In nations that subscribe to sustainable development principles, the environmental effects of MREDs should be a decisive consideration during the planning, licensing and decommissioning processes. However the scale and pace of development and installation has outpaced knowledge of MRED effects, particularly of cumulative effects (MMO, 2013). In many jurisdictions, an expanding MRED industry also overlaps in time with marine management ambitions that hinge on managing cumulative effects to maintain ecosystem services and benefits (Elliott 2011; McLeod et al. 2005). Thus the impetus to reduce greenhouse gas emissions from the energy generation sector using renewable energy resources (Gibon and Hertwich, 2014) is constrained by the imperative to use coastal and marine waters sustainably. In countries where legally-binding targets for greenhouse gas emission reductions exist and overlap with viable energy resources, proponents of MREDs are calling for accelerated development (e.g. in EU waters; European Commission 2014). However, the absence of consensus about the nature of cumulative effects and the consequent uncertainty about how to conduct CEA (see Duinker et al. 2012; Judd et al. 2015) prevents thorough strategic planning and causes delays. In the UK, for example, MRED development commenced prior to the government's strategic environmental assessment (Glasson et al., 2012) and delays during the consenting process of up to 42 months for individual MREDs are reported (RenewableUK, 2013). As a result, project costs increase, development timelines extend and investor confidence is impacted (DECC 2012).

In European waters, where the development and operation of MREDs (but not yet decommissioning) is well advanced, research has focussed on identifying and quantifying effects of construction and operation on particular receptors (notably seabirds, marine mammals and some fish species). Lindeboom et al. (2011) reported on the short-term effects of an individual offshore wind farm noting no significant direct impacts were identified relative to the studied receptors. Similarly for wave and tidal devices, no clear evidence for significant impacts on fish and shellfish arising from individual devices have been observed (Freeman et al., 2013). Studies from monitoring offshore wind farms in Belgian (Degraer et al., 2013) and German (Federal Maritime and Hydrographic Agency (BSH) and Federal Ministry for the Environment, 2014) waters do not point to clear long-term significant impacts to studied receptors, but as noted by Degraer et al. (2013), assigning positive (e.g. fish aggregation) or negative values (e.g. collisions with turbine blades) to observed effects requires local observations to be put in context of receptor populations and the ecosystem more broadly. Thus, significant cumulative effects and significant environmental change cannot be ruled out. There are clear gaps in the current understanding of how effects from multiple, large-scale developments will propagate over time and space through an ecosystem. The effects of MREDs on ecosystems, rather than on individual receptors, remain largely unexplored (Bailey et al., 2014; MMO, 2013; OSPAR Commission, 2008; van der Molen et al., 2014) and uncertainties remain high (Masden et al., 2015) . In the EU, EIA legislation requires developers to undertake CEA and for marine managers to make licensing and consenting decisions cognisant of likely cumulative effects. As with marine planning and licensing more broadly, EIAs submitted as part of the consenting process for individual developments are the principle source of information about MRED cumulative effects (OSPAR, 2008). However, confidence in CEAs contained within EIAs is limited (Maclean et al., 2014), in large part due to the “EIA-plus” (Therivel and Ross, 2007) approach applied, which is not well suited to determining if effects arising from individual developments are cumulatively significant (Harriman and Noble, 2008).

Assessing MRED cumulative effects is made more challenging by MREDs being located within a dynamic environment that hosts multiple users and activities. As a result of decades or centuries of use, many marine ecosystems where MREDs are or are planned to be installed are already degraded (Lotze & Milewski 2008;

Halpern et al. 2008; Andersen et al. 2013). In such areas, ecosystems are less resilient and more susceptible to incremental increases in pressures (Crowder & Norse, 2008; Thrush & Dayton, 2010; Thrush et al., 2008). Assessing MRED cumulative effects also, therefore, requires an understanding of how the existing environment is changing as a result of the multiple activities acting on it. However, knowledge gaps also exist about the effects of other maritime activities (Table 2). As effects from multiple activities frequently overlap and interact in time and space to have a greater net effect on the environment or ecological components (Duinker and Greig, 2006), these uncertainties compound. An additional layer of complexity is introduced by the ways in which effects can interact, which can result in a net, cumulative effect that may be linear, nonlinear, positive or negative (Crain et al., 2008; Piggott et al., 2015).

Table 2. Other maritime activities with footprints that may overlap with MRED effects and where effect uncertainties also exist.

Maritime activity	Example uncertainties	Example references
Oil & gas exploration and extraction	Effects of: seismic noise; habitat change; oil pollution	(Barker and Jones, 2013; Hauge et al., 2014)
Aggregate extraction	Effects of: habitat loss; increased sediment concentrations	(Cooper et al., 2007; Foden et al., 2010)
Navigational dredging	Effects of: habitat loss; increased sediment concentrations	(Tecchio et al., 2016)
Commercial fishing	Effects of: direct mortality; trophic changes; habitat change	(Rice, 2008; Shannon et al., 2014)
Artisanal and recreational activities	Effects of: direct mortality; trophic changes; habitat change	(Hoover et al., 2013; Riera et al., 2016)
Shipping	Effects of: noise and vibration	(A. D. Hawkins et al., 2014)

The additional and novel stressors introduced into the environment by MREDs hence pose a risk that significant environmental change may result that conflicts with objectives to protect and sustainably manage the marine environment. Deciding how significant the change is likely to be and thus whether the risk is acceptable requires CEA to advance to enable the ecological effects of MREDs to be identified, measured or estimated, and placed in context of the receiving environment. Recognising that MREDs present a significant opportunity to deliver climate change mitigation plans (Gibon and Hertwich, 2014), enhance national and regional energy security, and are touted as a source of economic growth (European Commission, 2014), reducing the uncertainty surrounding MRED cumulative effects is timely and vital for climate change mitigation and marine management ambitions.

2.4 Key considerations for cumulative effects assessment

The concept of cumulative environmental change points to CEAs needing to identify, measure, mitigate and manage the effects of multiple human activities on the environment. CEAs hence need to address key considerations, which are introduced and discussed in sections 2.4.1 to 2.4.7.

2.4.1 Ecological connectivity

The connectivity between components of social-ecological systems introduces interdependencies that influence cumulative environmental change (Spaling and Smit, 1993). The practicalities of CEA are complicated by a complex reality of interactions between causations, processes and organism populations, and of human activities, past and present, combining to simultaneously affect numerous areas within an area of study (Bedford and Preston, 1988). Thus the standard approach for impact assessments of projects, plans and programmes, which typically assess direct relationships between stressors and individual receptors (Glasson et al., 2012) are incomplete assessments of the social-ecological consequences of projects, plans and programmes.

As marine management objectives expand to a more holistic perspective, the limitations of standard impact assessment approaches become more apparent.

CEAs of how activities and stressors influence ecosystem relationships and functions, rather than individual species alone, would support a more efficient means of monitoring ecosystem health (Strong et al., 2015). For example, in seafloor systems, many benthic organisms perform essential functions, helping the broader system to deliver ecosystem goods and services. Under the EU's Marine Strategy Framework Directive there is now a pressing need to ascertain seabed and ecosystem functions to support sustainable use and management of marine resources (Birchenough et al., 2013, 2012). If assessments of the effects of, for example MREDs, included an assessment of the effect on the relationships between abiotic and biotic components of the seafloor system, this would support progress towards a better understanding of how seafloor systems operate and, hence, better inform management of human activities.

Cumulative Effects Assessment therefore requires a broader perspective to be applied that takes into account the connections and effects on biodiversity and ecological functions in a given area (Strong et al., 2015; Thrush and Dayton, 2010). Maintaining the narrow, linear perspective applied by standard impact assessment approaches risks significant indirect impacts being missed, for example the recruitment failure of seabirds caused by a change in prey abundance and distribution, in turn caused by human activities (e.g. Perrow et al. 2011).

2.4.2 Temporal accumulation

Time is one of the less examined attributes of cumulative environmental change and is less considered in CEA in large part due to the shortfall of historical data that can be correlated with spatial data (Halpern and Fujita, 2013). Temporal accumulation refers to change brought about by disturbances or perturbations accumulating as the period between perturbations is shorter than the period of ecological recovery (Spaling and Smit, 1993). Typologies of cumulative effects have been developed, including different means of temporal accumulation, or time crowding and time lags (Cooper, 2004; Glasson et al., 2012), however cumulative effect typologies are debated (see Cocklin et al. 1992). Duinker & Greig, who initially developed a classification of cumulative effect types, subsequently argued that classifications can distract from the critical point, which is to assess the net effect of stressors on valued receptors (Duinker and Greig, 2006). A key consideration is thus recognising that effects can accumulate over time in a continuous, periodic, or irregular manner and occur over long or short time-scales (Spaling & Smit, 1993).

The temporal accumulation of effects typically manifest as functional effects, where processes (such as the flow of energy) or controlling properties (for example, environmental carrying capacity) are altered (Smit and Spaling, 1995). From a management perspective, CEAs should thus be designed to inform an iterative process, which includes the flexibility to account for incremental changes over time (Cooper, 2004; Parr, 1999), as well as considering the relevant historical evidence to take account of the relevant changes to support assessments (Bull et al., 2014; Squires & Dubé, 2013). This latter point is crucial to avoid assessments failing to account for "shifting baselines"(Elliott et al., 2015; Pauly, 1995), where assessments of change are measured against a baseline which is significantly different from the original state of the receptor (Hobday, 2011). Where predictions about future effects due to development are required, as with MREDs, scenarios should incorporate a sufficient time horizon to account for forecast development and changes, including climate change (Cornwall and Eddy, 2015; Duinker and Greig, 2007).

Assessments of the potential cumulative effects of MREDs in a given area should thus consider the temporal footprint of MREDs set within a sufficient historical perspective to determine trends in associated pressures and receptors (e.g. Andrews et al. 2014) and be forward looking to consider how predicted effects will interact with forecast environmental change (for example due to climate change).

2.4.3 Spatial accumulation

Spatial accumulation, where the effects of perturbations overlap in space (Spaling and Smit, 1993), can result in cumulative change, as the space between perturbations is less than that required to disperse the disturbance (Cooper, 2004; Spaling & Smit, 1993). Spatial accumulation, as with temporal accumulation, can occur over variable scales, from local to regional to global (Spaling & Smit, 1993). Consideration of spatial accumulation is more developed than temporal accumulation enabled by information technology developments such as geographic information systems (GIS) that can analyse and visualise georeferenced datasets (Halpern and Fujita, 2013). Spatial effects typically manifest as structural effects, such as fragmentation of habitats and population shifts (Smit & Spaling, 1995). CEAs thus need to identify what spatial scale is appropriate based on the characteristics of the stressors included in the assessment and the characteristics of the social-ecological system components affected by the stressors (Smit & Spaling, 1995) and also the extent of the area over which management jurisdictions apply. Hence, assessing the potential cumulative effects of MREDs also requires consideration of the spatial footprint of pressures arising from MREDs, existing and planned, together with the spatial effect footprints of other human activities.

2.4.4 Effect interactions

A critical knowledge gap for CEA is the potential for non-linear effects (Brown et al., 2014; Crain et al., 2008; Teichert et al., 2016). Evidence for non-linear effects typically stems from experimental research and, for ecosystems, from statistical analysis of suitable survey data to identify stressor interactions. Experiments indicate that non-linear effects are commonplace, particularly when an organism or system is stressed (Ellis et al., 2015). Experiments by Neumann-Lee (2016) show stress responses can be highly context dependent, with similar species reacting differently to the same stressors and populations responding differently across geographical scales, pointing to the site and species-specific nature of cumulative effect responses.

An assumption of an additive response to additional effects is advisable in the absence of information to the contrary (Judd et al., 2015). The potential for effects to cumulate at different levels of biological and ecological organisation points to the need for laboratory, field, modelling and conceptual studies. Experimental studies and observational data are often important means of locating thresholds and to provide insight into recovery pathways. The combination of different study methods is important to strengthen insights gleaned from one study form. For example, the shortcomings of laboratory studies, such as the challenges of replicating the conditions found in the natural environment and issues tracking recovery pathways for longer-lived organisms or communities (Standish et al., 2014) can be partially addressed by combining findings with comparable observational or modelled studies.

2.4.5 Endogenic and exogenic sources of pressure

Sources of effects contributing to cumulative environmental change can be singular or multiple in origin (Cocklin et al., 1992), but in environments where multiple activities occur, the state of the environment reflects the effects of multiple pressures arising from multiple sources (Duinker and Greig, 2006). CEAs variably assess similar or dissimilar pressure types often chosen for inclusion depending on the driver of a CEA, whether legal or scientific (Judd et al., 2015). CEA addressing cumulative environmental change requires consideration of the effects of multiple sources of perturbations, as the ambition is to understand how environmental condition has been and is likely to be affected by human activities (Cocklin et al., 1992; Squires and Dubé, 2013).

There are two categories of pressures that contribute to change in the system being studied: endogenic and exogenic (Elliott, 2011). Endogenic pressures are those where the cause and consequence occur within the system and hence both can be managed (Elliott, 2011). Exogenic pressures, such as climate change, are those that emanate from outside the system or operate at scales beyond the system, hence within the system being studies only the consequences can be managed (Elliott, 2011). Feedback loops and nestedness challenge this binary distinction; endogenic activities may contribute to exogenic pressures (Levin et al., 2013), such as the local generation of carbon emissions contributing to global climate change. The effects of climate change are already being felt in coastal environments and changes to date are a fraction of the change predicted (Bamber et al., 2019), as the seas and oceans respond to physically-driven and chemically-driven changes (Cox et al., 2000; Harley et al., 2006). Climate change adds complexity to the understanding of anthropogenic cumulative effects by introducing stressors that interact with endogenic pressures (Harley et al., 2006). However, CEAs of MREDs would be incomplete without consideration of potential climate change effects given the time scale of MRED lifecycles (MMO, 2013).

2.4.6 Placing receptors at the centre of assessments

A key criticism of CEAs completed as a sub-component of EIAs is the weakness of applying a stressor-led approach (Dubé et al., 2013; Duinker et al., 2012; Squires and Dubé, 2013). EIAs and the CEAs within, typically assess how isolated stressors arising from a proposed development combine with the same stressor arising from proximal developments or activities to impact a valued receptor (Dubé et al., 2013; Duinker et al., 2012; Squires and Dubé, 2013). However, receptors experience multiple stressors and effects accumulate over broad temporal and spatial scales to impact receptors, hence EIAs do not assess how receptors are impacted by cumulative effects (Duinker et al., 2012; Therivel and Ross, 2007). Placing receptors at the centre of an assessment forces a broader, more integrative perspective. Receptors, rather than stressors, should be the focal point of CEA and guide the identification of the various stressors to include in an assessment of how an activity or activities will impact receptors (Duinker et al., 2012; Duinker and Greig, 2006).

The use of the term “impact” also brings into play the distinction between “effects” and “impacts” of stressors. To determine whether a stressor effect is of sufficient magnitude and intensity to have a meaningful impact on a receptor (positive or negative), typically requires more information or research than is available or completed for impact assessments, however many studies use the term impact based on findings that suggest an effect (Boehlert and Gill, 2010). MRED CEA studies typically assess receptor responses to individual stressors, such as habitat loss, generated by a limited number of activities, such as offshore wind farm construction and aggregate dredging (e.g. Smart Wind 2015). The results contained in such CEAs are presented as determinations of impact significance, however to determine the cumulative effect of a stressor on a receptor requires consideration of the range of stressors acting on the receptor (Duinker and Greig, 2006). That is to say, many impact assessments and the CEAs within have assessed effects, not impacts (*sensu* Boehlert & Gill (2010)) of the project or plan.

CEA methodologies that consider the traits and sensitivities of receptors to guide the design of an assessment are better able to identify and predict multiple stressor effects (Segner et al., 2014; Teichert et al., 2016). Receptor-led approaches may also support improved consistency between CEAs; consistent metrics can be applied to a receptor or function independent of pressures, such as effect on reproductive capacity (Segner et al., 2014).

Assessments that have placed receptors at the centre of MRED CEA have been instructive in identifying the potential risks of widespread MRED deployments relative to wide-ranging mobile receptors (e.g. underwater noise effects on marine mammals; Heinis & de Jong 2015; collision risks for seabirds and bats; Leopold et al. 2014). Such CEAs also enable investigation into one of the longstanding uncertainties surrounding CEA, that of appropriate temporal and spatial boundaries. CEAs that centre on the receptor imply boundaries being applied based on temporal and spatial footprints of the receptors (Segner et al., 2014; Therivel and Ross, 2007).

2.4.7 The purpose of cumulative effects assessment

The final CEA consideration discussed here is the purpose of a CEA and the context that shapes the design of a CEA. Why a CEA is undertaken influences the approach taken, the receptors included and thus the output. CEAs that are poorly-defined and overly generic result in variability and uncertainty of outcomes that are problematic for marine managers (Judd et al., 2015). While drivers behind marine CEA are varied (being stimulated by legal requirement or scientific inquiry for example; Judd et al. 2015), the intention of CEAs is, ultimately, to support sustainable development. Identifying a purpose that is common to all CEAs, independent of activity, scale and receptor, provides a starting point from which to develop other principles and guidelines to reduce the variability in practice (Foley et al., 2017; see also Chapter 4).

The ecosystem approach to management has emerged as a tenet around which marine management is centred (Elliott 2011; Long et al. 2015; McLeod et al. 2005), recognising that the combined sources of pressures require management if sustainable use of the seas is to be achieved (Borja et al., 2013; Curtin et al., 2015; Elliott, 2011). In Europe, the obligation of EU Member States to achieve Good Environmental Status (see Borja et al., 2013) for marine waters by 2020 has led to regional assessments of the state of the environment (e.g. HM Government, 2014) and the mapping and assessment of the effects of multiple human pressures on environmental status (e.g. Andersen et al. 2013). Regional studies provide context for CEAs relating to discrete activities and could form the basis for a common baseline to support future CEAs. Many of the uncertainties that apply to CEA broadly also apply to regional CEA, for example cause-effect knowledge gaps, data paucity and a lack of assessment tools (Foden et al., 2011). Clarifying the purpose of CEA to establish a starting point from which to develop guidelines is also relevant to regional CEAs.

2.5 Key challenges to improving cumulative effects assessment

Current literature on CEA points to a series of challenges that need to be addressed for CEA to evolve into a consistent, meaningful decision-making tool. Key to advancing CEA are: coordinating the multitude of approaches to CEA to enable currently disparate methodologies to contribute to improving regional understandings of cumulative environmental change; overcoming the dominance of EIA-led CEA in the planning and licensing systems; enabling CEA to provide ecosystem-relevant information; and, applying CEA within the context of an appropriate baseline. To meet these challenges requires common ground to be established within a defined area by provision of an overarching frame of reference. These challenges are expanded on in the following sections.

2.5.1 Convergent thinking, divergent approaches

From predictive, EIA-based origins, CEA today includes retrospective, pressure-based approaches (e.g. Halpern et al. 2008), predictive, stressor-based approaches (e.g. standard EIAs), and frameworks seeking to integrate both predictive and retrospective approaches (Dubé et al., 2013). The focus of CEAs ranges from individual species (e.g. caribou, Johnson et al. 2015; harbour porpoises, Heinis & de Jong 2015), to habitats (e.g. seagrass, Grech et al. 2011; fish habitat in estuaries, Teichert et al. 2016), to ecosystem functions and services (e.g. biodiversity; Andersen et al. 2015). The scale of CEAs varies correspondingly, from boundaries defined by the extent of stressors arising from a single development, by species distribution (e.g. seabirds and bats, Leopold et al. 2014), to ecologically meaningful areas (e.g. watersheds, Squires & Dubé 2013; the Baltic, Korpinen et al. 2012), increasing to global marine areas (e.g. Halpern et al. 2008).

The emergence of regional CEAs owes much to the conceptual and practical advances associated with improving the management of wetlands (e.g. Preston & Bedford 1988) and watersheds or catchment areas (e.g. Dubé 2003). Recognising that EIA and project-driven CEA could not match the spatio-temporal dynamics of valued receptors or the broader environment, researchers assessed effects of multiple stressors acting on broader spatial scales (Preston and Bedford, 1988; Squires and Dubé, 2013). In the marine environment, management of the North Sea has inspired improved CEA tools, developed in response to ongoing and expanding industrial activities. Regional boundaries have been applied in response to legislative drivers to assess human pressures in the marine environment (e.g. Andersen et al. 2013). The expansion of MREDs in the North Sea has driven CEA forward, with cumulative effects of MREDs stressors coming under scrutiny (e.g. Bailey et al. 2014; Kershaw et al. 2013; Pine et al. 2014; Wright & Kyhn 2015). CEAs for MREDs that apply broader spatial scales include those completed under FAECE (Framework for Assessing Ecological and Cumulative Effects of offshore wind farms), a structured methodology developed for the Netherlands government, that distinguishes between a legal and ecological approach, recognising that legally compliant CEA may not be ecologically relevant (Ministry of Economic Affairs, 2015). The FAECE framework has been applied regionally, investigating cumulative disturbance to marine mammals caused by impulsive underwater noise (Heinis and de Jong, 2015) and the cumulative effect of collision and habitat loss on seabirds and bats (Leopold et al., 2014). As with many marine CEAs, the paucity of data and uncertainties about cause-effect relationships require assumptions to be made that limit the confidence in the outputs (Heinis and de Jong, 2015; Leopold et al., 2014). However, the application of novel methodologies that define the spatial boundaries based on the receptor, and which determine significance in context of the receptor population are important advances for marine CEA.

While data paucity is problematic, regional CEAs are developing rapidly building on advances in understanding stressor-receptor relationships (e.g. stressors affecting fish in estuarine waters; Teichert et al. 2016), receptor traits (e.g. spatial behaviours of seabirds relative to offshore wind farms; Bradbury et al. 2014); mapping (e.g. iterating a CEA using novel temporal data; Clarke Murray, et al. 2015), and applying novel conceptual frameworks (e.g. Vries et al. 2012). Literature points to the development of CEAs, particularly CEAs completed for MREDs, advancing via progress grounded in academic research, rather than advances driven by the EIA process. For example, elucidating the cumulative effect of collisions of seabirds with offshore turbine blades has progressed by applying advances in distribution modelling (e.g. Miller et al. 2013) and species sensitivity modelling (e.g. Bradbury et al. 2014). Such advances have in turn enabled CEAs at scales appropriate to receptors.

A similar process of iterative CEA development can be observed with the application and refinement of the spatial analysis methodology published by Halpern et al. (2008). The Ocean Assessment mapping approach developed by Halpern et al. (2008) has been instrumental in progressing marine CEA by building on advances in geospatial analysis techniques to match broad-scale habitats with anthropogenic activities and using expert judgement to estimate the sensitivity of, and thus impact to, the habitats. Adaptations of the approach have been applied to regional waters (e.g. Canada's Pacific coast; Ban et al. 2010; Mediterranean Sea and Black Sea; Micheli et al. 2013), to include indirect pressures as well as direct anthropogenic pressures (e.g. climate change and industrial development; Clarke Murray et al. 2015), and to enable effects of anthropogenic activities on specific ecosystem components to be assessed (e.g. on marine predators; Maxwell et al. 2013).

Mapping approaches to CEA require further refinement is required to adapt advanced spatial analyses to meet the needs of marine managers, by identifying and responding to the scales at which practical management decision-making happens (from projects to regional programmes). Validation of predicted stressor intensities and the interactions of the stressors with sensitive receptors is necessary to improve confidence in the predicted cumulations of effects. Spatial analyses also need to be supported by appropriate temporal analyses to assess environmental change (Halpern and Fujita, 2013; Judd et al., 2015).

Conceptual frameworks, such as the driver-pressure-state-impact-response (DPSIR) framework (e.g. (Elliott, 2002), have been influential in bringing systems thinking to understanding relationships between drivers and effects (Atkins et al., 2011) and the DPSIR approach has been recommended for marine CEA (Kelly et al., 2014; MMO, 2013). DPSIR continues to develop with the integration of human welfare as a link in the framework (DSPWR; Cooper 2013) and to identify activities resulting in pressures (Driver-Activities-Pressures-State-Impact-(Welfare)-Response; DAPSI(W)R(M); Elliott 2014). Reflecting the connectivity between natural systems, effects and responses, the DPSIR approach has further developed to account for interactions between linkages, a networked approach, to support prioritisation of marine management interventions (Knights et al., 2013). A variation on the driver-effect framework, CUMULEO (Cumulative Effects of Offshore activities) has been developed and proposed as a “conceptual umbrella” (Tamis et al., 2015) to bring direction to the various forms of environmental assessment, working from the strategic level down to project level (Tamis et al., 2015). Network thinking is applied to map the relationships between multiple activities developed by Knights et al. (2013) to address the assumed independence between linkages that limits standard DPSIR approaches (Gregory et al., 2013; Knights et al., 2013). A variation of CUMULEO, CUMULEO-RAM, has been tested in Dutch coastal waters, translating spatial information about activities and stressors into indicators of ecological significance

(Vries et al., 2012). As well as considering relationships between activities, the model output includes estimates of the contribution of each activity to effects on receptor survival and reproduction, an important step forward for CEA in context of marine management.

2.5.2 The need for multidisciplinary action

The increasing awareness of the role cumulative effects have in shaping social-ecological systems has also raised awareness of the need for multidisciplinary research. Analyses of multiple stressor effects and ecological modelling, which seek to elucidate cause and effect relationships in complex networks are highly relevant to CEA. Multiple stressor analyses seeking to identify and rank stressors to enable targeted management interventions (e.g. conservation of seagrasses, Giakoumi et al. 2015; quality of fish habitat within estuaries, Teichert et al. 2016) hold promise to enable more effective CEAs by providing methodologies and models from which the most influential stressors can be identified relative to the receptor being assessed.

Marine ecosystem models assist with analysing and testing the dynamics of foodwebs within marine ecosystems and provide a means of estimating how ecosystems respond to stressors (Steenbeek et al., 2013). As such, the models hold promise to support CEA by enabling stressor effects to be modelled at ecologically meaningful scales and by supporting the establishment of a baseline by assessing ecosystem status (Piroddi et al., 2015). Ecopath with Ecosim (Christensen et al., 2005) is a widely used modelling approach that is evolving to enable the integration of spatial and temporal dynamics within ecosystem models (Coll et al., 2015; Steenbeek et al., 2013). Physical models have also been applied to test the effects of physical disturbance due to MREDs on ecosystems (van der Molen et al., 2014). Modelling effects is an attractive option, as empirical studies at sea tend to be prohibitively expensive (Alexander et al., 2016), but despite the mathematical complexity, models are necessarily simplified simulations of the real world that rely on assumptions derived from our current understanding of what is being modelled. Thus validation of models is critical to test, refine and improve modelling tools (Forrest et al., 2015). The paucity of data, issues of scale and data resolution, and the knowledge gaps about cause-effect relationships pose challenges for model development and validation (Alexander et al., 2016).

In the context of identifying and managing sources of cumulative environmental change, the different approaches vary in terms of the receptors considered, methodologies applied, and stressors assessed. Additionally significance, specifically the likelihood of an effect occurring that has a significant impact on a valued receptor (see Boehlert & Gill 2010) is variably interpreted (Ehrlich and Ross, 2015). The outputs of the approaches also differ, from spatial outputs, to diagrammatic outputs highlighting key stressors, to networks of linked drivers and ecosystem components. Thus, while many research streams are relevant to managing cumulative environmental change and to CEA, a key challenge is to enable the outputs of relevant research streams to converge on resolving a commonly understood problem, and to encourage interdisciplinary and cross-border research.

2.5.3 The reliance on cumulative effects assessments derived from EIAs

The majority of CEAs considered during planning and licensing are contained within EIAs or apply EIA approaches (Duinker et al., 2012). This is despite the known and recognised limitations of EIA approaches at delivering meaningful CEA (Gunn and Noble, 2011; Squires and Dubé, 2013; Therivel and Ross, 2007). While EIA struggles to meet increasing expectations around CEA, EIAs have become increasingly resource-heavy and burdensome (Smart et al., 2014; Wright, 2014). EIAs have become expensive and time-consuming while failing to meet the evolving information needs of regulators and decision-makers tasked with protecting and maintaining the overall condition of the environment (Hegmann and Yarranton, 2011; Judd et al., 2015).

The continued focus of EIA practice is on complying with regulation (Ball et al., 2012), not on investigating uncertainties about the interaction between a project and a social-ecological system. Without fundamental change, the CEAs contained within EIAs (hereafter EIA-led CEA) are unlikely to aid resolution of the “conundrum of cumulative effects assessment” (Judd et al., 2015). Whether individual developments can reasonably be expected to assess effects at the spatio-temporal scales that apply to receptors, which may include migratory species, catchments or ecosystems, is moot (Freeman et al., 2013), and it has been argued that CEAs should be done by governments (e.g. Duinker & Greig 2006).

A counterpoint to the argument that EIA-led CEA should be scrapped is the strength of decision-making processes associated with EIA and the widespread acceptance of EIA as a process to support sustainable development (Glasson et al., 2012). That said, there is clear evidence that the relationship between EIA and CEA must be redefined if EIAs are to remain a key decision-making instrument. The arguments against standard EIA approaches as a means of addressing cumulative environmental change are well established and have been strengthened by empirical research. For example, EIAs failed to identify that incremental declines in habitat connectivity for woodland caribou have increased the risk of extinction of this species (Johnson et al. 2015). EIAs failed to identify that the incremental loss of habitat for burrowing birds resulted in significant population declines of the species (Heneberg 2013). A question arises whether the EIA system could be adapted to contribute to meaningful CEA. The data collected by the multitude of project-level EIAs could, if made available, support improved distribution modelling of species by increasing the resolution of data available to researchers investigating effects at broader scales.

Numerous authors have pointed to the need for cross-border regional or strategic approaches to CEA (e.g. Duinker et al. 2012; Duinker & Greig 2006; MacDonald 2000; Gunn & Noble 2011) and generic frameworks to coordinate tiered environment assessments have recently been proposed (e.g. CUMULEO; Tamis et al. 2015). While the rationale for strategic approaches to proceed project-level assessments is intuitive and well founded (Lobos and Partidario, 2014; Tetlow and Hanusch, 2012), the reality in many areas, for example United Kingdom waters of the North Sea, is that project-level assessments precede strategic assessment (Glasson et al., 2012). At a methodological level, strategic environmental assessments (SEAs) tend to apply an “EIA-plus” (Therivel and Ross, 2007) approach, but over a greater geographical extent (Lobos and Partidario, 2014). As with EIAs, SEAs tend to assess the effects of a proposed action on receptors rather than providing the more complete picture required to assess how receptors are being impacted by multiple pressures (Figure 2). At an institutional level, SEA decision-making structures are weaker than those of EIA, limiting SEAs capacity to influence planning and management (Gunn and Noble, 2011; Noble et al., 2019). In the context of cumulative effect uncertainties, the CEA considerations discussed in Sections 3.4.1 to 3.4.6 are applicable to SEA also. Until SEAs also account for these considerations, the effectiveness of SEAs over EIAs at reducing cumulative effect uncertainties is questionable.

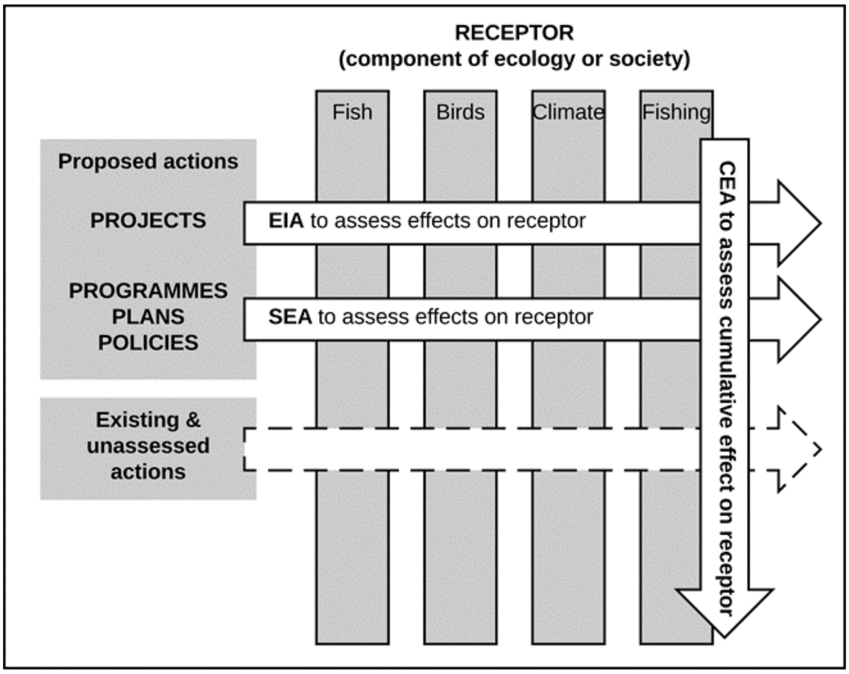

Figure 2. Relationship between EIA and SEA, and the theoretical role of cumulative effects assessment in cutting across the various assessment levels to provide a comprehensive understanding of how a receptor is impacted by the many actions effecting change. The dashed arrow indicates actions that are not subject to assessment, but which contribute to incremental change in receptor condition. Example of ecological and/or societal receptors are shown. Adapted from Therivel & Ross (2007).

Distinct from stressor-based assessments are effects-based assessments that put the environment as the focal point of the assessment, and which seek to measure changes in indicators relative to a reference condition (Dubé et al., 2013). This addresses the consideration to place receptors at the centre of an assessment, however the priority of effects-based assessment tends to be the monitoring and measurement of past ecological change (Dubé et al., 2013). This is of limited use for managers and planners who require forecasts of predicted change that would result from proposed development activities (Judd et al., 2015).

A move towards an effects-based assessment approach, as is recommended by numerous proponents of CEA, introduces a challenge, as EIAs invariably focus on stressors associated with the proposed development. This is the essence of EIA practise (Glasson et al., 2012; Noble, 2014) and a movement towards effects-based approaches would require a significant shift in thinking among EIA practitioners, away from a comparatively narrow, easier to assess approach, towards a broader approach with greater uncertainties attached, and thus potential for greater confusion if not accompanied by clarified expectations of what project-specific or activity-specific CEAs should deliver.

While there are limitations to stressor-based assessment approaches, combining stressor-led and effects-led approaches holds promise of enabling effective CEAs rather than developing one approach in isolation (Dubé, 2003; Dubé et al., 2013). Coordination of project and regional CEA also offers the potential to combine strengths of each approach (Figure 3). In countries where development activities are required to submit EIAs in support of a license or permit application, the frequency of assessments offers inputs of data obtained during characterisation and monitoring studies that could improve the resolution of regional baselines. Furthermore, regional CEAs that apply meaningful spatial boundaries relative to cumulative environmental change could inform the determination of appropriate spatial boundaries for project CEAs.

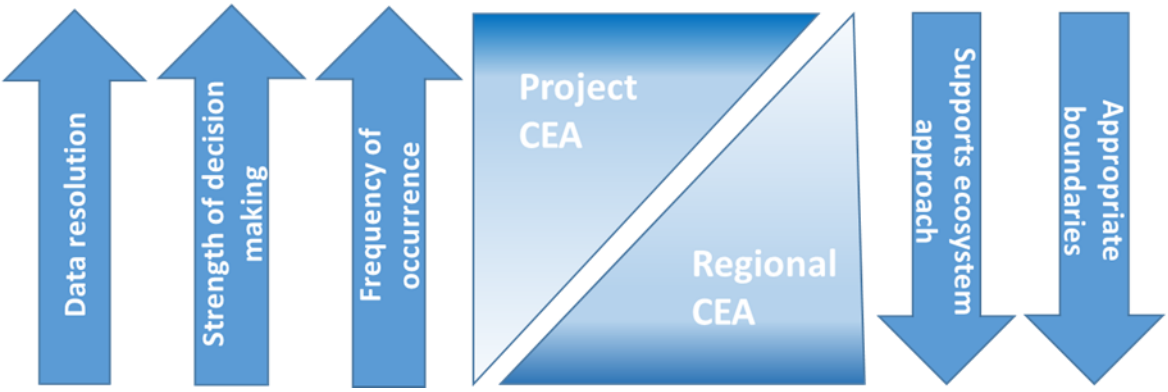

Figure 3. Comparison between characteristics of CEAs that apply project-scales and regional scales. The direction of the arrow indicates increasing strength of the characteristic relative to the need to identify and manage cumulative environmental change. Coordinating these scales of assessment to resolve a common problem could enable more efficient progress towards resolving cumulative effect uncertainties.

2.5.4 Adapting CEA to support ecosystem assessments

Realising the potential of CEA to support holistic marine management requires CEA to provide information about the effects, current and forecast, of human activities on an ecosystem. This is challenging due to the natural variability of ecosystems and the many knowledge gaps that exist about ecosystem structure and functioning (Thrush and Dayton, 2010). The potential for interactions between effects, which may result in non-linear responses (Crain et al., 2008; Piggott et al., 2015) and between nested ecosystem components (Malone et al., 2014) have led CEA to be labelled an intractable problem (Stakhiv, 1988). The nature of the marine environment exacerbates the CEA challenge as the three-dimensional scale over which biota ranges is vast, as are the distances between connected areas that play a role in the lifecycles of many marine animals (Carr et al., 2003; Crowder and Norse, 2008).

Visual observation of the marine environment is also difficult, making marine research expensive and logistically challenging (Parsons et al., 2014). Sustained observations of the dynamics of marine systems are often lacking (Malone et al., 2014). In the context of CEA, while advances in spatial analyses improve predictions about where cumulative effects concentrate (e.g. Halpern et al. 2008) and progress in environmental modelling to predict the significance of cumulative effects (e.g. van der Molen et al. 2014), verification remains difficult due to the paucity of appropriate data (Halpern and Fujita, 2013). To this end, the diverse research streams investigating, for example, cause-effect relationships and multiple stressor interactions improve CEA by providing data and insights into how cumulative effects arise and interact. Equally, published results of monitoring programmes that observe the environmental effects of, for example MREDs (e.g. Degraer et al. 2013; Federal Maritime and Hydrographic Agency (BSH) & Federal Ministry for the Environment 2014) provide important data that could verify predicted effects and which could enable local observations to be scaled to predict ecosystem-level effects. Critical to advancing CEA will be integrating scientific advances from research into multiple stressor interactions (e.g. Teichert et al. 2016; Tran et al. 2009; Jackson et al. 2015), systematic approaches to mapping cause-effect relationships (e.g. Gregory et al. 2013; Knights et al. 2013) and ecological studies illuminating the sensitivities of species and ecosystems (e.g. Nimmo et al. 2015; Thrush et al. 2008a). Providing CEA practitioners with access to fit for purpose information and appropriate CEA tools that enable disparate datasets to be combined will be a key development to advance CEA in a given region.

2.5.5 Establishing a baseline

For CEA to support environmental management in an area with ongoing and forecast activities, it is necessary to establish a fixed baseline against which to evaluate predicted effects (Bull et al., 2014). Establishing a baseline or reference condition for CEAs is contentious, as approaches alternatively recommend hindcasting or integrating historical data (e.g. Squires & Dubé 2013) or using the present condition of the environment as the baseline (e.g. Vries et al. 2012). EIAs for MREDs apply the latter approach by establishing a reference condition that has been affected and continues to be affected by existing activities (see Chapter 3). This introduces an implicit assumption into the assessments that the current condition of receptors is normal. The consequences of cumulative effects past, the cumulative effects load carried by a receptor, tend not to be accounted for (discussed in Section 3.4.1 in Chapter 3). As subsequent EIAs apply the same approach, the baseline shifts and risks accommodating and masking environmental change (Pauly, 1995). This is problematic for longitudinal management, as reference points continually change (Gatti et al., 2015) and confidence in EIA conclusions is reduced.

However, set against the argument for a fixed baseline is the reality of rapid environmental change to the extent that restoration of changed ecosystems to meet historical targets and reference points may be counter-productive (Harris et al., 2006; Hobbs et al., 2014). Marine systems tend to experience a wide range of perturbations, which can result in a series of succession patterns. Depending on the level of the perturbation, systems may return to a pre-impacted state or in some cases experience further levels of disturbances (Birchenough & Frid, 2009). The perturbed nature of most marine ecosystems suggests that an “original” state is unlikely to be recovered, particularly in light of climate change (Hobday, 2011). This presents a challenge for contemporary management, as the concept of a former equilibrium state is entrenched in ecological thinking (Hobday, 2011), despite evidence that social-ecological system resilience is influenced by the capacity to adapt and transform (Folke et al., 2016).

The challenge of defining a baseline also hinders the establishment of thresholds, which are considered to be essential if the significance of effects are to be quantified relative to a receptor (Duinker et al., 2012; Seitz et al., 2011; Westbrook and Noble, 2013). However, thresholds are frequently not known and determining defensible thresholds based on empirical evidence is scientifically and socially challenging (Duinker and Greig, 2006; Foley et al., 2015; Groffman et al., 2006). As with CEA, the concept of thresholds is open to interpretation, which, exacerbated by questions about scale, natural variability and nonlinear system responses, can reduce confidence in defined thresholds (Groffman et al., 2006). Thresholds can also vary between jurisdictions, hindering regional assessments for receptors that range beyond national boundaries, for example sound exposure thresholds for marine mammals in European waters (Luedeke, 2012).

Where thresholds are absent, pragmatic alternatives are required to support managers, particularly in areas where maritime activities continue to expand and where the environment is changing rapidly and heterogeneously.. Where thresholds are absent, the determination of trends based on the integration of historical data, where available, provides an opportunity to guide management decisions (Mcclenachan et al., 2012). The use of trends can identify the extent to which a population has changed over time and can provide insights into how resilient a receptor is likely to be and how it may recover from additions to the cumulative effects load carried (Mcclenachan et al., 2012).

The use of different baselines in assessments that may be assessing analogous development activity raises a question about determinations of significance. EIA is concerned with identifying significant environmental impacts (Beanlands and Duinker, 1984; Glasson et al., 2012), but significance is a difficult term to pin down; it can relate to statistical, ecological, social or project significance (Duinker & Beanlands 1986). Without common temporal and spatial reference conditions between assessments that are in a shared social-ecological system, the context from which determinations of significance are made may vary, including temporal and spatial scales, interpretations of value, ecological sensitivity and so on (Wood, 2008). For CEA, which requires that the effects of different activities and stressors on receptors can be compared, such variation is problematic.

As with temporal scale, the spatial scale applied to assessments can influence the determination of significance. The spatial scale applied and how variability in time and space are defined influence the likelihood that a significant effect will be detected (Hewitt et al., 2001). What appears significant at a local level may appear insignificant in a regional context, for example. The spatial scale, in comparison with the temporal component of CEA, is easier to conceptualise and integrate into an assessment, in large part due to advances in geographic information systems (GIS). The temporal scale is difficult to integrate into assessments (Halpern and Fujita, 2013), although recent iterations of CEAs have investigated temporal change in pressures in an area compared with previous iterations (Halpern et al. 2015; Clarke Murray et al. 2015).

A challenge for CEA in a given area is thus to put an appropriate frame of reference in place, including a baseline against which future CEAs can determine the significance of changes to receptors, and which can be used to measure changes caused by permitted but not yet constructed developments. Further investigation is required to identify suitable receptors for CEAs for which historical data exists that enables trends to be determined and against which counterfactual scenarios (without development) could be modelled (Bull et al., 2015). Further debate should be directed at specifying what reference conditions environmental assessments should be relative to, or if a less front-loaded, dynamic form of assessment with increased monitoring to detect effected change would be beneficial.

2.5.6 Establishing common ground

A universal definition for cumulative effects and of CEA is unlikely given the variety of legislative and scientific drivers behind CEAs and CEA research, and because there remains a lack of consensus about the nature of cumulative effects (Duinker et al., 2012). The flexibility of interpretation can also be viewed positively, as different CEAs seek to address discrete and perhaps more tractable parts of the problem. Thus, the range and breadth of CEAs may lead to more rapid advances in CEA. To support the accumulation of knowledge, however, all CEAs should include a clear statement of the objective, scope and boundaries of the assessment (Cooper, 2004; Duinker et al., 2012; Judd et al., 2015). All CEAs should be guided by an explicit definition of cumulative effects appropriate for the task in hand (Duinker et al., 2012; Judd et al., 2015).

From a marine management perspective, variability between CEAs is problematic (Ball et al., 2012; Judd et al., 2015). Thus while the breadth of CEAs undertaken in an area could present an advantage, it is appropriate that common ground is established from which to guide CEAs relative to the licensing and management of marine activities. This would require a common position to be agreed about the objective and outputs of CEAs completed for proposed activities, such as MREDs, in a given area. This common ground would need to apply to all activities within a given area. Ultimately improvements in environmental condition will require integrated management of the variety of effects generated by the multitude of users (Elliott, 2013), thus marine managers require compatible information from CEAs regardless of the activity or pressures considered. Hence, the elaboration of CEA principles specific to marine management (see Judd et al. 2015) is an important development.

2.6 Conclusions

Reducing uncertainty regarding MRED cumulative effects is given impetus by the pressing nature of climate change mitigation targets, the need to meet energy security quotas, the demand for blue growth and the drive to ensure the sustainable use of the marine environment for this and future generations. However, the effects of MREDs need to be assessed in context of the receiving social-ecological system, which introduces additional knowledge gaps in relation to the effects of other human activities, and of the structure and functioning of the social-ecological system.

Beyond MREDs, there is an urgent need to improve assessments of how human activities change social-ecological systems and there is growing recognition that the condition of social-ecological systems reflects the cumulative effects load carried. Improving CEA is a logical step to address this need, but CEA is a broad topic made broader by the challenges of assessing changes in complex, non-linear social-ecological systems (Levin et al., 2013; Levin, 1998). Assessing cumulative effects is a wicked problem, as it defies easy resolution, is highly complex, is located at the boundaries of social and ecological systems, and is value-based (Crowley and Head, 2017). For CEA to become a consistent, meaningful tool for assessing environmental change requires conceptual, methodological and practical advances supported by interdisciplinary research. Key considerations and challenges were introduced and discussed in this chapter, which require attention when seeking to advance CEA practice.

Having established that there are challenges involved, there is also a substantial body of research to draw on. Further, the potential for CEA to become an established and important decision-making tool is increased by CEA already being a legal requirement in many countries under EIA and SEA laws, and in the European Union, under marine management law. The question that is investigated further in this thesis is whether discrete CEAs completed for projects or development activities could provide information that is better suited to ecosystem approach management of marine waters.

Before concluding the chapter, the working definition of CEA that arises from the literature review is specified here. CEA is an assessment of the consequences of human activities on receptors within social-ecological systems. This is a working definition as later research, presented in Chapter 4, inquired into the conceptual underpinnings of CEA leading to further consideration of what is CEA. In light of the research presented in Chapters 4, 5 and 6, the definition is revisited in Chapter 7.

The next chapter seeks to identify what shortcomings exist in current CEA practice to better understand the problem and to investigate if project-specific CEA shortcomings can be overcome, or if a more radical rethink of CEA is warranted.

3 Short-comings in current CEA practice[2]

3.1 Introduction

This chapter presents the evaluation of CEAs contained within the planning application documents submitted by large-scale offshore wind farms in UK waters. A novel framework was developed to test how effective these CEAs were relative to a set of attributes designed to reflect the legislated requirement to make planning decisions cognisant of the cumulative effects of development. The aim of the evaluation was to investigate whether the long documented shortcomings in CEA practice discussed in Chapter 2 remain current and are pertinent to MRED CEAs today.

Governments worldwide are looking to secure future energy supplies and to mitigate climate change through generating electricity from renewable energy sources (Gasparatos et al., 2017). Of these sources, wind energy is a mature technology that has seen consistent growth in capacity (Dai et al., 2015; Kaldellis and Zafirakis, 2011; Leung and Yang, 2012). This growth is likely to continue as wind energy is envisaged as a key component of future low carbon energy generation sectors in numerous regions of the World, for example, Brazil, China, the European Union, India, and the USA (Kaldellis and Zafirakis, 2011). For wind energy to meaningfully contribute to a 'green' transformation of the electricity generation sector requires significant upscaling of wind energy infrastructure (Hofmann, 2011; Sithole et al., 2016; Tabassum et al., 2014). Large-scale deployment also enables scale economies to take effect, further increasing the financial attractiveness of investing in wind energy developments (Hofmann, 2011; Snyder and Kaiser, 2009).

Upscaling wind farm developments onshore is increasingly difficult, as locations with sufficient exposure and size become scarce, and due to societal objections to expansion on land (Kaldellis and Zafirakis, 2011; Leung and Yang, 2012;

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[2] Chapter adapted from: Willsteed, E. A., Jude, S., Gill, A. B. & Birchenough, S. N. R. Obligations and aspirations: A critical evaluation of offshore wind farm cumulative impact assessments. *Renewable and Sustainable Energy Reviews* **82,** 2332–2345 (2018).

Tabassum et al., 2014). Thus the benefits of locating wind farms offshore become more apparent, particularly as technological and economic barriers are overcome (Hofmann, 2011; Snyder and Kaiser, 2009). However, the expansion of offshore wind farms (OWF) has not been straightforward. In various jurisdictions, regulatory and consenting procedures are consistently highlighted as a brake on development (O'Hagan, 2012). Developers have identified delays during the consenting process as a significant financial and administrative burden (Freeman et al., 2013; O'Hagan, 2012; RenewableUK, 2013), burdens that also apply to emerging marine renewable energy technologies, such as wave and tidal energy (Greaves et al., 2015; Leeney et al., 2014), adding an additional barrier to attracting necessary capital investment. Understanding why such delays arise in established marine renewable energy markets is key to enabling improvements in existing regulatory and consenting procedures, to facilitate the development of better guidance for developers and investors, and to provide insights that may assist nations in earlier stages of deployment.

The uncertainties surrounding the environmental consequences of marine renewable energy developments and how to assess them have been identified as significant contributing factors to delays (Masden et al., 2015; O'Hagan, 2012). While the potential for environmental effects to arise is well documented (Boehlert and Gill, 2010; Dai et al., 2015; Gill, 2005; Leung and Yang, 2012; Tabassum et al., 2014), the significance of effects on important ecological resources is not known (Boehlert and Gill, 2010; Marine Management Organisation, 2013). Regulators are unsure how best to discharge their legal obligation to protect the marine environment (Judd et al., 2015).

This uncertainty is well documented, as reviewed in Chapter 2, but there is an opinion that the marine renewable energy sector receives disproportionate regulatory scrutiny relative to pre-existing maritime industries (Wright, 2015) and that many predicted environmental impacts are “myths” (Kaldellis and Zafirakis, 2011). However, advances in our understanding of how human activities accumulate to effect significant environmental change (e.g. Duinker et al., 2012; Halpern et al., 2008; Jones, 2016; Therivel and Ross, 2007) provide ample reason to challenge this opinion and to re-investigate the predictions of no significant environmental impact.

Heeding the call from developers and regulators to clarify expectations of CEA (Greaves et al., 2015; O'Hagan, 2012; Wright, 2015), this chapter presents a critique of the assessments of cumulative effects found in the Environmental Statements of large-scale offshore wind farms. The intention was to identify where CEAs do and do not meet the requirements of 'good' CEA, as defined by the key CEA considerations established in Chapter 2.

3.2 Materials and methods

3.2.1 Rationale

The evaluation targeted Environmental Statements completed for the most recent OWF development round in United Kingdom (UK) waters. The UK has experienced rapid growth in the deployment of OWF and UK waters now contain the world's largest offshore wind projects, with 28 wind farms comprising approximately 40% of the 12,631 MW of installed capacity in European waters as of the end of 2016 (Wind Europe, 2016). In the UK, areas of seabed have been made available for lease by The Crown Estate to developers in leasing 'rounds'. The most recent round, 'Round 3', includes nine zones that are of much greater area that preceding rounds (Figure 4 and Table 3), which will enable large-scale OWFs that will make a significant contribution to meeting the UK's renewable energy targets for 2020 (The Crown Estate, 2012).

As the size of the OWFs increase, the risk of significant cumulative effects arising also increases (Busch et al., 2013; Marine Management Organisation, 2013; Masden et al., 2015, 2010). The adoption of the UK Marine Policy Statement in 2011, prepared and adopted under section 44 of the Marine and Coastal Access Act 2009, makes explicit the requirement to implement holistic marine management (UK Parliament, 2011). Expectations of and aspirations for CEAs in UK waters are therefore likely to increase, not decrease. Hence the UK experience with CEAs completed for OWFs provides a valuable case study from which to evaluate the strengths and weaknesses of CEAs relative to emerging marine management information needs.

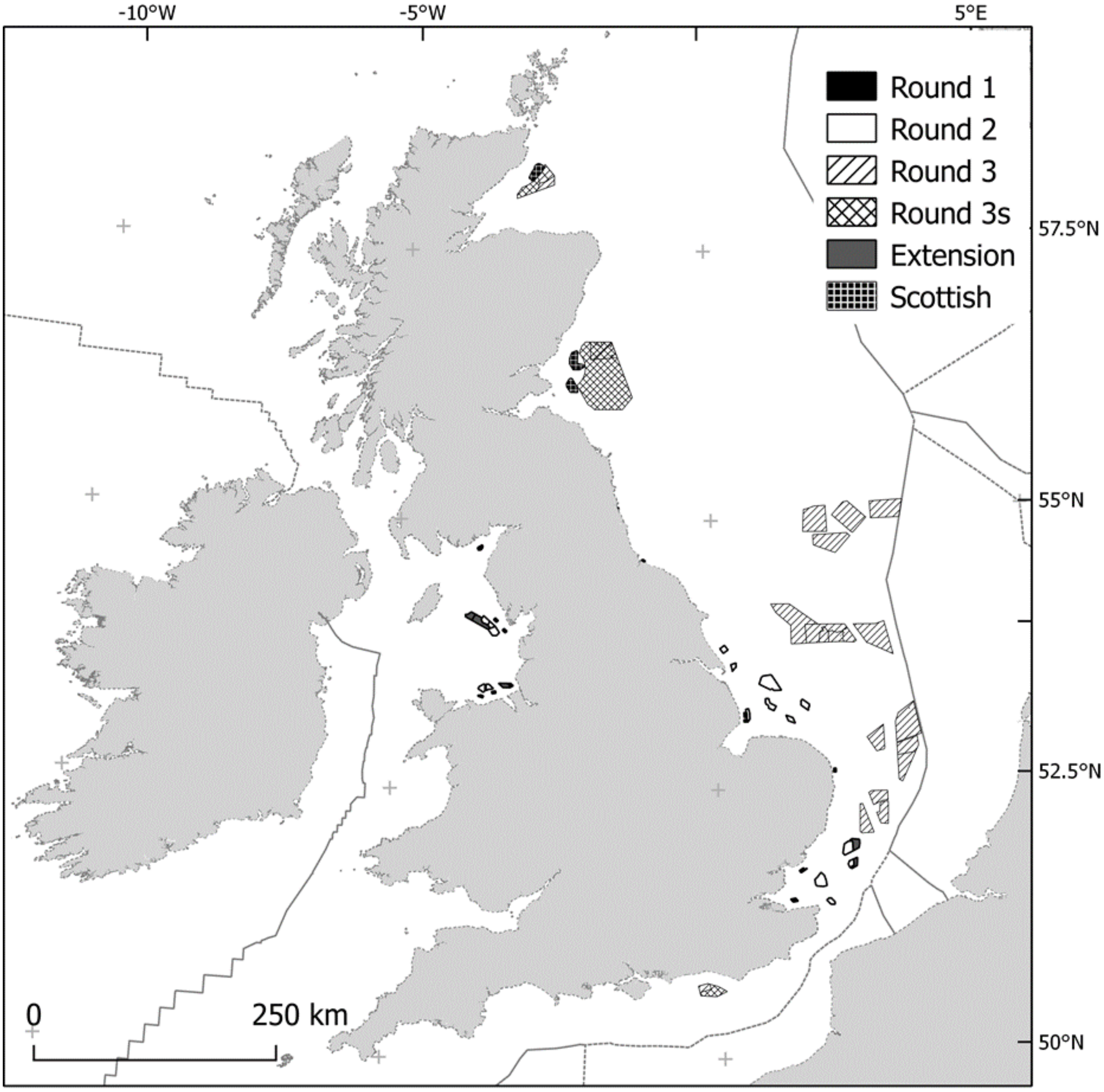

Figure 4. Offshore wind farm developments in UK waters. Round 1, 2 and 3 developments are differentiated, indicating the much increased scale of Round 3 projects in comparison with existing offshore wind farms (data from Department for Environment, Food and Rural Affairs and figure produced by Roi Martinez at Cefas).

Table 3. Increasing size and capacity of offshore wind farm developments in UK waters, from the first to the most recent development 'round', indicating the significant upscaling of Round 3 developments.

Development round	Number of projects	Total capacity	Status	Maximum project capacity	Example turbine capacity	Example project area
Round 1	13	1.2 GW	Operational	194 MW	3.6 MW	20 km^2
Round 2	16	~6 GW	Operational / construction / pre-construction	900 MW	3.6 MW	140 km^2
Round 3	9	Up to 33 GW	Consenting / pre-construction	4,000 MW	8.0 MW +	>2,000 km^2

3.2.2 Materials

Environmental Statements for nine developments were accessible via the National Infrastructure Planning portal[3]. Environmental Statements typically comprise introductory and method statement chapters, and a series of chapters that focus on assessing the predicted impacts on receptor categories (such as marine mammals, seabirds, fish and shellfish, and benthic ecology). Each receptor chapter presents an Environmental Impact Assessment, within which is included a CEA[4].

To understand how each Environmental Statement approached the CEA completed, for each Environmental Statement, chapters with information explaining the CEA methodology were downloaded. Relevant information about the CEA methodologies were found in the introductory chapters, method statement chapters and in some cases within the receptor chapters also.

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[3] http://infrastructure.planninginspectorate.gov.uk/

[4] EIAs and Environmental Statements typically contain Cumulative Impact Assessments (CIAs). The intention of CIAs is broadly the same as CEAs (see definitions, Chapter 1). For consistency throughout the thesis, the term CEA is used in this chapter.

To evaluate how the stated CEA methodologies were implemented, two receptor chapters were downloaded for each Environmental Statement; the benthic ecology chapter and the fish and shellfish ecology chapter. These two receptor categories were selected, as both are critical to the healthy structure and functioning of marine ecosystems (Thrush and Dayton, 2010), are sensitive to environmental disturbance at various levels of biological organisation (Teichert et al., 2016), yet the effects that offshore renewable energy developments may have on these components remain uncertain (Bergström et al., 2014). Significant effects on these ecosystem components are of increasing legislative concern, as marine legislation moves towards implementing the ecosystem approach to marine management (Elliott, 2011). In the European Union, for example, the revised EIA Directive (2014/52/EU) requires the effects of development on biodiversity to be assessed, and the Marine Strategy Framework Directive (2008/56/EC) requires human activities to be managed while prioritising Good Environmental Status (see Borja et al., 2013).

3.2.3 Methodology

The purpose of the evaluation was to critique OWF Environmental Statements to identify where CEAs were adequate and where they were less adequate in context of the need to identify, assess and manage potential cumulative effects. To do so, a novel evaluation framework was developed applying evaluation principles developed to assess the quality of risk assessments in a variety of fields (Drew et al., 2009; Jude et al., 2017). The procedure followed to prepare and implement the framework is shown in Figure 6. Preparation of the framework involved the identification of attributes against which CEAs would be evaluated and the development of a supporting evidence table that enabled CEAs to be scored against each attribute based on the completeness of evidence found in the CEA (see Table 4).

The attributes were selected following a review of:

i) European Union legislation relevant to the protection and sustainable development of the marine environment and where the assessment of cumulative effects is explicitly or implicitly required (including: Directive

2008/56/EC of the European Parliament and of the Council (MSFD), Council Directive 92/43/EEC (Habitats Directive); Directive 2014/52/EU of the European Parliament and of the Council (EIA Directive); and Directive 2001/42/EC of the European Parliament and Council (SEA Directive));

ii) ii) Key literature on the principles of cumulative effects assessment and cumulative environmental change theory (e.g. Duinker et al., 2012; Judd et al., 2015; Smit and Spaling, 1995; Therivel and Ross, 2007);

iii) Taking into account the general steps involved in undertaking a CEA (Figure 5); and

iv) Key literature on the principles of marine ecosystem management e.g. (Crowder and Norse, 2008; Curtin and Prellezo, 2010; Long et al., 2015).

The legislation and scientific literature gathered was reviewed and criteria identified that constitute ‘good’ CEA practice, relative to the legal obligations to conduct CEA, to principles of marine ecosystem approach management, and to key CEA considerations and principles.

Criteria were adapted to generate a set of 21 attributes for ‘good’ CEA relative to project-level assessments, listed in Table 4. The attributes focused on testing the performance of CEAs as meaningful sources of information about the likelihood of cumulative environmental change *sensu* Cocklin et al. (1992) occurring due to a proposed development, and taking into account recent literature emphasising the importance of identifying effect pathways and interactions (Judd et al., 2015), and dealing with uncertainty (Masden et al., 2015).

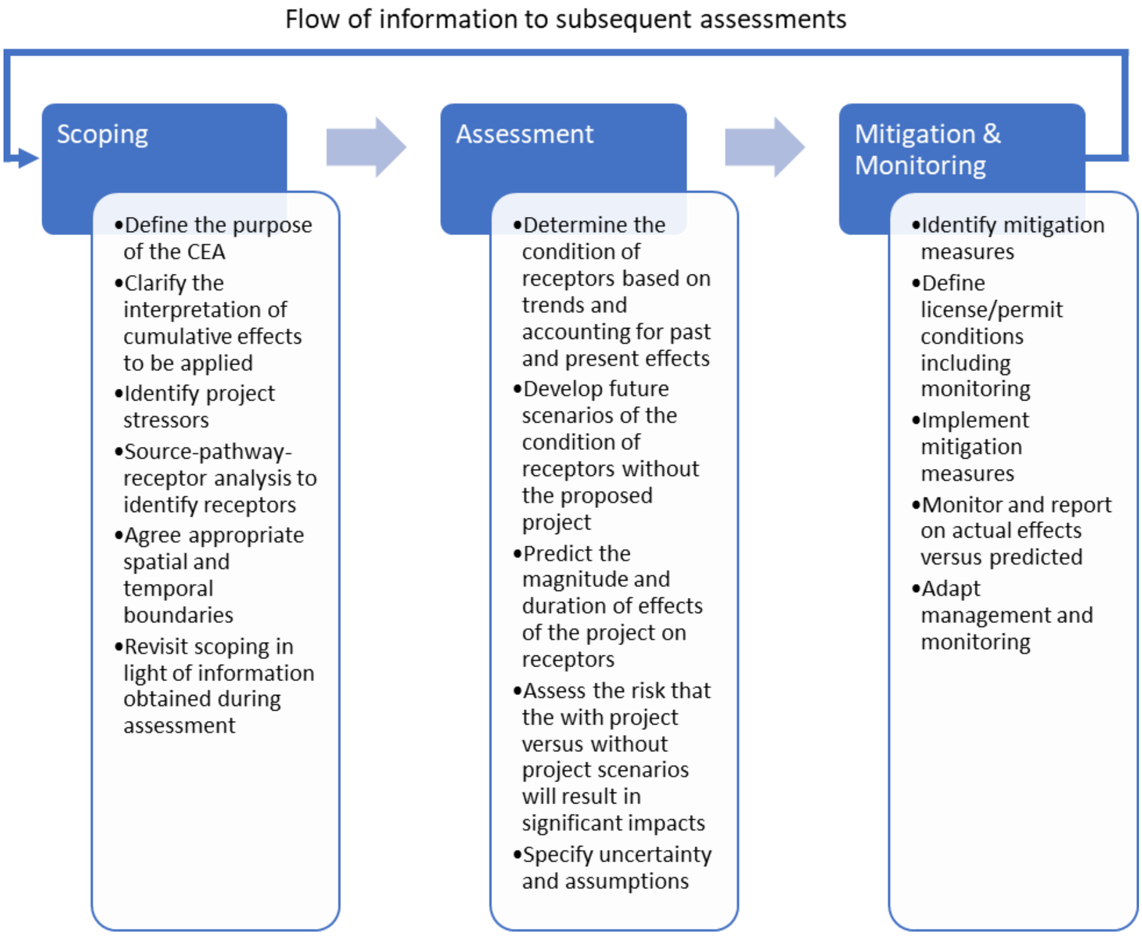

Figure 5. Generic process for completing a CEA, adapted from Cooper (2004); RenewableUK (2013); Therivel and Ross (2007); and Judd et al. (2015). There is currently no agreed standard for CEA, hence the figure presents a broad-brush approach adapted from the cited studies. The arrow represents where feedback from monitoring should support subsequent CEAs.

The 21 attributes were subsequently grouped into four categories. Attributes in category ‘Procedure’ sought to identify strengths and weaknesses in the procedural aspects of the CEA. Attributes in category ‘Space & time’ investigated how CEAs identify and describe the spatial and temporal aspects of pressures arising from the proposed project and from proximal activities, and how these were applied to valued ecosystem components (VEC, see Table 1 for definitions). Attributes in category ‘Pathways & receptors’ address the process by which VECs were selected and whether pathways between pressures and VECs were documented. Attributes in category ‘Cumulative effects’ investigated how CEAs addressed the assessment of multiple stressors effecting VECs, how significance determinations were derived, and whether uncertainty (which is an intrinsic characteristic of CEA; Judd et al., 2015; Masden et al., 2015) is explicitly accounted for. Attributes were considered to have equal weighting. To score the completeness of evidence found in Environmental Statements relative to the CEA attributes, a linear scoring system from 1 (very weak) to 4 (very strong) was developed. Each attribute was supported by a definition together with descriptions of the evidence expected to be found within an Environmental Statement to indicate how completely the CEA addressed each attribute (Table 4).

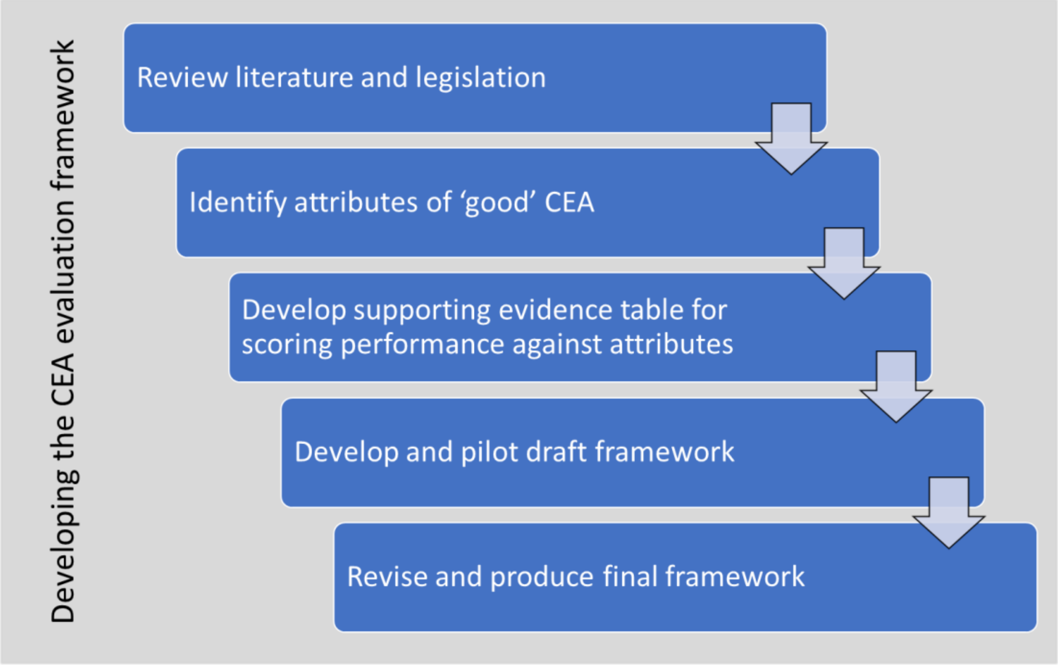

Figure 6. Steps followed to develop the CEA evaluation framework

The framework was piloted by evaluating two Environmental Statements, to determine how well the attributes could be applied in practise and to validate the scale system. Following a review of the results from the pilot, attributes were revised to improve clarity and purpose, and to improve consistency of the scale applied. During the pilot, variability within Environmental Statements became apparent. For example, an Environmental Statement may include a detailed description of the spatial extent of one pressure, e.g. underwater sound, warranting a score of 3 (strong), but weak descriptions of other pressures, warranting a score of 2 (weak). To record where evidence was observed of better practise within an Environmental Statement, which pointed to the potential for CEA practise to improve, a mid-point between scores was deemed appropriate (e.g. 2.5 in the preceding example). The framework was then applied to evaluate the evidence found in the Environmental Statements following the process shown in Figure 7.

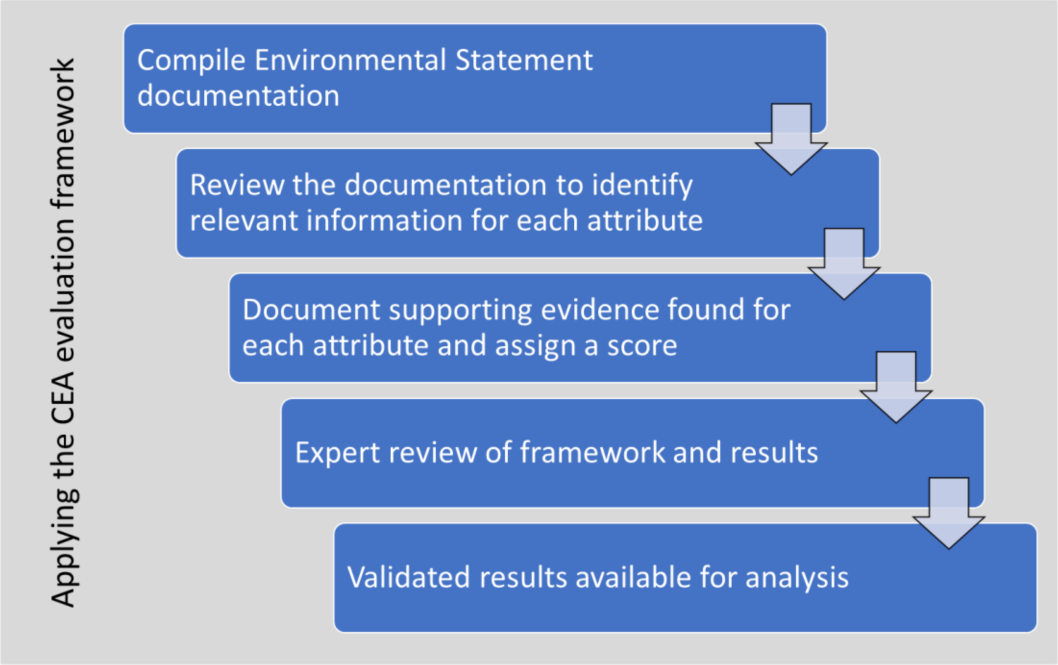

Figure 7. Steps followed to apply the CEA evaluation framework and to validate the results of applying the framework to nine Environmental Statements of Offshore Wind Farms in UK waters.

Following the evaluation, the methodology and draft evaluation outcomes for the nine Environmental Statements were validated by convening an expert panel (n=6) of regulatory and ecological experts at the Centre for Environment, Fisheries and Aquaculture Science (Cefas) Laboratories in Lowestoft, UK, which is a statutory advisor to the UK government. Documentation detailing the rationale and methodology of the evaluation was distributed to panel members prior to the review. The review commenced with an examination of and discussion about the methodology, including the attributes and the strength of evidence specified to assign an attribute score. Following this, a review of the evaluation outcomes was completed, firstly by repeating the evaluation of one

Environmental Statement against the 21 attributes, and secondly by the expert panel randomly selecting attribute outcomes recorded in the evaluation tables and repeating the step-wise approach outlined in Figure 7 to test whether draft attribute scores were a fair reflection of the evidence identified within ESs and CEAs therein. The expert panel review concluded with a discussion of the preliminary results and of the implications of the results, including where improvements to CEA guidance and practise could be made.

Following the expert panel review, validated evaluation outcomes were taken forward for analysis. The analysis sought to identify and present a representation of the strengths and weaknesses of the ESs as a group, thus outcomes recorded were averaged across the sample set. The results were presented using radar plots, one for each of the four attribute categories. To investigate the consistency of the approach and practise applied to CEAs in the Environmental Statements, attribute scores were compared between Environmental Statements. To investigate patterns in strengths and weaknesses both across the group and between Environmental Statements, average attribute scores from across the group were ranked from high to low and a note taken of the variance from the average attribute score to further consider variance between Environmental Statements. Results are anonymised to prevent identification of individual ESs.

Table 4. Cumulative impact assessment evaluation framework comprising 21 attributes aggregated into 4 categories: (i) Procedure; (ii) Space & time; (iii); Pathways & receptors; and (iv) Cumulative effects. Adjacent columns set out the scoring system, which defines the evidence required to be found in the offshore wind farm Environmental Statements relative to each attribute for a score of 1 (very weak) to 4 (very strong) to be ascribed. Att = attribute.

Att. category	Att. number	Attribute description	Supporting evidence required to record score 1 (very weak) to 4 (very strong)			
			Very weak (1)	**Weak (2)**	**Strong (3)**	**Very strong (4)**
Procedure	**1**	The CEA explicitly defines cumulative in context of the CEA, reflecting the three components of cumulative environmental change	Cumulative not defined	Cumulative' implicitly defined for the CEA	Cumulative' explicitly defined for the CEA	Cumulative explicitly defined for the CEA. Definition recognises the three attributes of cumulative environmental change.
Procedure	**2**	The purpose and scope of the CEA specifically are clearly set out in the supporting documentation	CEA purpose and scope not defined	CEA purpose and scope not explicitly defined, but can be inferred from EIA/CEA methodology	Explicit CEA purpose and scope documented	Explicit CEA purpose and scope documented. Expanded spatial and temporal boundaries and interaction of effects between activities referenced.
Procedure	**3**	The CEA documents and applies a clear, systematic CEA methodology, from scoping through to mitigation	Assessment methodology is not clear or systematic	Assessment methodology is systematic but the processes within each step are not clear	Assessment methodology is systematic and processes within each step are clear	Assessment methodology is systematic and processes within each step are clear. Time, space and activity components of CEA are clearly accounted for.

Att. category	Att. number	Attribute description	Supporting evidence required to record score 1 (very weak) to 4 (very strong)			
			Very weak (1)	Weak (2)	Strong (3)	Very strong (4)
Procedure	**4**	The assessment makes use of appropriate data, tools and analytical methods, makes use of quantitative and qualitative methods where data allows. Assumptions and uncertainties are clearly stated and incorporated into the assessment.	The assessment is purely qualitative and lacks transparency. Linkages between data presented and the assessment outcomes are not clear.	Assessment process is qualitative and makes use of appropriate data where available. Assessment outcomes are not transparent.	Assessment process is qualitative and quantitative based on appropriate data. Analytical tools are used and described resulting in a transparent assessment process.	The assessment makes use of appropriate data, tools and analytical methods, makes use of quantitative and qualitative methods where data allows. Assumptions and uncertainties are explicitly stated.
Procedure	**5**	The conclusions of the CEA are accessible and are compiled in a document that clearly states predicted impacts before and after proposed mitigation measures, assumptions and uncertainties.	The conclusions of the CEA are difficult to access and supporting assumptions are unstated	The conclusions of the CEA are scattered and supporting assumptions are unstated or are unclear	The conclusions of the CEA are compiled and easy to access. Supporting assumptions and uncertainties are partly addressed or are unclear in the conclusion section.	The conclusions of the CEA are compiled and easy to access. Supporting assumptions and uncertainties are explicitly addressed and are presented within the conclusion section.
Space & time	**6**	The temporal extent of pressures predicted to arise from the proposed activity are identified by a scoping process and documented.	Temporal extent of proposed project activities or pressures are not documented	Temporal extent of proposed project activities leading to pressures are described without a clear process to scope/screen which are described	Temporal extent of **pressures** arising from proposed project activities are described	Temporal extent of **pressures** arising from proposed project activities are described following a clear scoping/screening process to identify pressures to take forward in the EIA/CEA.

Att. category	Att. number	Attribute description	Supporting evidence required to record score 1 (very weak) to 4 (very strong)			
			Very weak (1)	**Weak (2)**	**Strong (3)**	**Very strong (4)**
Space & time	**7**	The temporal extent of pressures associated with other activities included in the CEA are identified by a scoping process and documented.	Temporal extent of 'other' activities or pressures are not documented	Temporal extent of 'other' activities leading to pressures are described without a clear process to scope/screen which 'other' activities are described	Temporal extent of **pressures** arising from 'other' activities are described	Temporal extent of **pressures** arising from 'other' activities are described following a clear scoping/screening process to identify pressures to take forward in the EIA/CEA
Space & time	**8**	The spatial extent of pressures predicted to arise from the proposed activity are identified by a scoping process and documented.	Spatial extent of proposed project activities or pressures are not documented	Spatial extent of proposed project activities leading to pressures are described without a clear process to scope/screen which are described	Spatial extent of **pressures** arising from proposed project activities are described	Spatial extent of **pressures** arising from proposed project are described following a clear scoping/screening process to identify pressures to take forward in the EIA/CEA.
Space & time	**9**	The spatial extent of pressures associated with other activities included in the CEA are identified by a scoping process and documented.	Spatial extent of 'other' activities or pressures are not documented	Spatial extent of 'other' activities leading to pressures are described without a clear process to scope/screen which 'other' activities are described	Spatial extent of **pressures** arising from 'other' activities are described	Spatial extent of **pressures** arising 'other' activities are described following a clear scoping/screening process to identify pressures to take forward in the EIA/CEA.
Space & time	**10**	The CEA applies appropriate temporal boundaries relative to the VECs selected for assessment in the CEA	Temporal boundaries not defined	Temporal boundaries defined but relate to duration of activity or sub-activity, not to VEC	Temporal boundaries defined and supported by rationale for decision relative to VECs	Temporal boundaries defined, supported by rationale for decision and clearly relate to temporal pressures relative to the VECs

Att. category	Att. number	Attribute description	Supporting evidence required to record score 1 (very weak) to 4 (very strong)			
			Very weak (1)	Weak (2)	Strong (3)	Very strong (4)
Space & time	**11**	The CEA applies appropriate spatial boundaries relative to the VECs selected for assessment in the CEA	Spatial boundaries not defined	Spatial boundaries defined but not supported by rationale for decision	Spatial boundaries defined and supported by rationale for decision	Spatial boundaries defined, supported by rationale for decision and clearly relate to spatial pressures relative to the VECs
Pathways & receptors	**12**	The source-pressure-receptor pathways for the proposed activity are identified by a scoping process and documented, including potential interactions between pathways	Pathways between sources, pressures and receptors are not identified	Source-pressure-receptor pathways are documented without clear process of scoping and screening pathways	Source-pressure-receptor pathways are documented and supported by a clear process of scoping and screening pathways	The source-pressure-receptor pathways for the proposed activity are documented, including potential interactions between pathways. Assumptions about interactions are clearly stated
Pathways & receptors	**13**	The source-pressure-receptor pathways for the proposed activity and other activities are identified by a scoping process and documented, including potential interactions between pathways	Pathways between sources, pressures and receptors are not identified	Source-pressure-receptor pathways are documented without clear process of scoping and screening pathways	Source-pressure-receptor pathways are documented and supported by a clear process of scoping and screening pathways	The source-pressure-receptor pathways for the proposed activity and other activities are documented, including potential interactions between pathways. Assumptions about interactions are clearly stated

Att. category	Att. number	Attribute description	Supporting evidence required to record score 1 (very weak) to 4 (very strong)			
			Very weak (1)	**Weak (2)**	**Strong (3)**	**Very strong (4)**
Pathways & receptors	**14**	A clear rationale is documented for selecting receptors for inclusion in the CEA (VECs) based on source-pressure-receptor pathways, likelihood to exposure and sensitivity of the VEC to pressure	No evidence of a systematic process to identify receptors for assessment found	Process of identifying receptors documented but is not transparent and rationale for receptors assessed is unclear	Systematic process of identifying receptors documented including source-pressure-pathway-receptor analysis	Systematic process of identifying receptors documented including source-pressure-pathway-receptor analysis. Receptors included in assessment are those at highest risk of adverse effects based on pathway analysis.
Pathways & receptors	**15**	The current condition of VECs is documented based on appropriate data and referencing the historical condition of the VEC	Current condition of VECs not documented	Current condition of VECs documented based on qualitative description without reference to condition relative to historical condition of VEC	Current condition of VECs documented based on appropriate use of data but does not reference condition relative to historical condition of VEC	Current condition of VECs documented based on appropriate use of data and referencing condition relative to historical condition of VEC
Pathways & receptors	**16**	The future condition of VECs without the proposed activity is predicted based on appropriate analytical methods. Assumptions are clearly stated	Future condition of VECs not documented	Future condition of VECs documented based on qualitative description	Future condition of VECs documented based on appropriate use of data but assumptions are unclear	Future condition of VECs documented based on appropriate use of data. Description is supported by clear statement of assumptions

Att. category	Att. number	Attribute description	Supporting evidence required to record score 1 (very weak) to 4 (very strong)			
			Very weak (1)	Weak (2)	Strong (3)	Very strong (4)
Cumulative effects	**17**	The effects of multiple stressors from the proposed activity on VECs are assessed	Effects of multiple stressors not considered	Effects of multiple stressors from proposed activity on VECs are assessed, but rationale for combination of stressors not clear	Effects of multiple stressors from proposed activity on VECs assessed supported by clear rationale for selection of stressors relative to VECs	Effects of multiple stressors from proposed activity on VECs assessed supported by clear rationale for selection of stressors relative to VECs. Assumptions and uncertainties clearly stated.
Cumulative effects	**18**	The effects of multiple stressors from the proposed activity and other activities on VECs are assessed	Effects of multiple stressors not considered	Effects of multiple stressors from proposed activity and other activities on VECs are assessed, but rationale for combination of stressors not clear	Effects of multiple stressors from proposed activity and other activities on VECs assessed supported by clear rationale for selection of stressors relative to VECs	Effects of multiple stressors from proposed activity and other activities on VECs assessed supported by clear rationale for selection of stressors relative to VECs. Assumptions and uncertainties clearly stated.
Cumulative effects	**19**	The cumulative effect of the proposed activity and other activities on ecological connectivity is explicitly considered	Effects on ecological components not considered	Individual project pressures identified and effects on ecological components assessed	Combined project pressures identified and effects on ecological components assessed	Combined project pressures identified and incremental effects on ecological components assessed

Att. category	Att. number	Attribute description	Supporting evidence required to record score 1 (very weak) to 4 (very strong)			
			Very weak (1)	Weak (2)	Strong (3)	Very strong (4)
Cumulative effects	**20**	A clear rationale for determining impact significance is presented and conclusions clearly relate to predicted change against an appropriate measure of population change	Method used to determine impact significance unclear	Method to determine impact significance is clear, however relies on qualitative decision making and/or without reference to measure of population change (threshold, PBR, etc)	Quantitative and/or qualitative methods used to determine impact significance supported by appropriate use of tools and with reference to a measure of population change.	Quantitative methods used to determine impact significance supported by tools and with clear reference to thresholds, PBR or other measure of population change
Cumulative effects	**21**	Uncertainty is explicitly considered and clearly identified	Uncertainty not explicitly considered	Uncertainty referenced in the CEA methodology but not defined. The process of considering uncertainty is not clear.	Uncertainty referenced in the CEA methodology and is defined. The process of considering uncertainty is clear.	Uncertainty referenced in the CEA methodology and is defined. Uncertainty clearly included in assessment sections.

3.3 Results

Nine Environmental Statements associated with 'Round Three' planning applications were interrogated, for which documentation was publicly available. The developments included Moray Firth, Dogger Bank Creyke, Dogger Bank Teeside, Hornsea One, Hornsea Two, East Anglia Three, East Anglia One, Rampion, and Navitus Bay. Results are presented so that specific developments are not identifiable. Radar plots showing the attribute scores averaged across the Environmental Statements evaluated using the evaluation framework are presented in Figure 8. The radar plots provide a graphical representation of the strengths and weaknesses of the Environmental Statements relative to the 21 attributes of 'good' CEA defined in Table 4. The evaluation results for each Environmental Statement are included in Table 5.

Environmental Statements were strongest in relation to attributes linked to the procedural aspects of CEA (Figure 8a) including the provision of a definition for 'cumulative', provision of a scope for the CEA, provision of a systematic methodology, evidence of appropriate use of data and tools, and the presentation of CEA conclusions. Scores varied between Environmental Statements (Figure 10). Six Environmental Statements included an explicit definition of cumulative impacts (attribute 1), but no definition explicitly recognised the key components of cumulative environmental change. Most Environmental Statements included a clear purpose and scope clarifying the CEAs (attribute 2), with four Environmental Statements scoring 4 (very strong). A systematic methodology was described and applied in all but one Environmental Statements and CEA methodologies tended to be an extension of the EIA methodology. In Environmental Statements with strong or very strong method statements, the application of the methodology as evaluated by subsequent criteria was found to be less robust, perhaps indicating the challenges of translating CEA theory into practice.

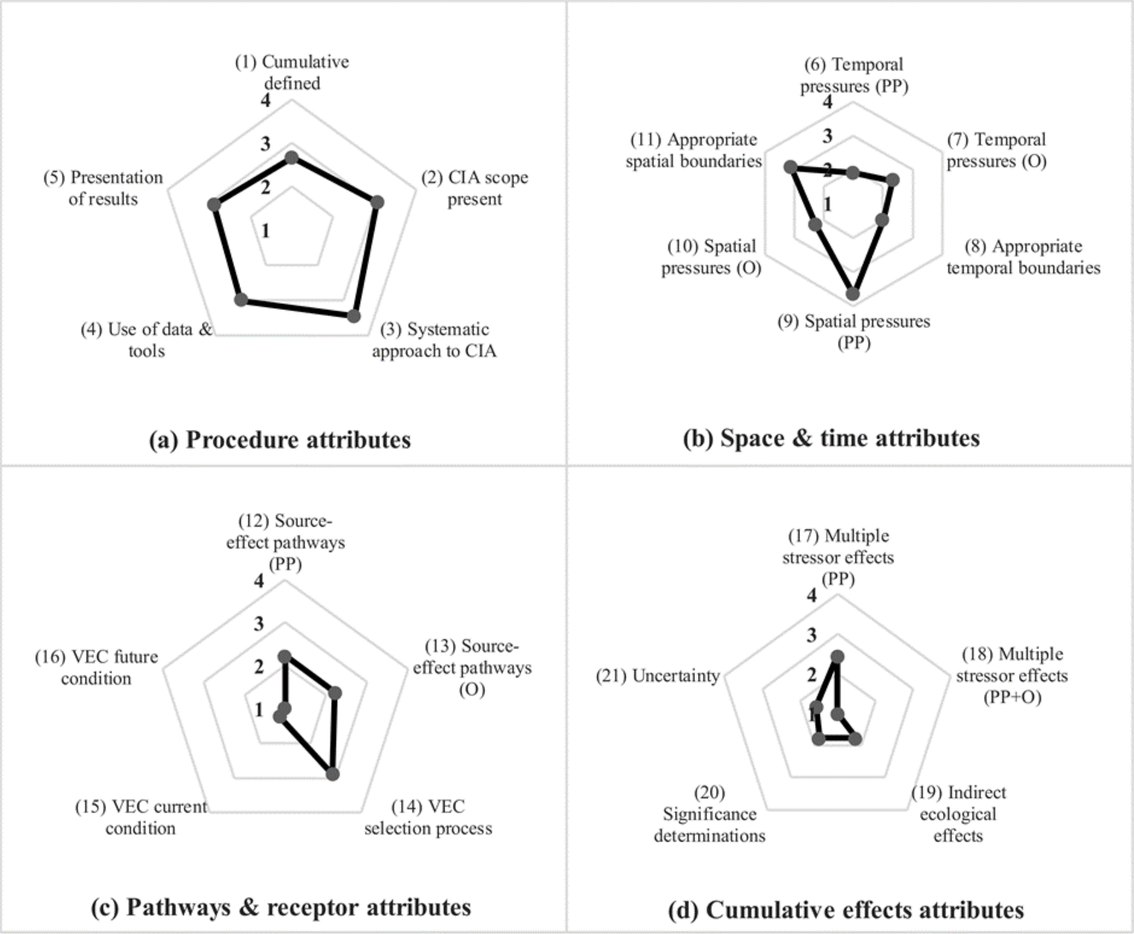

Figure 8. Radar plots presenting the attribute score averaged across all Environmental Statements evaluated (n=9), aggregated into Procedure; Space & time; Pathways & receptors; and Cumulative effects categories. 'PP' = proposed project. 'O' = other activities. 'PP+O' = proposed project and other activities. 'VEC' = valued ecosystem component. Attribute scores range from 1 = very weak to 4 = very strong.

Evidence of the use of appropriate data from baseline surveys and literature reviews was identified in all but one Environmental Statements, and all applied a mixture of qualitative and quantitative analytical tools. The use of analytical tools varied, for example modelling methods were widely applied to create underwater noise contours but only rarely were quantitative assessments of the percentage loss of particular habitat types applied. Qualitative methods, specifically expert judgement, were invariably used to determine how significant the impact of pressures identified would be regardless of whether the assessment process involved quantitative or qualitative analysis. The presentation of CEA results varied, but all but one of the Environmental Statements presented CEA results clearly. However, to obtain detail about how CEA conclusions were derived required delving into the main CEA chapter or the benthic ecology and fish and shellfish ecology chapters.

Evaluating how pressures or the activities that create pressures were identified and described, both for individual MREDs and for other nearby activities, such as aggregate dredging or proximal OWFs, highlighted a marked difference between the consideration of spatial and temporal components of potential effects (Figure 8b). The spatial aspect of activities and pressures tended to be dealt with more comprehensively than the temporal aspect. All but two Environmental Statements clearly documented how spatial pressures were identified (attribute 9), resulting in spatial boundaries being applied that were straightforward to understand and apply relative to valued receptors included in the assessment (attribute 11). By contrast all Environmental Statements scored weak or very weak regarding the identification and documentation of temporal pressures (attributes 6 and 7). A common assumption appeared to be that temporal pressures exist for the duration of an activity rather than demonstrating consideration of the temporal aspects of pressures relative to valued receptors. Thus temporal boundaries (attribute 8) scored less well on average.

In general, Environmental Statements included a clear process documenting how valued receptors were identified (attribute 14), however, consideration of pathways (attributes 12 and 13) and consideration of the current and future, without development, conditions of the valued receptors (attributes 15 and 16) were on average weak (Figure 8c). Notable variation between Environmental Statements was observed (Figure 10). Valued receptors in the chapters evaluated were the same as those included in the EIA section of the chapters and broadly align with receptors of conservation/legislative interest. Examples of better practise were observed whereby potential pathways were subject to a scoping process and potentially significant pathways scoped in were clearly set out and the likelihood of a receptor being disturbed was discussed. In Environmental Statements that scored less well, pathways could generally be inferred through the text within the Environmental Statements chapters, and by working backwards to link the assessed impact on a receptor back to the receptor sensitivity matrix and impact magnitude matrix. However, this is not an intuitive process. Environmental Statements that included graphical representations of pathways were far clearer to interpret.

A consistent weakness identified was the consideration of the condition of valued receptors included in the assessments. Unless a valued receptor was of conservation interest, e.g. marine mammals, trends in the status of the receptor (attribute 15) tended not to be assessed with all Environmental Statements recording scores of 1 or 2. The trajectory of valued receptor condition without the proposed project (attribute 16) was invariably not considered, reducing confidence in the impact significance determinations due to the difficulty this poses when attempting to understand the consequences of an incremental change to the condition or abundance of a valued receptor.

The most striking results were observed in the final attribute category, 'Cumulative effects', which sought to evaluate how CEAs assessed multiple stressor effects on receptors, how impact significance determinations were derived, and how uncertainty was incorporated into the CEA. From a perspective of wanting to understand the cumulative effect of a development on the environment, all Environmental Statements provided incomplete information (Figure 8d) and there were clear differences between Environmental Statements (Figure 10) Environmental Statements tended to include a chapter on interrelationships, within which the effects of different stressors arising from the OWF on valued receptors were considered. Significance determinations in the interrelationship chapters were qualitative and based on significance determinations associated with individual stressors being combined. An unstated assumption appeared to be that minor stressor effects could not interact to have a greater effect on a receptor, contrary to cumulative effects theory (Johnson et al., 2015; Noble, 2014; Raiter et al., 2014).

The specific CEA components of the Environmental Statements (as distinct from the interrelationships chapter or section) considered the potential accumulation of effects arising from the OWF and proximal activities. However, the CEAs consistently assessed stressors in isolation, i.e. assessed the potential for accumulation of like-for-like pressures, for example, overlapping sound contours from temporally coincident percussive piling. As with the inter-relationships chapters, the CEA chapters used significance determinations transposed from the main EIA chapters. The unstated assumption observed in the interrelationships chapter, that effects assessed as being insignificant could not interact to have a greater net effect on a receptor, also appeared to apply to the CEA chapters.

The average score associated with the consideration of uncertainty (attribute 21) was low (1.6, see Table 5). Better practise was observed in some Environmental Statements that included a description of and approach to dealing with uncertainty in the CEA methodology. As with the CEA methodology, a discrepancy between the stated methodology for dealing with uncertainty and application in the CEA was observed in some cases. It was difficult to establish how uncertainties associated with, for example, cause-effect relationships were incorporated into the EIA or CEA.

Significance determinations tended to be based on qualitative, expert opinion. Information about how pressures from other activities could interact with pressures from the proposed development to affect a valued receptor was typically qualitative and assessed that cumulative effects could occur where temporally coincident, spatially overlapping activities were identified. In context of the fish and shellfish ecology and benthic ecology chapters, it was difficult to interpret how the potential for pressures to accumulate were assessed. Whether it is reasonable to expect individual developments to obtain detail about other activities to enable a more robust CEA is moot, however uncertainties and assumptions related to other activities were rarely cited. As a result, significance determinations (attribute 20) scored low across the Environmental Statements, resulting in an average score of 1.8 (Table 5). Examples of better practise were observed in more recent Environmental Statements that applied a tier system to define the likelihood of pressures from the OWF overlapping with future activities or developments.

The variance between Environmental Statements was considered in more detail by calculating the percent coefficient of variance of the attribute scores (Table 5 and plotted in Figure 10). This indicated patterns in the strengths and weaknesses of the ESs: for example, attributes relating to the procedural aspects of CEA tended to have higher average outcomes than attributes relating to assessing cumulative effects; spatial aspects of the pressures are generally considered more comprehensively than temporal aspects. Aspects of better CEA practise (rather than procedure) were also observed, such as a clearer and more comprehensive scoping process, suggesting that elaboration and dissemination of better practise could improve CEA practise for little cost.

Table 5. Data table of results of the evaluation of nine Environmental Statements against the 21 attributes, including the average attribute scored (AVG), averaged across the nine Environmental Statements, and the percentage coefficient of variance (%CV)

	Attribute (full)	ES1	ES2	ES3	ES4	ES5	ES6	ES7	ES8	ES9	AVG	%CV
1	The CIA includes a definition of cumulative that reflects the three components of cumulative environmental change	3	3	3	2	2	2	3	3	3	2.667	0.188
2	The purpose and scope of the CIA specifically are clearly set out in the supporting documentation	3	4	1	1.5	4	4	3	3	4	3.056	0.370
3	The CIA documents and applies a clear, systematic CIA methodology, from scoping through to mitigation	3	4	3	3	4	4	2	4	4	3.444	0.211
4	The assessment makes use of appropriate data, tools and analytical methods, makes use of quantitative and qualitative methods where data allows. Assumptions and uncertainties are clearly stated and incorporated into the assessment.	4	3	3	3	3	3	2	3	3	3.000	0.167
5	The conclusions of the CIA are accessible and are compiled in a document that clearly states predicted impacts before and after proposed	3	3	3	2	3	3	3	3	3	2.889	0.115

	Attribute (full)	ES1	ES2	ES3	ES4	ES5	ES6	ES7	ES8	ES9	AVG	%CV
	mitigation measures, assumptions and uncertainties.											
6	The temporal extent of pressures predicted to arise from the proposed activity are documented	2	2	2	1	2	2	2	2	2	1.889	0.176
7	The temporal extent of pressures associated with other activity included in the CIA are documented	2.5	2.5	2.5	1	2.5	2.5	2.5	2.5	2.5	2.333	0.214
8	The CIA applies appropriate temporal boundaries relative to the VECs selected for assessment in the CIA	2	2	2	2	2	2	2	2	2	2.000	0.000
9	The spatial extent of pressures predicted to arise from the proposed activity are documented	4	4	4	3	4	4	2	4	4	3.667	0.193
10	The spatial extent of other activities and pressures associated with other activity included in the CIA are documented	2.5	2.5	2.5	2.5	2	2	1.5	2.5	2.5	2.278	0.159
11	The CIA applies appropriate spatial boundaries relative to the VECs selected for assessment in the CIA	3	4	4	3	3	3	2	3	3	3.111	0.193

	Attribute (full)	ES1	ES2	ES3	ES4	ES5	ES6	ES7	ES8	ES9	AVG	%CV
12	The source-pressure-receptor pathways for the proposed activity are documented, including potential interactions between pathways	3	2	2	2	2	2	2	3	2	2.222	0.198
13	The source-pressure-receptor pathways for the proposed activity and other activities are documented, including potential interactions between pathways	3	2	2	2	2	2	2	3	2	2.222	0.198
14	A clear rationale is documented for selecting receptors for inclusion in the CIA (VECs) based on source-pressure-receptor pathways, likelihood to exposure and sensitivity of the VEC to pressure	4	2.5	2.5	2	3.5	3.5	2	4	2	2.889	0.297
15	The current condition of VECs is documented based on appropriate data and referencing the historical condition of the VEC	1	1	1	1	1	1	1	2	2	1.222	0.361
16	The future condition of VECs without the proposed activity is predicted based on appropriate analytical methods. Assumptions are clearly stated	1	1	1	1	1	1	1	1	1	1.000	0.000
17	The effects of multiple stressors from the proposed activity on VECs are assessed	3	3	3	1	3	3	1	2	3	2.444	0.361

	Attribute (full)	ES1	ES2	ES3	ES4	ES5	ES6	ES7	ES8	ES9	AVG	%CV
18	The effects of multiple stressors from the proposed activity and other activities on VECs are assessed	1	1	1	1	1	1	1	1	1	1.000	0.000
19	The cumulative effect of the proposed activity and other activities on ecological connectivity is explicity considered	2	2	2	1	2	2	1	2	2	1.778	0.248
20	A clear rationale for determining significance based on appropriate measures of change is documented	2	2	2	1	2	2	1	2	2	1.778	0.248
21	Uncertainty is explicitly considered and clearly identified	2	1	1	1	3	3	1	1	1	1.556	0.567

Plotting the average of the attribute scores achieved by the nine Environmental Statements indicates a trend of weaker performance as the attributes move from procedural to analytical (Figure 9). The variability of average attribute scores relative to the average (the mean) has been measured by calculating the percentage coefficient of variation, shown as the error bars in Figure 9.

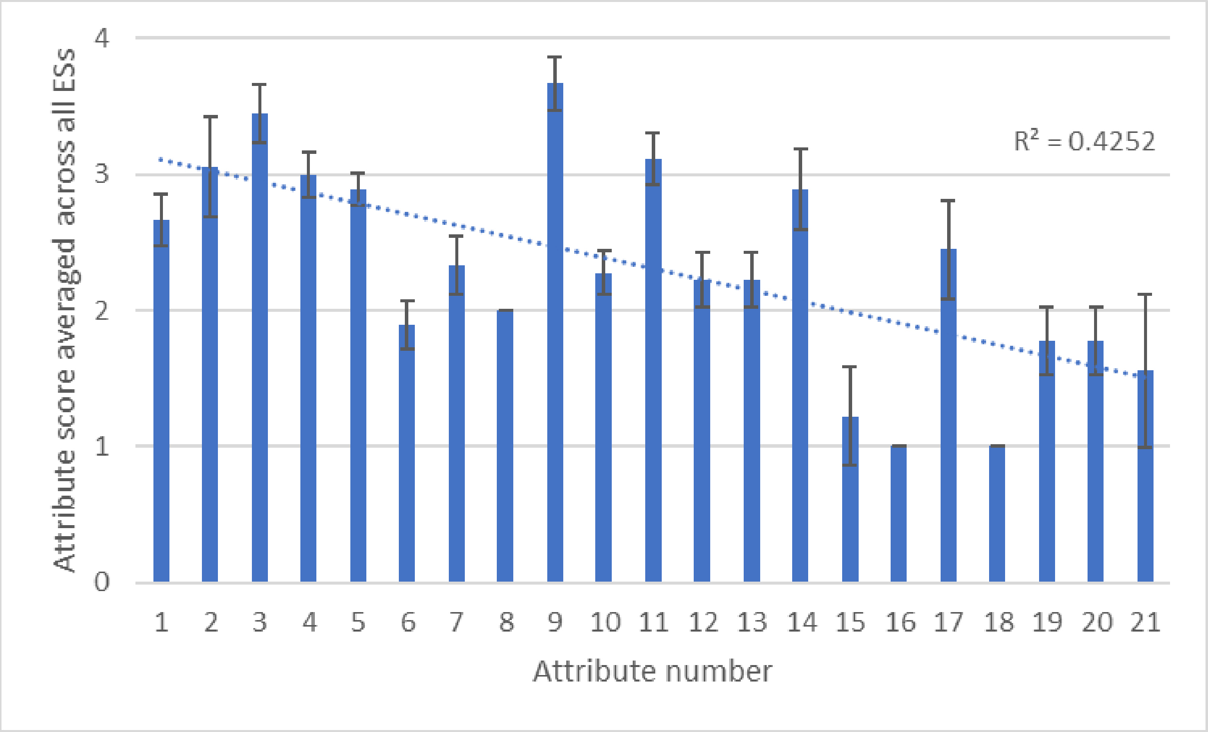

Figure 9. Averages of the attribute scores of Environmental Statements (n=9) against 21 attributes of 'good' CEA with the error bars indicating the percent coefficient of variation. A linear trend line is added showing the trend towards lower scores, indicating weaker performance, as attributes progress from procedural (attributes 1 to 5) to analytical.

Summing the attribute scores across the nine Environmental Statements points the shortcomings of all Environmental Statements, with the best performing Environmental Statement (ES1) achieving a total score of 54 (Figure 10). A total score of 63 would be achieved if an Environmental Statement averaged a score of 3 across all attributes, i.e. if Environmental Statements performed strongly against the 21 attributes.

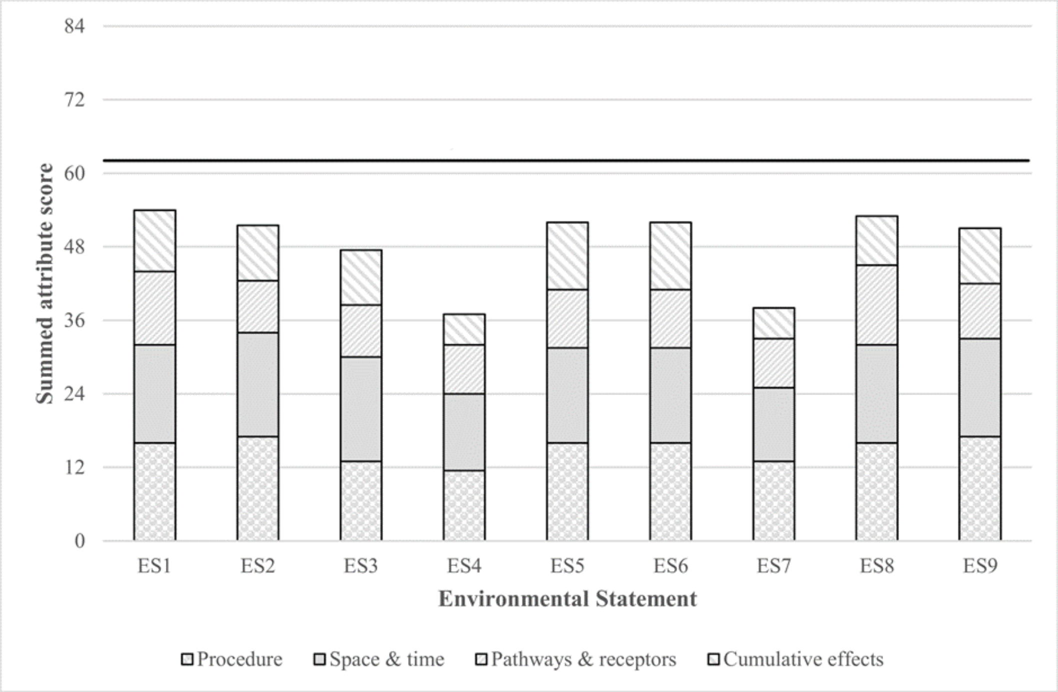

Figure 10. Variance in total scores following evaluation of the Environmental Statements (n=9) against 21 'good' CEA attributes. Attribute categories shown in the legend match the categories shown in Figure 8. The horizontal black line indicates the height of a column if attribute scores averaged 3 (strong), i.e. all Environmental Statements have clear room for improvement.

3.4 Discussion

3.4.1 Implications of the evaluation

The evaluation completed is the first known research that tests critical planning application documents against attributes specified relative to the information needs of marine regulators and managers. The key finding of the evaluation is that CEAs supporting planning applications for nationally significant energy infrastructure do not meet the information needs of regulators and managers who are required to make planning decisions cognisant of likely cumulative effects. This finding adds to the body of research that highlights shortcomings in CEA practise (Foley et al., 2017; Sinclair et al., 2017).

Relative to the key considerations for CEA discussed in Chapter 2, multiple shortcomings were identified. The CEAs evaluated invariably applied a standard EIA stressor-led approach, i.e. the foundation for the assessment relies on predicting the significance of impacts arising from individual stressors on a receptor. The interrelationships chapters brought together the individual significance determinations to consider multiple impacts acting on a receptor, but these chapters were distinct from the CEA chapters or sub-chapters, and only considered multiple impacts arising from the proposed development. Hence, the CEA and interrelationships chapters each present partial assessments of cumulative effects.

While highlighting an issue relating to terminology, clarification of which remains a pressing need (Duinker et al., 2012; Judd et al., 2015; Sinclair et al., 2017), the interrelationships chapters were conceptually closer to an assessment of cumulative effects than the CEA chapters. As receptors integrate effects arising from multiple stressors from multiple sources (Duinker et al., 2012; Segner et al., 2014), future CEAs would be more effective if the single stressor assessment approach applied in the CEA sections were integrated with the interrelationships chapter and transboundary chapter using a common methodology to a provide a combined assessment of the cumulative effects of a proposed development on receptors. Understanding the cumulative effect of a development on the environment requires, by definition, consideration of the sum total of effects on the environment to date and the incremental effect that a proposed development will have on that baseline (Smit and Spaling, 1995). The Environmental Statements evaluated only partially achieve this, perhaps providing insight into why regulatory reviews of CEAs has led to lengthy delays in the planning and licensing process.

As discussed in Chapter 2, CEAs that apply a standard EIA approach are not effective at assessing the cumulative effects of projects, plans or programmes. Yet CEAs that apply a standard EIA approach are the most common and accepted form of CEA used to decide if a proposed activity should be permitted or not (Canter and Ross, 2010; Jones, 2016; OSPAR Commission, 2008). The CEAs evaluated were of variable quality relative to the attributes specified, and did not provide meaningful assessments of the cumulative effects of the proposed MREDs, by inadequately assessing how the effects of the MREDs would interact with the cumulative effect load carried by receptors and by inadequately characterising the baseline condition of the receptors. The CEAs evaluated do not meet the requirements for CEA implicitly stipulated in the EIA Directive (Directive 2014/52/EU), or the Marine Strategy Framework Directive (Directive 2008/56/EC).

An argument can therefore be made that the Environmental Statements did not adequately assess the likely effect of a development on the status of the environment. This is a problem for regulators and managers who, as well as making planning and licensing decisions, are tasked with achieving 'Good Environmental Status' (discussed in Borja et al., 2013) by 2020, and who are faced with climate change effects adding a further layer of complexity (Elliott et al., 2015). Legislation is evolving to require regulators and, hence, practitioners to assess the effects of development on biodiversity and to include climate change in an assessment (Table 6). It remains an open question whether EIA-led CEA practice can evolve to deliver CEAs that meet the requirements set by ecosystem approach legislation, of if a more radical approach is warranted (Duinker and Greig, 2006; Greig and Duinker, 2014; Sinclair et al., 2017).

Table 6. Examples of increasing demands placed on cumulative impact assessments (CEAs) as a result of evolving legislation, and qualitative assessment of CEA compliance based on evaluation results.

Emerging information requirements demanded of CEAs as a result of evolving legislation	Example legislative instrument
Is the cumulative effect of a proposed development or activity on biodiversity assessed?	EIA Directive (Directive 2014/52/EU)
Is climate change considered with the assessment, as a receptor and as a risk to infrastructure?	
Does the assessment support the ongoing marine region assessment of cumulative effects on human pressures and impacts?	MSFD (Directive 2008/56/EC)
Does the assessment provide information to manage pressures and impacts relative to good environmental status targets?	

3.4.2 Can EIA-led CEA improve?

Given the institutional strength of the EIA system, strengthening activity-level CEA practise is highly desirable. One challenge encountered during the evaluation was the variability between Environmental Statements in terms of content and presentation, and the number of chapters and appendices that had relevance to the evaluation, that is, the volume of documentation that needed to be reviewed. It was difficult to be certain that all relevant information had been identified, a difficulty that presumably is also encountered during regulatory review of Environmental Statements. Variability between CEA methodologies was also identified. One key area of improvement for activity-level CEA practice is therefore to improve consistency between Environmental Statements and between CEAs specifically. Calls to clarify expectations regarding project-driven cumulative effects assessments (Freeman et al., 2013) were partially answered by the publication of Cumulative Impact Assessment Guidelines produced by RenewableUK for developers of offshore wind farms (RenewableUK, 2013). The guidelines include principles for CEA (Table 7), define cumulative effects and discuss what meaningful CEA is.

Table 7. Principles for Cumulative Impact Assessment included in RenewableUK (2013) guidelines

1. CIA is a project-level assessment, carried out as part of a response to the requirements of [EU legislation], designed to identify potentially significant impacts of developments, possible mitigation and monitoring measures.
2. Developers, regulators and stakeholders will collaborate on the CIA.
3. Clear and transparent requirements for the CIA are to be provided by regulators and their advisors.
4. Scoping principles: CIAs will include early, iterative and proportionate scoping.
5. Boundaries for spatial and temporal interactions for CIA work should be set in consultation with regulators, advisers and other key stakeholders, in line with best available data.
6. Developers will utilise a realistic Project Design Envelope.

7. Developers will consider projects, plans and activities that have sufficient information available in order to undertake the assessment.
8. The sharing and common analysis of compatible data will enhance the CIA process.
9. CIAs should be proportionate to the environmental risk of the projects and focused on key impacts and sensitive receptors.
10. Uncertainty should be addressed and where practicable quantified.
11. Mitigation and monitoring plans should be informed by the results of the CIA.

It is suggested here that the RenewableUK guidelines will not result in meaningful CEAs, as defined by the considerations and challenges discussed in Chapter 2. Improved CEA guidelines that clarify conceptual, methodological and practical uncertainties are required. The RenewableUK guidelines could support the production of better, more consistent CEAs and support meaningful future analyses. Principle 8 (the sharing and common analysis of compatible data will enhance the [CEA] process), for example, if adopted by developers and practitioners, would greatly enhance *a posteriori* analyses. Examples of data-sharing and joint research exist in the UK within the aggregate dredging industry, which pools resources and applies a regional, multi-operator approach to assessing environmental effects (TEDA, 2008). The advantages of such an approach are better ecological decision-making, cost benefits for the industry through streamlined monitoring over time and improved decision-making capacity for faster consenting/licensing process (Froján et al., 2016).

Examples of better practise were observed during the evaluation suggesting that research is warranted to identify and clarify what best practice could be based on current project-level approaches, and to provide examples in revised guidance. Step-wise frameworks for cumulative effects assessments exist that outline the integral steps in the CEA process, which could be used to improve project-level CEA guidelines, e.g. Judd et al. (2015). One of the steps that calls for increased attention is scoping (Figure 5), where the scope of the CEA is defined in terms of project stressors and social-ecological components to include and scales of assessment to apply. Strengthening and clarifying the scoping process could validate a focus on fewer receptors, which could be more ecologically meaningful and which better support regulatory requirements to consider the broader social-ecological system. By identifying receptors most sensitive to pressures predicted to arise from proposed developments, the number of receptors included in the assessment could be reduced and baseline and monitoring data collection focussed to provide for more robust analyses of effects on valued receptors. If an appropriate methodology for scoping could be designed that provides a robust means of determining which stressors, pressures and receptors to include in a CEA, e.g. (Knights et al., 2013; Tran et al., 2009), EIAs as well as CEAs could benefit in the longer term, by encouraging consistency and thus comparability between assessments, to improve the regional picture. Logically the methodology could be extended to apply across maritime activities submitting CEAs/EIAs in a given area, which would further aid the identification and resolution of key knowledge gaps through pooling effort and monitoring data. Whether there are meaningful regional indicator species, processes or functional groups that could be incorporated into assessments and transposed across activities with analogous pressures is a pressing research need (Boldt et al., 2014).

The treatment of receptors within an assessment warrants further discussion. CEAs evaluated were observed to have a greater focus on spatial considerations than temporal considerations. This reduces the capacity of the CEAs to identify significant environmental change arising through incremental changes that accumulate and interact over time (Spaling and Smit, 1993; Therivel and Ross, 2007). The reference condition of the receptors applied, the baseline, against which the significance of predicted effects were measured, were also questionable. The Environmental Statements evaluated typically stated that valued receptors have adapted to past and existing activities, implying that the current condition of valued receptors is normal. This approach enables the gradual accommodation of incremental declines in the condition of receptors (Pauly, 1995). The OWF Environmental Statements described already installed infrastructure, practiced licenced activities and implemented measures as part of the existing environment to which receptors have already adapted. Including existing activities within the EIA or CEA was referred to in some of the

Environmental Statements evaluated as introducing a potential risk of “double-counting” effects on receptors. However, Annex IV 5(e) of the EIA Directive requires that existing environmental problems within an area are considered (Directive 2014/52/EU) and simply excluding existing activities from the assessment is not appropriate (Pauly, 1995; Schultz, 2012; Squires and Dubé, 2013). That said, establishing an appropriate baseline is problematic, as discussed in Chapter 2, section 2.5.5.

Given the many uncertainties associated with OWF environmental effects, with CEA and with the marine environment in general (Judd et al., 2015; MMO, 2013), explicit consideration of uncertainty is crucial (Masden et al., 2015). The term ‘uncertainty’ observed within Environmental Statements evaluated more frequently referred to uncertainty about the likelihood of ‘other future activities’ occurring, which was used to justify the inclusion or exclusion of other activities from the CEA. This is in contrast to the more widely recognised meaning of uncertainty in environmental science, the uncertainty about cause-effect relationships, of receptor condition, and of analytical methods (Leung et al., 2015; Masden et al., 2015). This presents an opportunity for improvement as the explicit consideration and structured treatment of uncertainties would support more robust environmental risk assessments (Masden et al., 2015).

3.5 Conclusions

A novel evaluation framework was developed to assess offshore wind farm CEAs relative to the information needs of regulators and managers tasked with implementing the ecosystem approach, a key driver behind many maritime regulatory systems worldwide. The evaluation revealed procedural strengths and technical weaknesses, notably in relation to the key CEA considerations. The Environmental Statements evaluated did not deliver CEAs that adequately address uncertainties about the cumulative effects of MRED development on fish, shellfish and benthic ecology. Calls to reduce the assessment burden on developers and the perception of disproportionate scrutiny reported in Wright (2015) should therefore be balanced against the very real risk that cumulative effects pose to social-ecological systems.

Given the spatial and temporal scales over which cumulative effects propagate in social-ecological systems, and the complexity of those systems, it is improbable that project-specific CEAs alone will sufficiently answer questions about the risk to the environment of, for example, permitting MREDs. There are clearly straightforward improvements that could be applied to deliver better project-specific CEA, but such CEAs will need to be placed in context of regional assessments. There are strong reasons to adapt the EIA system to deliver better CEAs but answering the question whether project-specific assessments can evolve to provide meaningful CEAs is difficult. It will require evolution in assessments completed at different scales, as well as institutional and procedural change.

4 Principles and a pathway to promote better CEA[5]

4.1 Introduction

Chapter 2 identified seven key considerations that need to be taken into account by methodologies seeking to improve CEA practice. These considerations include ecological connectivity, temporal accumulation, spatial accumulation, endogenic and exogenic sources of pressure, putting receptors at the centre of assessments, and defining the purpose of CEA. Chapter 3 examined the performance of CEAs contained within Environmental Statements of large-scale offshore wind farms and identified shortcomings in practice relative to the considerations. An additional shortcoming observed was the variability of CEA content and approach between the Environmental Statements, pointing to the need to improve consistency of practice. This is essential if marine management and planning is to benefit from the data and knowledge generated by project- or activity-scale assessments that, in theory, could contribute to a reduction in uncertainty about local and regional cumulative effect questions.

This chapter presents principles and a pathway designed to lead to improved CEA practice. The principles for CEA and the CEA pathway are intended to enable better CEA than that currently observed. ‘Better CEA’ is defined as better accounting for the CEA considerations and addressing the shortcomings identified in the preceding chapters and reported in scientific literature (e.g. Burris and Canter, 1997; Canter and Ross, 2010; Foley et al., 2017). Prior to presenting the principles and pathway, additional considerations are presenting that are relevant to questions of: i) proportionality (what is reasonable to expect of a single development activity CEA); ii) coherence (enabling systematic consistency between CEAs); and, iii) relevance to decision-making in areas where management seeks to implement an ecosystem approach.

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[5] Chapter adapted from: Willsteed, E. A., Birchenough, S. N. R., Gill, A. B. & Jude, S. Structuring cumulative effects assessments to support regional and local marine management and planning obligations. Mar. Policy **98**, 23–32 (2018)

These additional considerations are then brought together to propose a general perspective of CEA, which sets the context for the CEA principles and CEA pathway. This effort is expended to provide a conceptual analysis that supports the definitions of cumulative effects and of CEA applied in this chapter. The conceptual analysis clarifies what definitions of cumulative effect and of CEA underpin the principles and protocol elaborated. Secondly, providing such an analysis illuminates the value set of the author, which is important to aid proper interpretation of the definition applied (Duinker et al., 2012).

4.2 Unpacking a cumulative effect question

Uncertainty about the cumulative effects of, for example, MREDs, raise questions that superficially appear straightforward but become complex when more closely investigated. For example, the Fish and Shellfish Ecology chapters of Environmental Statements for offshore wind farms evaluated in Chapter 3 each seek to answer whether one offshore wind farm will significantly impact fish and shellfish ecology. This thesis argues that the assessment within the Environmental Statement that in theory would best answer that question, is the CEA. However, such a question involves multiple relationships and interactions between social-ecological system components, and multiple temporal and spatial scales are relevant, and different levels of biological organisation (Figure 11).

Human components of social-ecological systems are also relevant. The focus in CEA research tends towards researching and assessing cumulative effects on ecological components. Cumulative effects occur, however, within social-ecological systems, coupled systems of people and nature embedded in the biosphere (Folke, 2016). Understanding how cumulative effect questions impact human wellbeing is equally important; ultimately managing cumulative effects is a human endeavour, and people will determine the effectiveness (or not) of management interventions (Levin et al., 2013). The range of relationships that require investigation to answer a cumulative effect question, therefore, and the multiple scales that result reiterate the need for CEA to be a multidisciplinary endeavour. As highlighted in chapter 3, there are concerns, particularly among developers and practitioners, that an increased assessment scope would put a disproportionate burden on developers (Hawkins et al., 2014; RenewableUK, 2013; Wright, 2015).

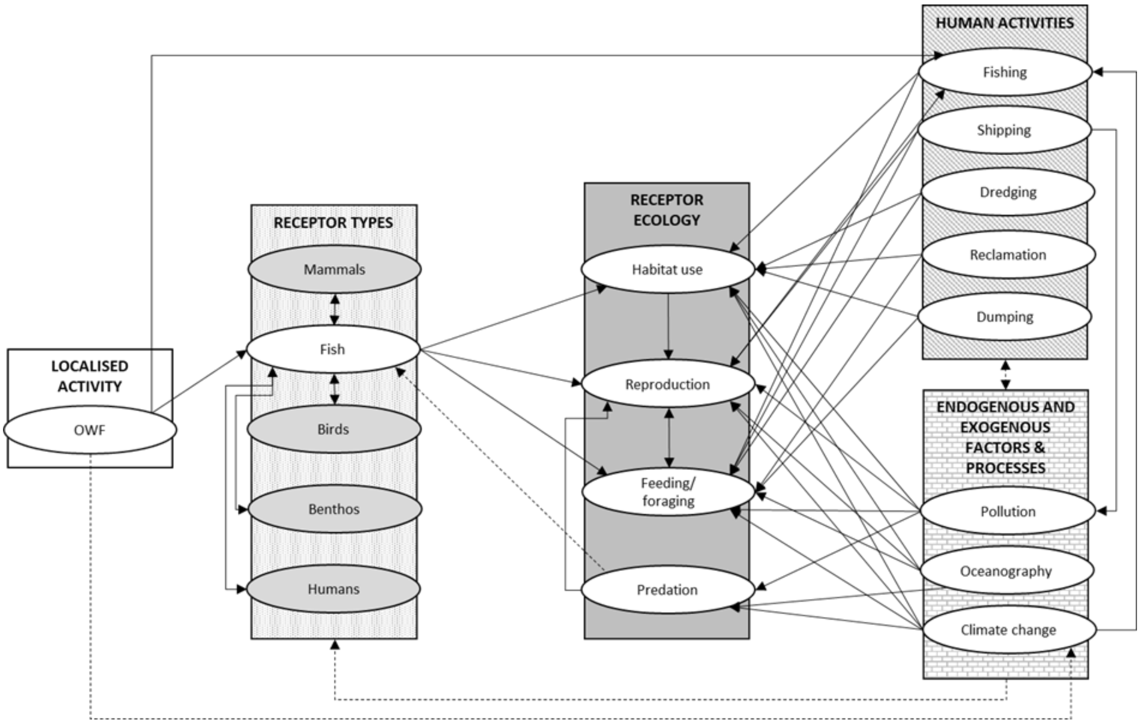

Figure 11. Relationships identified when unpacking a cumulative effect question, in this example, what is the cumulative effect of one offshore wind farm (OWF) on one receptor type (fishes) within a social-ecological system representative of the Southern North Sea. Dashed arrows indicate feedbacks, such as endogenous and exogenous processes feeding back to influence receptors.

Given the strength of the legislative and procedure infrastructure around environmental assessments driven by legal obligations, as argued in this thesis, there is a strong rationale for seeking to improve such assessments. However, expecting one assessment to resolve the many uncertainties associated with the nature of the relationships indicated in Figure 11 is unrealistic. There is a clear need to structure such assessments to enable knowledge to cumulate.

4.3 Enabling coherence between CEAs

In the European Union, CEA is explicitly or implicitly required under different Directives that can be concurrently active in the same area (Figure 12). Multiple assessments that in one form or another assess cumulative effects are likely to be available to marine managers and planners.

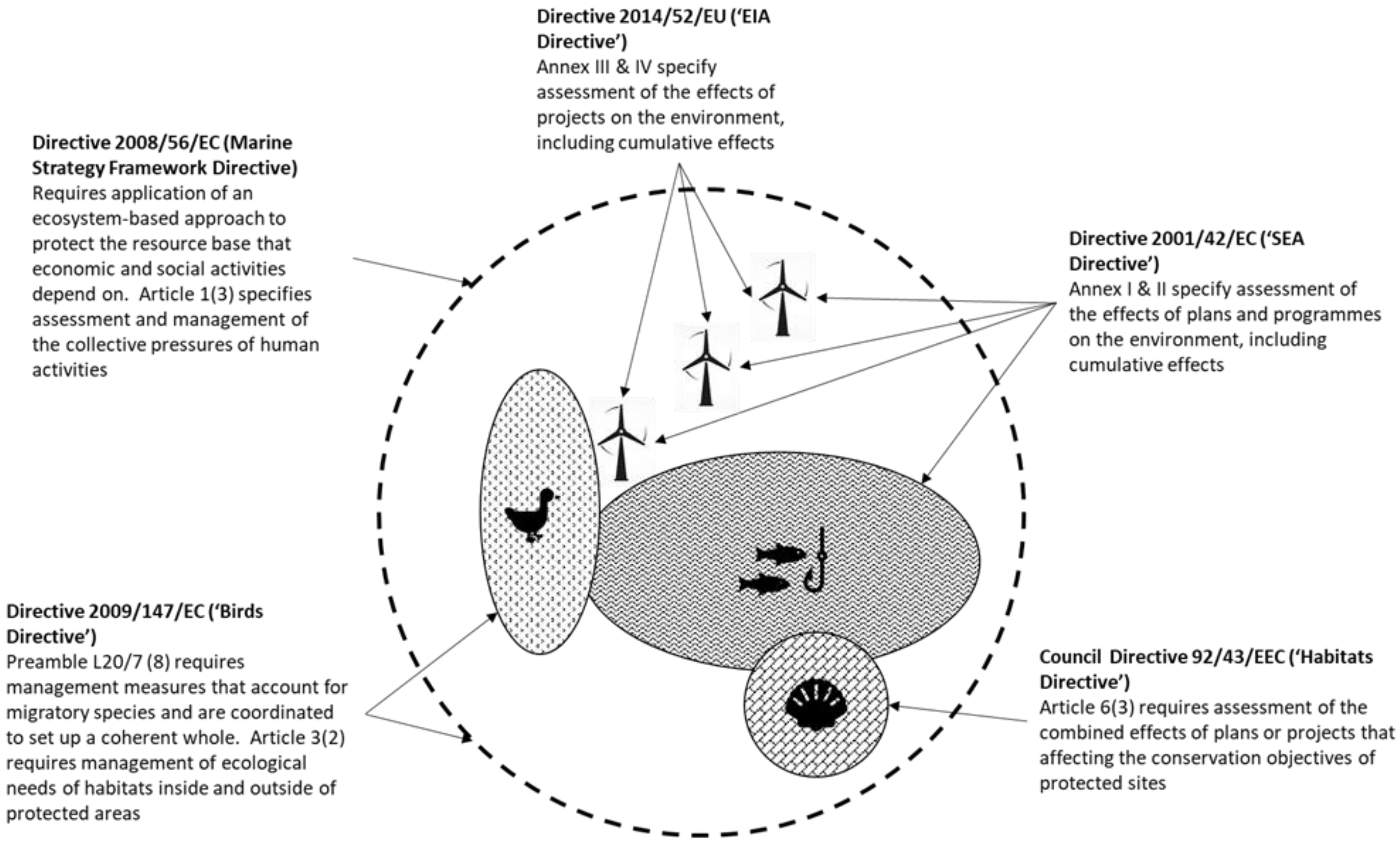

Figure 12. A social-ecological system in European Union waters where different legislative instruments are likely to drive assessments that should contribute to the knowledge held about cumulative effects in that system.

While the terminology behind the Directives driving these assessments is not identical, the intent relative to the stipulation to assess cumulative effects is the same: protection of the environment (Judd et al., 2015). At present, pertinent information is often scattered between incomparable assessment outputs, but knowledge cumulation requires systemic consistency between assessments and the ability to integrate reductionist assessments into a greater whole, i.e. coherence.

To support the integration of information from different CEAs, common ground in the sense of a shared goal and purpose would assist by increasing the likelihood that the conceptual thinking underpinning CEAs is coherent to promote similar structural characteristics that lead to assessments that can be compared. Coherence, rather than standardisation, is specified, as the complexity of assessing cumulative effects in social-ecological systems prevents standardisation across different scales of assessment (Jones, 2016). Complex problems need to maintain diversity and flexibility of approach and discourse (Folke, 2016) and current legislation requires different CEAs for different purposes (Judd et al., 2015). Attaining consistency between EIAs and SEAs is likely to be more challenging than attaining consistency between EIAs, for example. But the likelihood of enabling compatibility of the outputs of CEAs with different drivers could be increased if the CEAs share a common conception of the broader context and purpose of CEA.

4.4 Social-ecological systems and cumulative effects assessment

Social-ecological systems are complex adaptive systems where processes and components dynamically interact at different and linked temporal and spatial scales, where feedback loops play a defining role in influencing system behaviour, and where interactions tend to be non-linear (Folke et al., 2016; Levin et al., 2013). Localised changes can accumulate to cause slow, broad-scale change that in turn affect local processes and patterns via feedback loops (Levin et al., 2013). Interactions between system components evolve over time and have a self-organising capacity, and unpredictability and uncertainty are intrinsic to complex adaptive systems (Wu, 2013) (and hence are inherent in CEA).

The characteristics of complex adaptive systems give rise to management and policy challenges relevant to CEA. Local actions scaling up to effect change at higher scales that then feedback typically lead to slow structural change in the ecosystem over long time periods up to the point where abrupt changes occur that may be irreversible (Levin et al., 2013). Determining how significant past effects have been and predicted effects will be on ecosystems is complex, and will depend on the system's or component's capacity to recover and/or reorganise following a disturbance (Duarte et al., 2015).

The predominant approaches employed in environmental assessments to investigate relationships between development and components of social-ecological systems tend to be linear (Knights et al., 2013) and reductionist (Gasparatos et al., 2009). Reductionist approaches are necessary to investigate and describe a system, but need to be placed in a more holistic setting (Gasparatos et al., 2009). Sustainability issues are set in complex systems, thus assessments that apply single indicators, single dimensions (e.g. economic, social or environmental), and single scales of analysis are individually not effective decision-making tools (Gasparatos et al., 2009). Linear, reductionist approaches are simpler to apply, but risk giving misleading representations of system dynamics that could lead to ineffective or, worse, counterproductive management interventions (Levin et al., 2013).

Social-ecological systems thinking offers support to CEA, by drawing attention to the characteristics of complex adaptive systems. To benefit from systems thinking, though, requires a structuring object that aids the identification and analysis of relationships that may be nested at different spatial and temporal scales (Ostrom, 2009). Various such frameworks exist that differ in terms of how relationships between social and ecological components are conceptualised, whether an anthropological or ecological perspective dominates, and whether outputs are action or analysis oriented (Binder et al., 2013). Whether one specific framework could be appropriate for facilitating coherent CEA in a region requires testing, but adopting a common vocabulary and structure from which to construct and test alternative theories and models to determine which influences on processes and outcomes are critical in specific empirical settings would clearly be beneficial with regard to coherence (McGinnis and Ostrom, 2014).

4.5 Changing resilience as a measure for cumulative effects assessment

Marine policy-makers and managers are increasingly required to consider the resilience of social-ecological systems, but there are multiple interpretations of what resilience is (Gibbs, 2009). Resilience is a common lens of inquiry that has emerged in social-ecological systems thinking since Holling's seminal 1973 paper (Holling, 1973), as an approach to support interdisciplinary research investigating social-ecological systems sustainability (Folke et al., 2016). Resilience describes the capacity of a system to absorb changes and to persist after disturbance, requiring knowledge of thresholds (Holling, 1973; Standish et al., 2014). Resistance and recovery, by contrast, is a measurement of the change effected in a receptor due to a disturbance, and the time taken for the receptor to recover to its pre-disturbance state following the disturbance (Pimm, 1984 cited in (Standish et al., 2014). Human activities that incrementally and repeatedly disturb interactions between biotic and abiotic processes contribute to a loss of resilience that increases the likelihood of a shift to alternative states (Österblom et al., 2016). The risk with cumulative effects is that a small change can push a system into an alternative state (Standish et al., 2014). A state shift can result in irreversible loss of social-ecological capital and examples of system collapses resulting in massive disruption to human societies exist (Cumming and Peterson, 2017). State change may be desirable if shifting from a degraded system to a more desirable one (Walker et al., 2004), noting that perspectives of desirable vary and narrow perspectives can be problematic (Higgs et al., 2018).

The resilience concept integrates consideration of spatial and temporal dynamics of social-ecological systems, encouraging movement away from the shifting baseline phenomenon that affects many environmental assessments (Hobday, 2011), including those evaluated in Chapter 3. Change in resilience is a compelling conceptual metric for CEA, but application remains vague (Standish et al., 2014). Identifying how systems respond to disturbances requires insights into variables with slow and fast dynamics. Slow variables, such as temperature trends or habitat availability that define species distributions, tend to define system resilience (Carpenter et al., 2001). Assessments typically focus on the consequences of perturbations that affect faster variables (Carpenter et al., 2001). However, slight changes in slow variables may have a profound effect on the resilience of a system or receptor to absorb further perturbations (Carpenter et al., 2001). This highlights the need for discrete CEAs to have access to or be reviewed in context of longer-term information about the slow variables influencing the structure of the system.

Selecting metrics and indicators that can monitor and communicate how human activities individually and cumulatively influence resilience is an ongoing area of research (Folke, 2016), which in part reflects the varied conceptions of what resilience is and thus how it is defined, assessed and measured (Quinlan et al., 2016; Standish et al., 2014). In the context of CEAs, the significance of additional disturbance to a receptor and hence to a social-ecological system, will reflect the status of the receptor at the time (Figure 13). CEAs, then, need to consider how resilient a system is and how resistant receptors therein are . Considering resilience and resistance aids identification of the magnitude of disturbance that a receptor can absorb before the persistence of relationships between the receptor and the broader system are overwhelmed. Identifying how a system or component has changed over time can provide insight into how precarious a system or component is, whether close to or distant from a boundary of attraction (Walker et al., 2004). This temporal element is vital to CEA, particularly for CEAs seeking to identify how significant the introduction of additional stressors may be at a particular point in time.

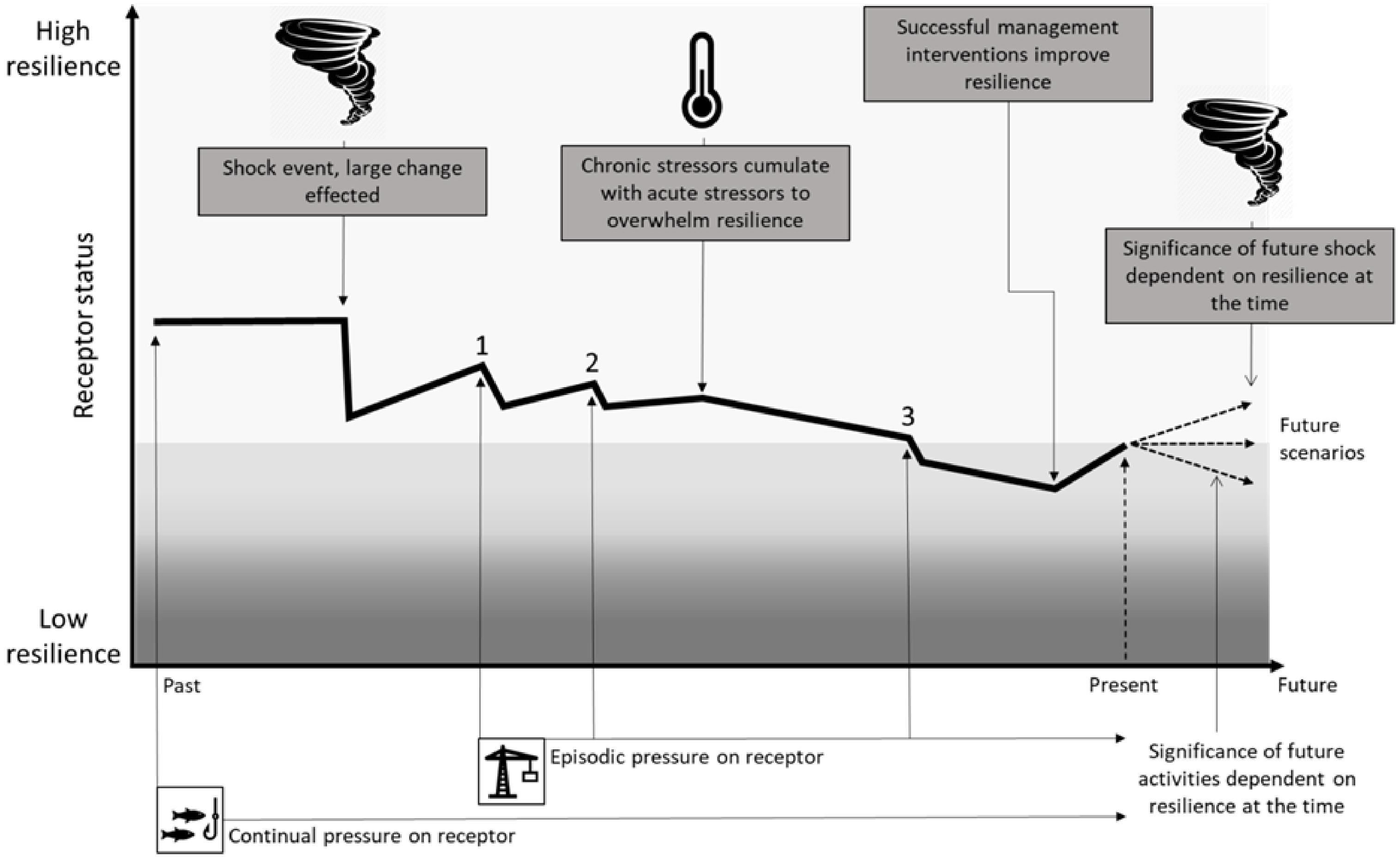

Figure 13. Change in the assimilative capacity (*sensu* Elliott et al., 2018) of a receptor over time as incremental disturbances are caused by individual activities and events. The significance of stressors at points 1, 2 and 3 is different, as the receptor is more or less resilient. The darker shading associated with low resilience represent the increasing risk of a threshold being crossed resulting in a state change.

Metrics are thus required that are able to detect the strength and direction of effects on receptors and which are able to account for the time lags that are often present between a stressor being introduced and the emergence of effects (Pasquaud et al., 2013). Typical metrics, such as species richness, can miss impacts of anthropogenic stressors on the persistence and hence resilience of critical ecological features (e.g. food webs; (Gilarranz et al., 2016)). Hence there remains a search for metrics and indicators that are better able to provide insight into the dynamics and interactions between receptors and their environments, and between system components that contribute to resilience (Folke, 2016; Rombouts et al., 2013). Whatever measures are chosen, they should be relevant to outstanding management questions, ideally would be empirically quantifiable and need to be tested over a range of temporal and spatial scales (Donohue et al., 2016). Key, also, is clarity within assessments about what is being measured relative to what effects, and at what temporal and spatial scales (Carpenter et al., 2001), particularly as the scale at which a phenomenon is studied can lead to different interpretations of what is influencing the dynamics of species and communities (Levin, 1992).

4.6 Establishing common ground between CEAs

Bringing the preceding information together, multiple CEAs are necessary to support the implementation of the ecosystem approach, CEAs need to consider the relationships between connected components of social-ecological systems, and ultimately CEAs should contribute to understanding how human activities are influencing the resilience of social-ecological systems.

Different legislation places different demands on specific assessments, but, as established, meeting regional and project-level obligations to account for cumulative effects requires coordination between multiple CEAs. One relevant question at this point is at what conceptual levels do CEAs share a common objective, and at what level do specific demands lead to divergence in objectives and hence approaches to CEA. That is, are there high-level objectives for CEA that are shared regardless of driver? Figure 14 presents a series of nested concepts that propose levels at which common ground between CEAs should exist, and the level at which divergence between CEAs is likely to occur.

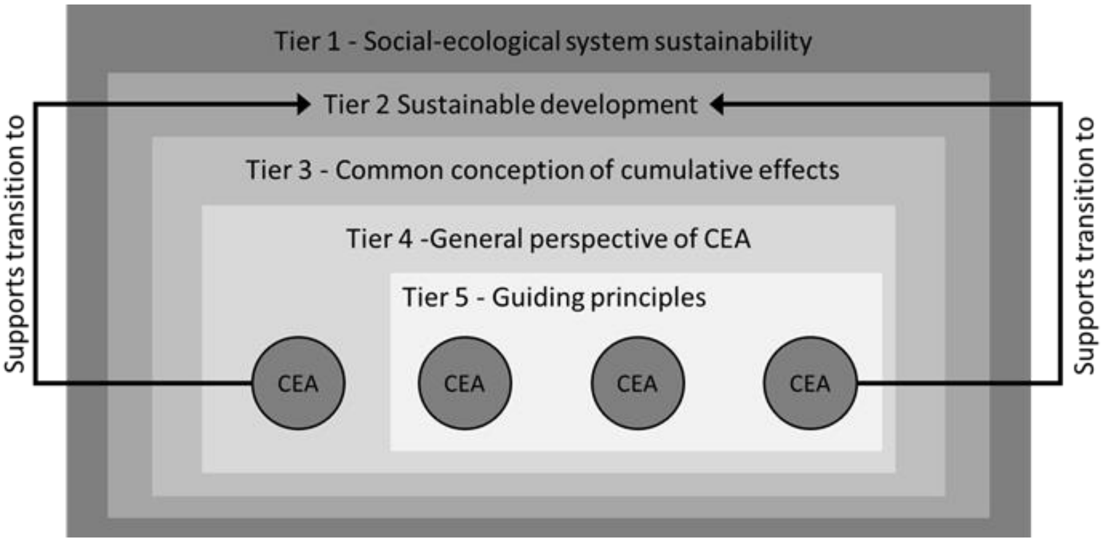

Figure 14. A tiered approach to identifying a general perspective of CEA that shares a common conception of cumulative effects and an overarching intent to support a transition to sustainable development. CEAs not applying guiding principles can apply the same intent to advance regional sustainable development.

The conception of CEA throughout this thesis and presented in this chapter is rooted in the sustainability imperative. The end goal of assessments stimulated by legislation that is intended to protect the environment is to contribute to the sustainability of social-ecological systems (Tier 1, Figure 14). This is the end goal of CEA as a process. CEA can contribute to progress towards this end goal by providing assessments of the effects of human activities and development on the capacity of seascapes and landscapes to provide long-term services essential for maintaining and improving human wellbeing in a regional context (sustainability *sensu* Wu, 2013). That is, CEA should seek to support the transition to sustainable development (Level 2).

For CEA to contribute efficiently to sustainable development, which requires a regional perspective (Wu, 2013) requires coherence between assessments that seek to identify and understand cumulative environmental change. As this is rooted in phenomena beyond the capacity of individual assessments to investigate, a common conception of cumulative effects need to guide CEAs (tier three). Further debate is required to determine a precise definition of cumulative effects that would be appropriate and sufficiently detailed to be applicable across CEAs, but, it is suggested here, the key characteristics of cumulative effects are well known, as discussed in Chapter 2. Commonalities in conceptions of cumulative effects include, *inter alia*:

- multiple agents of change, such as pressures or stressors, interactively act on receptors (e.g. Duinker et al., 2012; Segner et al., 2014; Sinclair et al., 2017);
- effects arise from multiple human activities and accumulate across space and time to act on receptors (e.g.Dubé et al., 2013; MacDonald, 2000; Sinclair et al., 2017; Therivel and Ross, 2007); and,
- interactions between effects may not be linear and seemingly minor incremental additions to the cumulative effects load may result in a significant change in the receptor (e.g. Canter and Ross, 2010; Harriman and Noble, 2008; Johnson et al., 2015; Therivel and Ross, 2007).

The key point made here is that the basic concept of cumulative effects is well understood and defined, hence a definition that is applicable to CEAs independent of legislative driver should be achievable. Agreeing such a definition is important to reduce the ambiguity of language between different legislative instruments that intend to achieve the same goal (Judd et al., 2015).

The general perspective of CEA (Level four, Figure 14 and Figure 15) is a conceptual reference point to guide CEA practice. It seeks to be sufficiently generic to avoid conflicting with practical requirements linked to specific legislation, while being sufficiently clear about the purpose of CEAs. The general perspective of CEA (Figure 15) seeks to account for the dynamism and multiple scales stressed in CEA theory and ecological theory, but which is not addressed in CEA practice (Foley et al., 2017; Jones, 2016) or in EIAs and SEAs (Cooper, 2011; Noble et al., 2019). The dynamic relationship between ecosystem services and human wellbeing points to CEA being an ongoing need to support strategic and localised decision-making about current and proposed human activities relative to management objectives. The term Strategic CEA is introduced here, which builds on a concept introduced by Therivel and Ross (2007) to refer to CEAs completed at a strategic level. This concept is developed here and in this thesis refers to an ongoing plan of management process that applies to a region and which evolves with information from individual, discrete CEAs and which in turn can support discrete CEAs with reference condition information Figure 15. The Strategic CEA (hereafter SCEA) is thus a process that is iteratively improved via the accumulation of knowledge gathered by CEAs completed for discrete developments and activities. This iteration and accumulation of knowledge is essential where management and policy formulation must make do with low-resolution evidence and need to be able to respond to unexpected change and revised ratings of system or system component resilience (Folke et al., 2016).

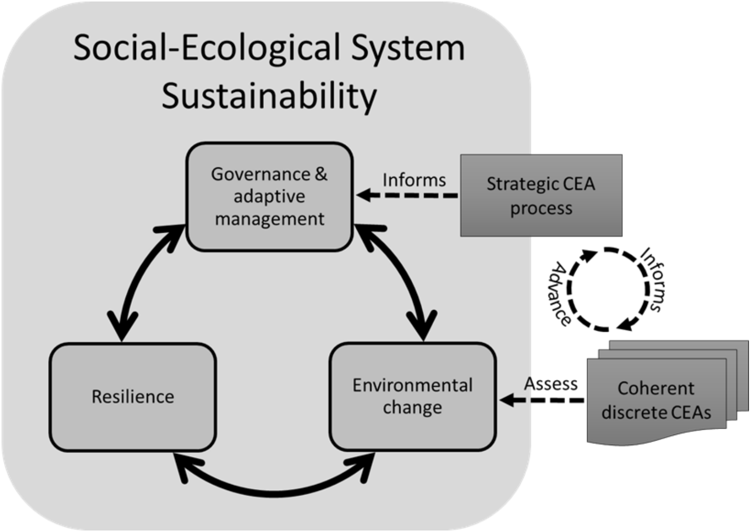

Figure 15. A general perspective of CEA comprising two forms of CEA: individual CEAs that assess the environmental change caused by discrete developments and activities, and a Strategic CEA (SCEA), which is an ongoing process informed by the individual CEAs. The SCEA supports local and regional governance by informing decision-makers about the cumulative effects of human activities on the state of the system. A feedback loop between the SCEA and individual CEAs indicates the mutually beneficial flow of information. The double-headed arrows between the three characteristics determining system sustainability (governance, environmental change and resilience) indicate the potential for each characteristic to influence the other characteristics.

In the general perspective of CEA, the sustainability of a social-ecological system is linked to three interlinked aspects: i) the scale, rate and trajectory of environmental change occurring within the system (Folke, 2016; Spaling, 1994);

ii) how resistant and resilient the system is (Folke, 2016); and, iii) the adaptive capacity of society, through governance, to manage and influence change (Walker et al., 2004). Sustainability requires specification of what is to be sustained, what is to be developed, the relationship between the two, and what scales are applicable (Wu, 2013). The SCEA/CEA approach can support specification of these parameters through assessments of the accumulated state of the environment, developing appropriate baselines for monitoring and planning, and by developing future scenarios to explore the implications of current trajectories and trade-offs (Dubé et al., 2013).

4.7 Candidate principles for coherent CEA practice

Judd et al. (2015) explored the principles and definitions underlying CEA and found inconsistent language, interpretation and parameterisation prevent scientifically more robust CEA approaches from effectively supporting marine management and policy-making. A recent review of regulator experience with the EIA Directive in UK waters reiterates the need for improved consistency of and guidance for cumulative effects assessments (Lonsdale et al., 2017). To reduce ambiguity, Judd et al. (2015) specify vocabulary for CEAs irrespective of driver and provide a set of recommended conventions for developing CEA methodologies. Here, these conventions are adapted and integrated with additional literature reviewed over the course of the research for this thesis to suggest principles for CEA practice (Table 8).

Table 8. Suggested principles for CEA practice based on recommended conventions in Judd et al (2015) and CEA/Social-ecological systems theory as referenced.

Principle	Rationale
1. Apply a cumulative mindset (Sinclair et al., 2017)	Assessments of the current condition and resilience of valued social-ecological system components seek to understand relative contributions of the spectrum of stressors/effects. Recognise that future cumulative effects may overwhelm resilience and require trade-offs and rebalancing of cumulative effects loads to avoid impacts/support recovery.
2. Apply a social-ecological systems mindset (Holling, 1973; Levin et al., 2013)	Characteristics of social-ecological systems should feature in management planning and policy-making. Non-linear interactions are the norm not the exception, requiring appraisal of how effects may cumulate. Qualitative views of system behaviour are valid and valuable.

Principle	Rationale
3. Apply common vocabulary (Judd et al., 2015; McGinnis and Ostrom, 2014; Ostrom, 2009)	Consistent vocabulary is necessary to make greater use of varied CEA approaches across marine management scales and purposes and to enable knowledge to cumulate to aid management of social-ecological systems.
4. Apply formalised environmental risk assessment principles (Judd et al., 2015)	Risk assessment principles enable scientifically defendable decision-making when faced with low-resolution evidence and where there is considerable uncertainty about the effects of decisions on management objectives. Judd et al. (Judd et al., 2015) specify a four-step framework, elaborated upon by Stelzenmüller et al. (2018). ISO 31000:2018 provides an internationally recognised standard for appropriate consideration and management of risk.
5. Link effort expended to risk of significant environmental change (MacDonald, 2000)	Link effort to risk, helping to focus on priority questions and receptors relative to management objectives and a transition to sustainability (mindful that legally unprotected species or functional groups may be more effective indicators of system change).
6. Assess a specific cumulative effect question (Judd et al., 2015; MacDonald, 2000)	Clearly formulate the problem and specify the elements/variables included and the purpose of the assessment.
7. Analyse pathways to refine variables to include (Judd et al., 2015)	Use a conceptual pathway model (e.g. Source-Stressor-Effect-Pathway-Receptors) to define and refine variables included in CEAs and to document the reductionist process.
8. Transparency about parameters selected for inclusion and the treatment of uncertainties and assumptions (Judd et al., 2015; Skinner et al., 2014)	The many uncertainties involved make structured and rigorous documentation of CEA processes, assumptions and uncertainties necessary, from start to finish. Skinner et al. (Skinner et al., 2014) provide a typology of uncertainties designed to support risk characterisation.
9. Integrate time into assessments (Carpenter et al., 2001; Judd et al., 2015; MacDonald, 2000; Therivel and Ross, 2007; Wu, 2013)	Short-term and long-term dynamics are critical components of social-ecological system sustainability. Assessing change in resilience, regardless of definition, has a temporal component, requiring measurement of at least two points in time. CEA theory is clear that CEAs should include time.
10. Focal receptor life history characteristics set assessment boundaries (Ball et al., 2013; Duinker and Greig, 2006)	Ecosystems and ecological receptors experience an array of anthropogenic stressors in addition to natural perturbations, the effects of which cumulate and interact over different spatial and temporal scales relative to each receptor. Receptors are the crux of CEA, as they experience a spectrum of stressors/effects that cumulate to have a net effect on the receptor. Receptors provide context and rationale for boundaries and baselines.
11. Account for known variables that contribute to the condition of focal receptors (MacDonald, 2000)	Assessments of the incremental and net effects (i.e. the cumulative effects) of anthropogenic stressors on receptors and hence on ecosystem structure and functioning should include consideration of variables that influence receptor condition. As well as anthropogenic effects, biophysical processes and disturbances are influential.
12. Assess the risk of significant change in the resilience of focal receptors/variables caused by	Sustainable development is intrinsically linked to enabling resilience of desired social-ecological system states. Marine ecosystems and receptors experience several types of disturbances. Resilience may vary depending on the

Principle	Rationale
effects associated with the guiding question	type of disturbance, the magnitude and footprint of effects arising from the disturbances. How resilience responds to additional disturbance requires a sound understanding of cause-effects relationships of receptors/variables.

4.8 A pathway for improved CEA

Building on the research conducted for the preceding chapters, the CEA principles described above, and with the general perspective for CEA in mind, a stepped pathway has been developed that seeks to enable improved CEAs in scenarios where EIAs are required (Figure 16).

The definition of cumulative effects adopted here is from Harriman and Noble (2008), that cumulative environmental effects are effects of an additive, interactive, synergistic, or irregular (surprise) nature, caused by individually minor, but collectively significant actions that accumulate over time and space". As argued in this thesis, meaningful CEA that can contribute to managing cumulative effects is beyond the scope of individual, reductionist assessments. Hence, an assumption lies behind the CEA pathway that strategic (holistic) CEA is necessary to support a transition to sustainability, and that coherence between reductionist CEAs is an efficient means of supporting a strategic (holistic) CEA.

The practicality of the CEA pathway is tested in Chapter 5, which investigates the availability of both data and appropriate methodologies that could be applied to complete the steps. Chapter 6 then seeks to apply the data to a hypothesis-driven cumulative effect question that specifically tests step 5 (assessing cumulative effects) of the CEA pathway.

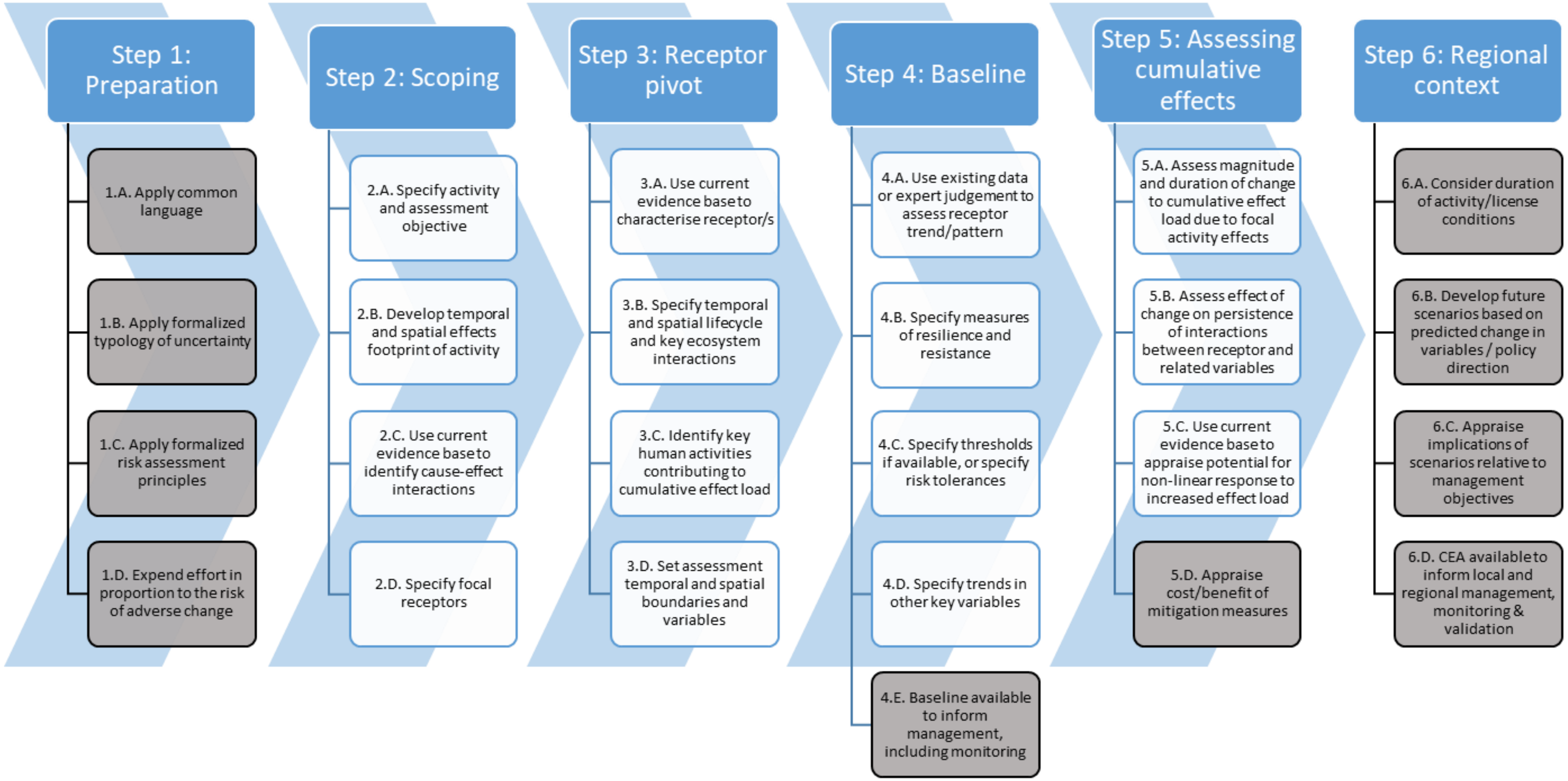

Figure 16. A CEA pathway comprising 6 steps that is proposed to enable improved CEAs in scenarios where EIAs are required. Steps highlighted grey are those where regulatory leadership is predicted to be necessary. Each step involves a process (sub-steps linked beneath each step heading), the outputs of which support completion of the subsequent step. Preparatory steps establish coherence between reductionist CEAs and apply throughout the approach. Resulting CEAs are intended to be comparable and to contribute to strategic management and planning. Step 5, the cumulative effects assessment step, seeks to define the risk that a development or activity may negatively impact the persistence of relationships between valued receptors and social-ecological systems, contributing to a decline in system resilience.

The pathway consists of six steps and a process nested within each step that guide a practitioner through the process of specifying a CEA through to identifying the risk of significant cumulative effects occurring if a development or activity is permitted. Recognising that uncertainties about cumulative effect interactions between a development or activity and receptors are highly likely, each step is designed to not be overly prescriptive, to enable qualitative and quantitative approaches to be employed as knowledge and data permit. Steps are intended to be followed sequentially, though iterations are likely as information from a subsequent step may require preceding steps to be revisited.

Step one, preparation, lays the ground for coherence between CEAs. The grey highlighted steps within the preparatory process (and elsewhere in Figure 16) are steps where regulatory leadership is recommended. Defining and adopting standardised language, for example, requires regulatory input to ensure the language and approach to environmental risk are consistent with regulator's information needs and management objectives.

Step two, scoping, seeks to establish proportionate boundaries to the scope of the assessment and analysis required. This is the reductionist step that seeks to identify the spatio-temporal footprint of effects of an activity. These footprints can be put into context of the environment by investigating known cause-effect pathways to scope the range of receptors that require assessment.

Step three, receptor pivot, is so called, as the receptor becomes the central point (pivot) on which the assessment revolves for subsequent steps. The characteristics of receptors need to be identified to specify the spatio-temporal footprint of the receptors, and to identify which system variables, including human activities, are influence the condition or status of the receptor. This then integrates the receptor-led approach into the CEA, as is necessary for meaningful CEA (Sinclair et al., 2017). Receptors guide specification of temporal and spatial boundaries recognising that proportionality relative to the activity proponent and "good enough" CEA (Therivel and Ross, 2007; pg 376) will come into play, as migratory and wide-ranging species, or poor data resolution influence what is reasonable relative to the scope of a reductionist CEA.

Step three seeks to move beyond the highly reductionist perspective applied in typical EIA and SEA by requiring consideration of the interactions between receptors and other system components (such as processes and activities) contributing to the cumulative effects load carried by a receptor. The intention is to improve the ability of such assessments to provide insights into the effects of development or activities on system interactions. The potential range of interactions that are relevant to system interactions raises, again, the question of what is reasonable and proportional to expect of EIAs and SEAs.

Slow changing variables, such as mean water temperature, and activities that influence the resilience of receptors to disturbance may be well beyond the standard temporal and spatial boundaries considered. Such variables should not be excluded without due consideration, however, given the importance these may have on the resilience on receptors and ecosystems to anticipated and future disturbance. Insights into the relationship between abiotic processes and receptors must also provide guidance about the suitability of existing datasets to reflect expected natural variability and sensitivity to human disturbance (MacDonald, 2000).

Step four, baseline, seeks to establish a baseline that accounts for trends and patterns in focal receptors, and to bring into consideration the resistance and resilience of receptors. The final sub-step in the baseline process is to specify trends in other key variables identified during scoping, to introduce into the CEA consideration of how other variables, such as mean water temperature, may influence receptor condition over the lifecycle of the activity being assessed.

Where data are available or can be collected to determine the receptor status and trends, assessments will be better able to qualify the risk additions to the cumulative effects load posed to receptors and hence on the resilience of the connected system (Stelzenmüller et al., 2018). CEA literature considers that identifying thresholds is vital (e.g. Duinker et al., 2012), however, in practice decisions very often need to be made without recourse to information about thresholds of disturbance (Groffman et al., 2006; Standish et al., 2014). In the absence of thresholds, formalised risk management processes, such as ISO

31000, can support evidenced specification of tolerance to risk relative to defined objectives, such as achieving good environmental status or maintaining a minimum population level (Cormier et al., 2013).

Step five, assessing cumulative effects, sets out a process that is loosely defined, for example step 5.2 requires an assessment of the effect of change on persistence of interactions between the receptor and related variables. CEA methodologies and approaches continue to develop, as detailed in Chapter 2; different approaches will be appropriate in different scenarios (Judd et al., 2015). Hence this step is intentionally less prescriptive to enable methodologies, current and emerging, to be applied to different scales of organisation within the system.

CEA research is a rapidly evolving field and novel methodologies addressing interactions between activities and system functions are emerging (e.g. spatio-temporal effects of environmental drivers and fishing on food webs; Coll et al., 2016). CEA approaches are available that provide explicit guidance to deal with the uncertainty inherent in CEA to derive evidenced risk-based outcomes (Stelzenmüller et al., 2018). Numerous relevant methodologies seek to identify cumulative effects operating at different biological and ecological scales (reviewed in Hodgson and Halpern, 2018). Furthermore, experimental research into interactions between stressors and receptors continues to provide critical insights into the prevalence of nonlinear responses and system feedbacks (Muthukrishnan and Fong, 2014; Thrush et al., 2014). Recent advances in modelling and statistical analysis are also enabling large datasets to be analysed to identify hierarchies of stressors influencing receptors (Feld et al., 2016; Teichert et al., 2016). To benefit from the plurality of methods available, step one, preparation, is key, to establish consistent practice between assessments and to enable coherence at a strategic level.

Where there is a pressing need to assess a CEA question and where uncertainties are hazardous, risk-based approaches (e.g. Judd et al., 2015; Stelzenmüller et al., 2018) become essential. Clarity and transparency within the CEA process are equally important and assumptions about the weight of focal activity effects relative to other activities and of the potential for non-linear effects (e.g. synergistic, antagonistic or surprise effects) should be specified and documented by CEA practitioners. Regulatory input is recommended to enable consistent approaches to weighting across sectors and activities.

Step six, broader context, requires a regional perspective, hence the involvement of and leadership by regulators is suggested to be essential. This step is intended to integrate the discrete CEA into the context of management and planning scales, and into context of the wider social-ecological system. To enable coherence, consistent approaches to defining future scenarios, management objectives and monitoring programmes are required. A regional perspective is required to make best use of future scenarios, which are an underused resource for EIAs (Duinker and Greig, 2007) and for exploring consequences of different courses of planning and strategic direction (Blenckner et al., 2015; Harris et al., 2014). Formal approaches to scenario development are well established (Duinker and Greig, 2007) and regional scenarios may support communication efforts to gain political and public commitment to sustainability by providing evidenced alternative future scenarios where trade-offs can be explored.

The end-point of the CEA pathway is intended to be an assessment that provides marine policy-makers, managers and planners with information that can be put into the broader context to determine if a development or activity poses a significant risk to the status or condition of a receptor, and to the connected system. an individual CEA is determining significance, whether the risk posed to receptors and system components by a development or activity is acceptable relative to defined objectives. Rather than being a conclusion reached by the proponent of an activity or development, it is suggested here that regulators should be required to determine significance, mindful of social equity, ecological integrity, and economic vitality.

4.9 Conclusions

The drive to extract greater economic returns from the oceans and the degraded state of many marine ecosystems makes progress in managing cumulative effects essential. Inconsistencies between CEAs driven by the regional (e.g. MSFD) and project-level (e.g. EIA) legislation need to be dealt with to efficiently reduce cumulative effect uncertainties, and to meet legal obligations to assess cumulative effects at regional and local levels. Methodological consistency between CEAs stimulated by different legislative drivers is challenged by the flexibility of approach required to assess, measure and manage cumulative effects in complex social-ecological systems. This complexity requires reductionist CEAs, but these CEAs require a regional, holistic perspective to provide the broader context required to manage cumulative effects. Hence the chapter proposes that meaningful CEA comprises two components: SCEA, a strategic process that informs and is informed by the second component: reductionist CEAs that assess the effects of discrete activities and developments.

To enable coherence where methodological consistency is unlikely, a general perspective of CEA is was proposed. Given the sustainability imperative, social-ecological systems thinking and system resilience are argued to be important foundations from which to define common ground for CEAs and underpin the perspective. The general perspective proposes a common conception of CEA that comprises a strategic process and individual CEAs that inform the strategic process.

The perspective and the research completed in the preceding chapters were brought together to propose principles for improved CEA, and to develop a CEA pathway that is intended to enable ‘better’ CEA in scenarios where EIAs are required. ‘Better’ is defined relative to the need to assess how developments and activities impact the interactions between receptors and social-ecological systems.

The next chapter seeks to investigate whether data and approaches exist that could be used to populate the CEA pathway. The subsequent chapter, Chapter 6, uses a case study to investigate how the data and information gathered in Chapter 5 can be applied to step 5 of the CEA pathway, assessing cumulative effects. The aim is to test whether the CEA pathway could be put into practice and then to test whether data collected for the pathway could be used to assess cumulative effects.

5 Testing the availability and appropriateness of data to populate the CEA pathway.

5.1 Introduction

The CEA pathway proposed in Chapter 4 is intended to be a practical alternative to CEAs completed as part of the EIA process. To be practical, appropriate data and information need to available that could be applied to implement the CEA pathway. To support consistent practice, there should also be broad agreement about how to apply the data and information to assess cumulative effect questions.

As a first step to testing the practicability of the CEA pathway, this chapter investigates whether data and information exist that would support implementation of the CEA pathway. The hypothesis tested was that appropriate evidence and approaches are available to populate the steps in the CEA pathway. The investigation also sought to identify where a paucity of evidence and/or appropriate methodologies would be problematic and, hence, where obstacles to implementing the CEA pathway may lie.

An assumption is made that if data are available to populate the CEA pathway, the CEA pathway would result in a more meaningful analysis than those typically encountered in EIAs and SEAs. The rationale behind the assumption is that a CEA approach grounded in CEA theory, as discussed in Chapter 2, is likely to result in improved CEA in comparison to CEAs that accompany planning assessments of projects and plans. An initial test of how well this assumption stands up to scrutiny is presented and discussed in Chapter 6.

Time and resource constraints for the thesis required a pragmatic approach to testing the CEA pathway be adopted. Hence, a case study was identified, and a tractable cumulative effects question defined to provide context and boundaries for gathering data.

5.2 A cumulative effects case study

The case study is the development of offshore wind farms in English waters of the Southern North Sea (Figure 17). The region is a good example to study in a cumulative effects context, as the number and size of offshore wind farms (OWF) permitted, constructed and operated[6] has been increasing over time, as have uncertainties about the associated cumulative effects (Marine Management Organisation, 2014, 2013). OWFs have increased in size from Round 1 (feasibility-scale, <10km^2, <12 nautical miles offshore) to commercial-scale projects in Round 2, and to substantially bigger Round 3 developments (Figure 17).

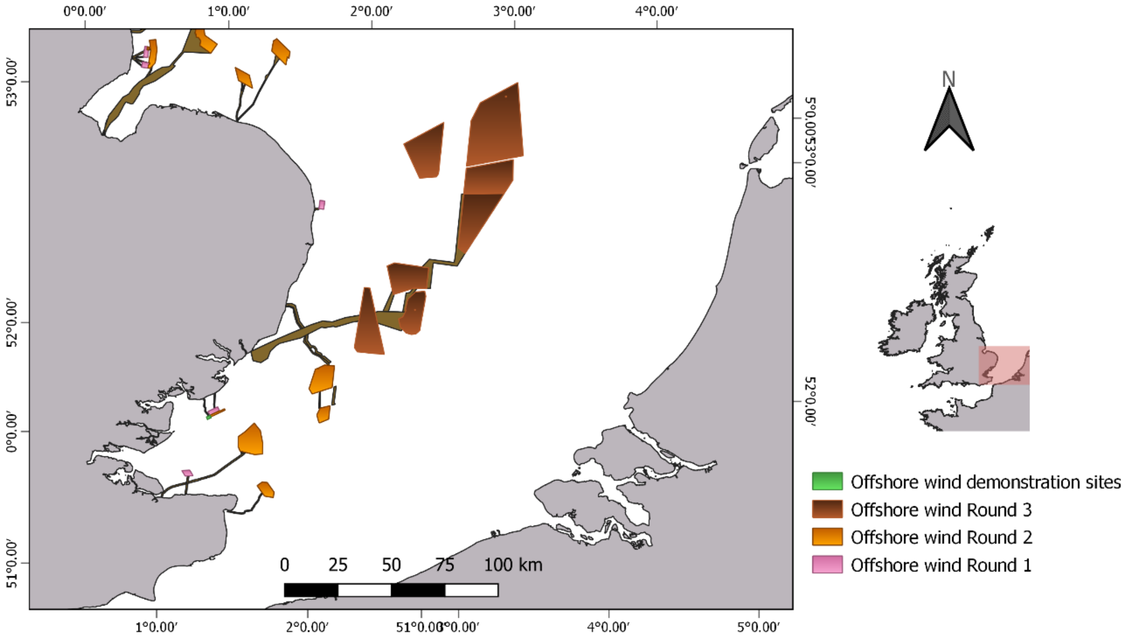

Figure 17. Map showing the increasing scale of offshore wind farms as development rounds progressed from 1 to 3. Data: OSPAR & MMO

The consenting process for Round 2 required substantially more time and cost per OWF than Round 1, with Round 2 OWF requiring between 15 and 43 months to be consented (Hawkins et al., 2014). The increasing scale of proposed

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[6] No offshore wind farms in the region have passed through the final stage in the lifecycle of a development, decommissioning, which will associated with positive and negative impacts depending on different stakeholder perspectives (Kerkvliet and Polatidis, 2016).

developments has coincided with a more precautionary perspective adopted by decision-makers in light of increasing awareness of potential cumulative effects on legally protected sites and species (Hawkins et al., 2014). As a result, the 540MW Docking Shoal project was refused consent in 2012 and cumulative effect uncertainties have become a dominant concern for regulators and developers as OWF increase in size (Hawkins et al., 2014). Uncertainties about MRED cumulative effects are a barrier to investment (Hawkins et al., 2014; O'Hagan, 2012; Wright, 2015), financially costly (Hawkins et al., 2014) and legally risky (Judd et al., 2015; Schultz, 2012).

The argument put forward in this thesis is that i) reducing MRED cumulative effect uncertainties is necessary before the consenting process is relaxed; ii) that reducing the uncertainties requires a CEA mindset, *sensu* Sinclair et al. (2017) and a social-ecological systems mindset. That is, project-specific effects need to be put into context of the cumulative effects load acting on receptors to assess what impact proposed additional human activities will have on receptors. The case study thus focuses on a known cumulative effects uncertainty: the effect of OWFs, specifically the noise generated during the construction phase, on the Atlantic herring (*Clupea harengus*). The justification for this focus is set out below.

The effects of underwater noise on marine ecosystems is an area of high uncertainty and underwater noise levels have been increasing for decades (Merchant et al., 2016; Slabbekoorn et al., 2010). Anthropogenic noise has primarily been researched in context of marine mammals (Slabbekoorn et al., 2010), but there is increasing evidence that indicates anthropogenic noise (including sound pressure and particle motion) negatively affects fishes and invertebrates with consequences for social-ecological systems (Hawkins and Popper, 2016; Popper and Hawkins, 2018; Slabbekoorn et al., 2019, 2010). Offshore wind farms are contributing to local and regional marine noise budgets, particularly during periods of impulsive piling (Merchant et al., 2017).

Herring are highly sensitive to noise energy as a result of the specie's physiological structure (Hawkins and Popper, 2016; SoundWaves Consortium, 2013). Evidence exists of strong behavioural responses by herring to impulsive noise, with Slotte et al. (2004) observing a reduced abundance of herring up to 37 km from seismic surveys. Evidence also exists that impulsive piling results in an absence of adult and juvenile herring that avoid the area for the duration of piling (BSH and Federal Ministry for the Environment, 2014; Perrow et al., 2011). With sound levels from impulsive pile driving reaching 261 dB, hearing specialists such as herring, may 'hear' offshore wind farm piling up to 80 km away (Thomsen et al., 2008).

Concerns about OWF noise impacts on herring have led to consenting delays and additional monitoring costs (Hawkins et al., 2014). Impulsive piling timing restrictions were imposed on the earliest OWF close to spawning grounds, but were relaxed for later developments, as surveys completed by the project proponents observed low abundances of herring (Cefas, 2009a), despite this perhaps indicating an issue with the stock and hence greater sensitivity to further human activity. The concerns raised in Chapter 3 about how effective project-level OWF assessments are suggests that the cumulative effects of OWF on herring remain uncertain.

Given the size of herring stocks and the wide distribution of the species, a valid question is whether a single human development or activity could negatively impact herring. Herring in the North Sea has a long history of exploitation and management and are a critical component in the North Sea ecosystem. The lifecycle of herring covers vast spatial scales, but stocks are associated with specific spawning grounds (Figure 18). Herring mature at 2-3 years of age, aggregate in high densities at specific locations at specific points in time, and produce masses of adhesive, heavier-than-water eggs that adhere to gravel or sandy gravel substrate (Dickey-Collas, in Petitgas, 2010). Transparent larvae hatch from the eggs after 3-4 weeks depending on water temperature and larval herring drift with the currents until metamorphosis, whereupon juvenile herring appear to remain in nursery grounds until about 2-years of age (Dickey-Collas, in Petitgas, 2010). This lifecycle results in potential bottlenecks, areas and periods when stocks of herring are vulnerable to human activities in addition to the fishing pressure put on stocks, particularly to activities that disturb spawning grounds and times (ICES HAWG, 2018).

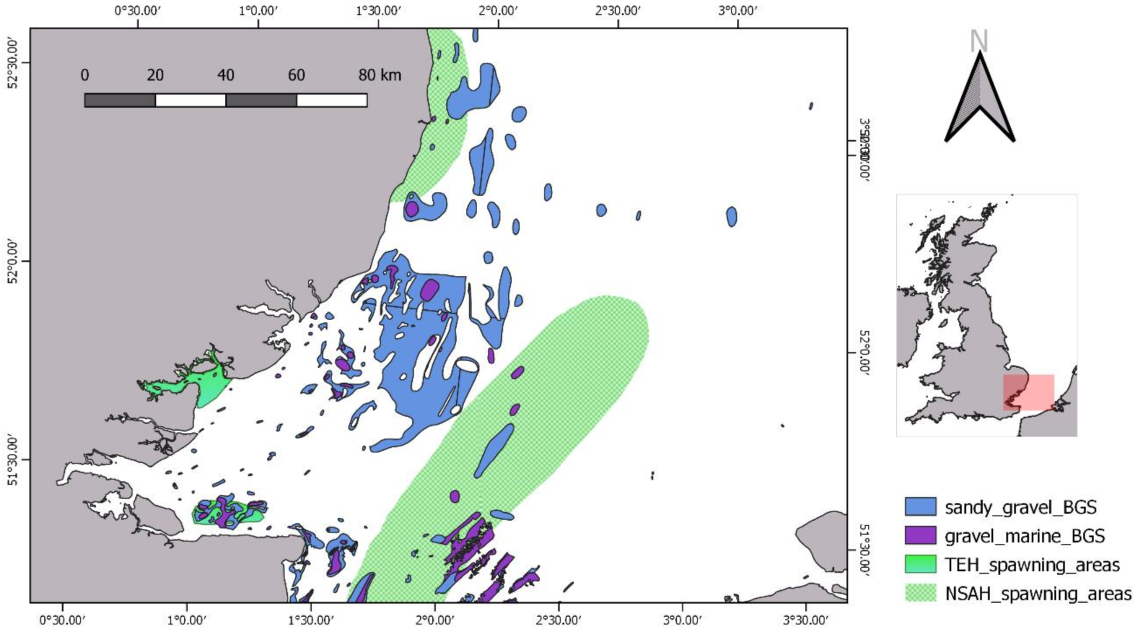


Figure 18. Extent of herring habitat within the case study area showing spawning grounds for the two stocks included in the case study and the known distribution of substratum associated with herring spawning. Data: Cefas & BGS

Within the case study area, there are two distinct stocks, the North Sea Autumn Spawning herring (NSAH), and the Thames estuary herring (TEH) (Dickey-Collas, in Petitgas, 2010). NSAH includes numerous substocks, including the Downs spawning component that spawns in Southern Bight of the North Sea and in the English Channel (Denis et al., 2016). The Downs spawning component aggregates in dense shoals at spawning grounds in the winter months (Nov-Jan) before adults continue along the migration route that is suggested to travel anticlockwise up to the northern reaches of the North Sea (Dickey-Collas, in Petitgas, 2010).

Thames estuary herring spawn in spring, from late February to early May, with spawning probably governed by water temperature (Wood, 1981). The extent of the spawning grounds for TEH is small (Figure 18) The major spawning site is thought to be the Eagle Bank slightly offshore from the mouth of the River Blackwater in Essex with a second spawning area north of Herne Bay in Kent

(Wood, 1981). TEH enter the case study area in abundance in October when it is targeted by inshore vessels from local ports (Wood, 1981). This historical pattern is still relevant, as indicated by landings statistics obtained from the MMO for the port of Southend, where a nearshore fishery targets the Thames estuary herring stock during the winter months (Figure 19).

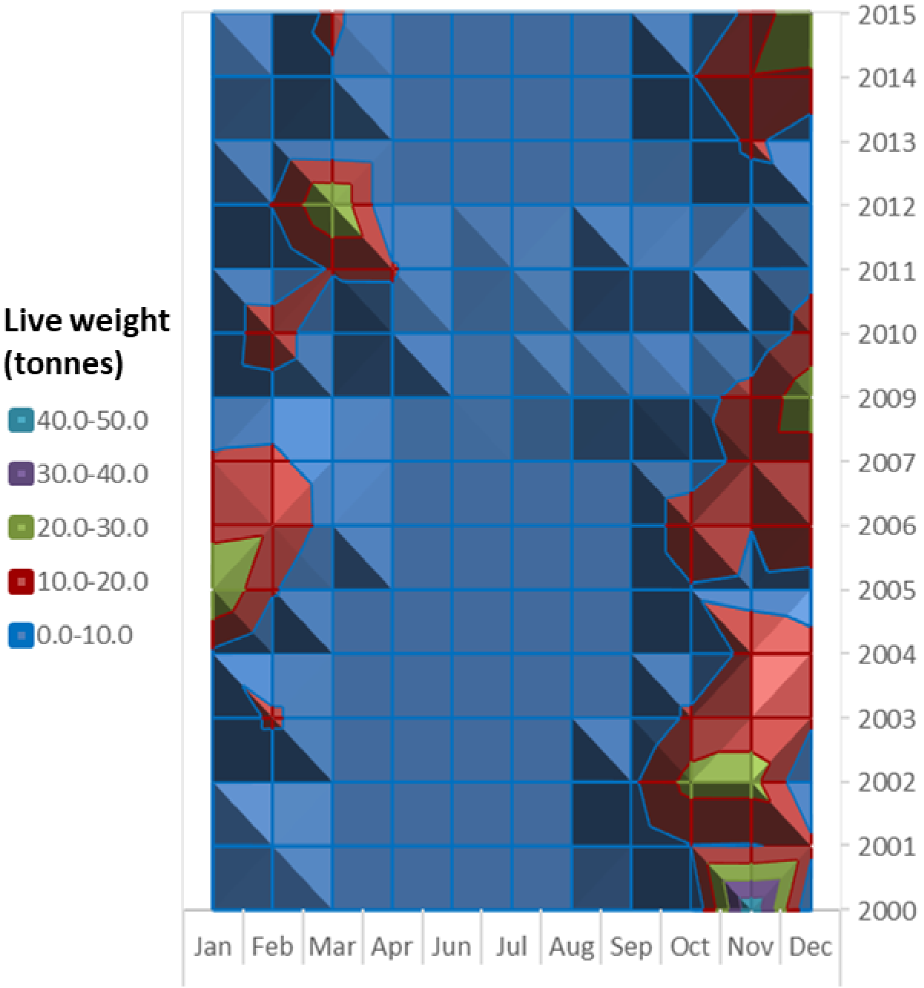


Figure 19. Contour chart of live weight of herring landed into Southend where a small-scale fleet targets the Thames estuary herring showing the seasonal presence of the species in the case study area (Data: MMO)

Herring stocks in the North Sea have long supported industrial and small-scale fisheries originating from the coastal states that bound the North Sea and are of cultural importance for many coastal communities. In addition to fishing, the North Sea hosts a range of human activities that directly affect herring stocks, including aggregate extraction, shipping, seismic surveying and OWF. Herring stocks are critical to the North Sea ecosystem (Mackinson et al., 2007). The North Sea ecosystem is suggested to be a wasp-waist ecosystem (Fauchald et al., 2011), where herring and a limited number of other small, planktivorous fish species dominate the intermediate trophic level and whose variability can strongly influence higher and lower trophic levels in the ecosystem (Bakun, 2006; Fauchald et al., 2011). Modelling of Alaskan marine ecosystems, where herring are an important component, point to changes in the intermediate trophic levels having the greatest effect on other trophic levels (Livi et al., 2011). Experimental data from the UK supports this modelled result, with the absence of herring caused by impulsive piling at Scroby Sands offshore wind farm resulting in a complete recruitment failure in 2004 at an important breeding colony of a protected seabird (Perrow et al., 2011).

How significant offshore wind farm expansion is for herring remains an open question, though one that has received less attention than impacts on protected species. In the case study area, there is additional impetus to study the effects, as the small spring-spawning stock, the Thames estuary herring (THE), is associated with very localised spawning grounds (Roel et al., 2004; Wood, 1981; and see Figure 18) and the stock appears to be in poor condition (Figure 20). Of concern, a comparable spring-spawning population in Scandinavian waters has been declared extinct (ICES, 2014).

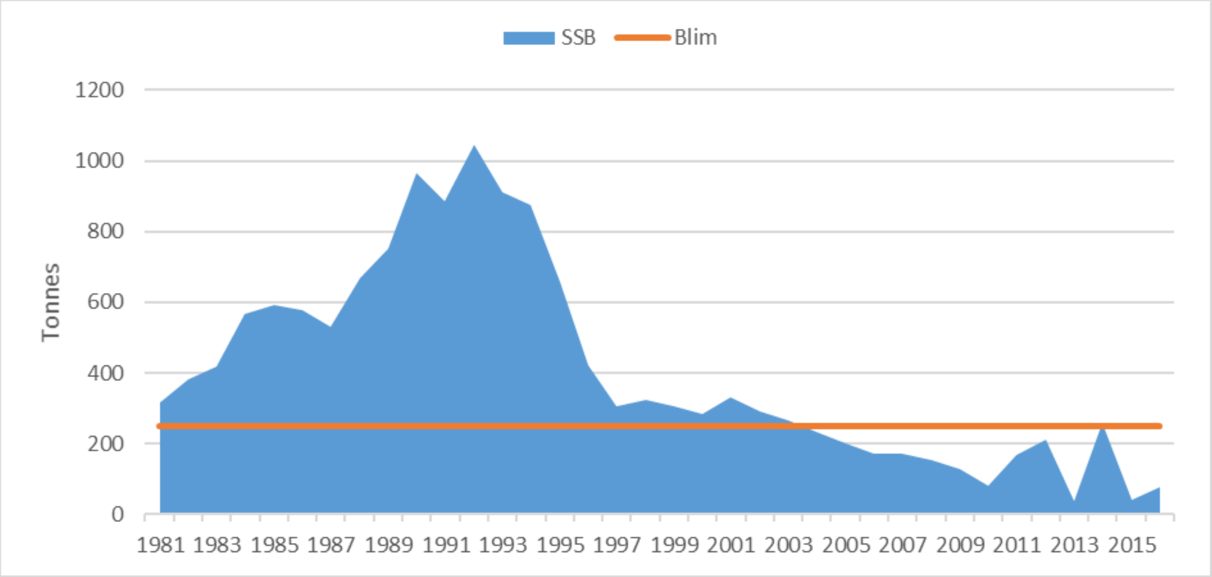


Figure 20. Spawning stock biomass of Thames estuary herring (1981-2016, data from L Readdy, Cefas) and B_{LIM} set at 250 tonnes (Roel et al., 2004). SSB has been below B_{LIM} since 2004 indicating the need for management intervention.

The case study thus seeks to investigate whether there is a risk that offshore wind farms could cumulatively impact herring stocks in the study area with an effect on herring resilience. This question is lent weight by the ICES advice that "activities that have a negative impact on the spawning habitat of herring should not occur, unless the effects of these activities have been assessed and shown not to be detrimental" (ICES 2015). The outstanding uncertainty about the significance of offshore wind construction on herring indicates that the ICES advice has not been applied.

Given that the test of data availability and appropriateness is limited to one human activity, one stressor and one species, it is reasonable to ask if this a CEA. The argument put forward here is that this is a valid CEA, firstly as the proposed human activity poses a risk to the receptor identified, which occupies a critical part of the local and regional socio-economic system. The cumulative effect uncertainty relative to herring warrants effort being expended (Step 1.4 of the CEA pathway). Secondly, the intention of the CEA pathway is that outputs of CEAs that follow the pathway will be comparable, enabling marine managers and planners to consider outputs of discrete CEAs with a strategic perspective.

Hence, in theory, the CEA scenario tested here could be combined with CEAs of other human activities. Thirdly, the CEA pathway includes steps that specifically address key CEA considerations discussed in Chapter 2 and which are not observed in assessments for projects and plans (Foley et al., 2017; Glasson et al., 2012; Jha-Thakur and Fischer, 2016; Therivel and Ross, 2007). Methodology

5.3 Methodology

5.3.1 Evaluating the availability of evidence for the CEA pathway

To test whether appropriate evidence and approaches are available to populate the steps in the CEA pathway, the evaluation process shown in Figure 21 was applied.

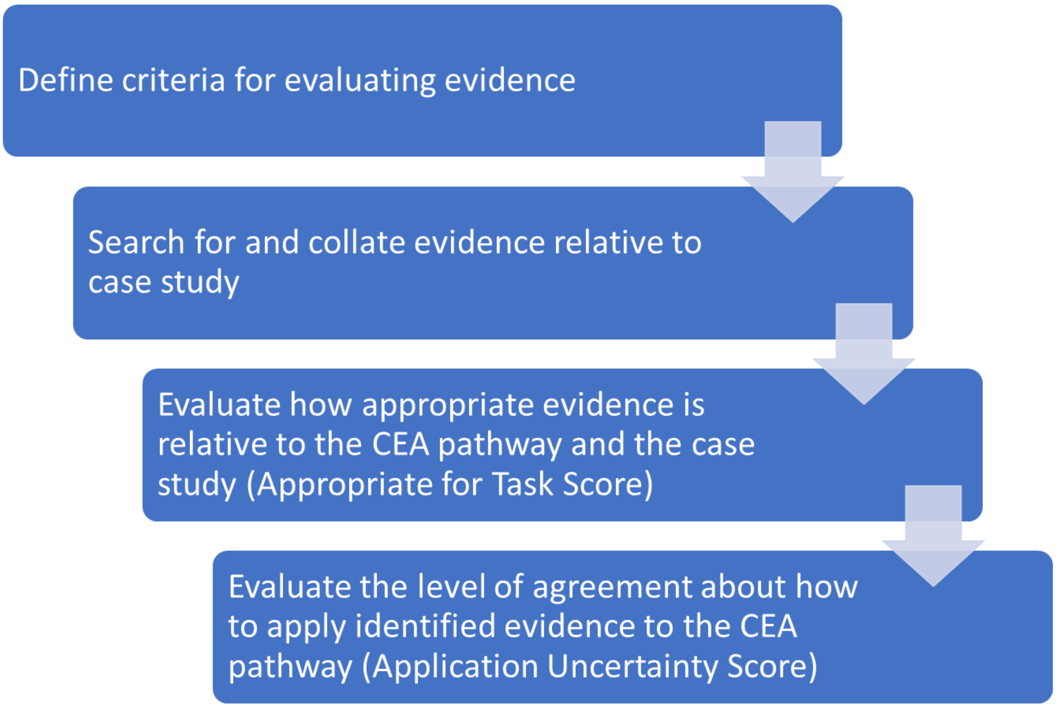


Figure 21. The process applied to test whether existing data and information are evidence is suitable and can be applied unambiguously to support putting the CEA pathway into practice.

5.3.2 Defining evaluation criteria and scoring

To evaluate whether data and information exist that would support implementation of the CEA pathway, six criteria were established:

1. *Sufficiency of data/information for each step.* The CEA pathway relies on data and/or information being available for analysis to produce the outputs that feed into the subsequent steps. The first criterion considers whether data/information identified qualifies as sufficient to attempt each step.
2. *Information quality.* The quality of data/information can have a considerable influence on the results of CEAs (Stock and Micheli, 2016) warranting inclusion of a criterion that considers the how rigorous and credible the evidence found is.
3. *Accessibility.* Access to data/information has been identified as a challenge for CEA (Foley et al., 2017; Judd et al., 2015). Hence, the accessibility of data/information identified was assessed, whether the information was opensource or known by not available.
4. *Temporal resolution.* Temporal information is one of the key CEA considerations (Chapter 2), hence a criterion was included to evaluate the temporal resolution of data/information identified.
5. *Spatial resolution.* Spatial information is one of the key CEA considerations (Chapter 2), hence a criterion was included to evaluate the spatial resolution of data/information identified.
6. *Application uncertainty.* The CEA pathway includes concepts that lack agreed definitions and performance measures, such as resilience (Gibbs, 2009), hence a criterion was included to consider if uncertainties about how to apply the evidence identified are manageable or impede progress.

The description used to guide scoring of the evidence against each criterion is shown in Table 9. A qualitative assessment of the evidence relative to the criteria to derive a score from 0-2, where 0 reflects weak or inadequate evidence, and 2 indicates strong or adequate evidence relative to the information requirements of each step of the CEA pathway.

Table 9. Criteria and scoring rationale applied to the evaluation of existing information and data for the CEA approach.

Criteria	Description	Scoring
1. Sufficiency of data/information available relative to step	Does the data/information specifically address the need identified in the step? Are the data/information available sufficient and appropriate for delivery of the required output?	0 - insufficient 1 - enables progress 2 - sufficient to fulfil step
2. Information quality	Are the data/information available scientifically/technically rigorous and credible?	0 – low confidence 1 – medium confidence 2 – high confidence
3. Accessibility	Are the data/information easily accessible for use in the step?	0 - not available 1 - restricted access 2 - accessible
4. Temporal resolution	Are the data/information of appropriate temporal resolution for the step?	0 - inadequate for step 1 - historical or low resolution 2 - current and ongoing
5. Spatial resolution	Are the data/information of appropriate spatial resolution for the step?	0 - inadequate for step 1 - low resolution or close proximity 2 - directly applicable to study area
6. Application uncertainty	What are the uncertainties associated with the application of existing information/data to the step? What degree of ambiguity exists about appropriate methodologies to complete the step?	0 = multiple/critical 1 = limited/important 2 = manageable/non-critical

To represent the strength or weakness of evidence found and of the level of acceptance/uncertainty about how to apply the evidence, a traffic light scheme was applied (Figure 22). Criteria 1-5 were aggregated to provide an ‘appropriate for task’ score and criterion 6 provided an ‘application uncertainty’ score. The ‘appropriate for task’ score is a composite score reflecting the average score of five criteria scores: i) the qualitative review of whether information available is sufficient to deliver the output required, ii) the quality and iii) accessibility of the information, and iv) the temporal and v) spatial resolution relative to the case study. Where decimal numbers result, scores were rounded up to one decimal place and scores were placed into one of five scoring bins (Figure 22). A descriptive summary of evidence and the sources of information identified were recorded in a table, which is included in the Appendices (Table A-1).

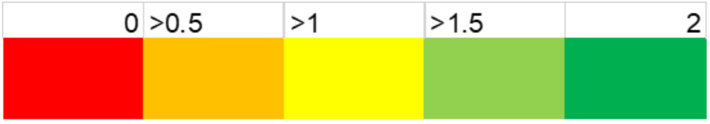


Figure 22. Traffic light scheme applied to the evaluation scores providing a graduated indication of where the CEA approach is operational now (green) or where further investigation (data or research) is required (red).

The ‘application uncertainties’ score reflects a qualitative assessment of the clarity with which an appropriate, defendable methodology can be identified that could be applied to complete each step in the approach. Uncertainties relating to the application of information identified and/or to the identification of an appropriate methodology were classified using the typology developed by Skinner et al. (2014), included in Table 10. The typology was developed following a review of 171 peer-reviewed environmental risk assessments and categorises uncertainties to support consistent identification across assessments and to support consistent qualification of statements about risk (Skinner et al., 2014). There is research that reviews methodologies that are appropriate to resolve various uncertainties (e.g. Cardenas and Halman, 2016; Leung et al., 2015), however the typology developed by Skinner et al (2014) provides an important preceding step, which is the consistent identification of uncertainties, to then support consistent treatment of those uncertainties.

The uncertainty typology from Skinner et al. (2014) was applied to the evidence identified to consistently classify data/methodological uncertainties observed, and hence to score how critical or manageable uncertainties were relative to completing each step of the CEA pathway. Identifying and classifying the uncertainties was also undertaken to seek to determine where future research is needed to support implementation of each step and of the CEA pathway. Uncertainties were classified and recorded in a table, including a descriptive summary of the appropriate for task score for each step. This information is included in Table A-3 in the appendices, together with identified improvements and enabling mechanisms to support progress for each step (Table A-4 in the appendices).

Table 10. Typology of uncertainties in environmental risk assessments developed by Skinner et al. (2014).

Nature	Location	Sub-location	Definition
Epistemic	Data	Availability	Referring to the incompleteness, scarcity, or absence of data
		Precision	Concerning the lack of accuracy or precision in obtained data
		Reliability	Reflecting its trustworthiness i.e. data is erroneous for some specified reason
	Language	Ambiguity	Where multiple meanings are possible
		Under-specificity	Where meanings are not clear and understandable
		Vagueness	Where meanings are not exact
	System	Cause	Concerning a lack of clarity regarding the source(s) of harm
		Effect	Relating to the influence a particular stressor (source) has upon the receptor(s)
		Process	Where the risks are not understood or a process vital to a successful assessment is not identified
Aleatory	Variability	Human	Results primarily from intentionally biased and subjective actions, but extends to all qualities of humans which are, either literally or from the viewpoint of the risk analyst, stochastic in nature
		Natural	Pertains to the stochastic traits of natural systems
	Extrapolation	Intraspecies	Where information specific to members of a species is used to represent other members of the same species
		Interspecies	Where information specific to members of a species is used to represent members of a different species

Nature	Location	Sub-location	Definition
		Laboratory	Where information specific to laboratory conditions is used to represent real-world scenarios
		Quantity	Where information specific to one quantity is used to represent another where
		Spatial	Where information specific to one spatial scale is used to represent another
		Temporal	Where information specific to one timescale is used to represent another
Combined	Model	Structure	Concerning the representation of real-world processes in model form
		Output	Reflecting the level of confidence in the produced results
	Decision	Decision	Where doubt surrounds an optimal course of action, often in the face of differing objectives.

5.3.3 Finding and collating data and information

Using the case study to provide context, online searches were conducted to identify sources of qualitative information and quantitative data pertinent to each step. Online data resources held by reputable sources (Cefas, International Council for the Exploration of the Seas, OSPAR, Marine Management Organisation, the Crown Estate, and the European Union European Environmental Agency) were interrogated for relevant datasets and reports. Insights into spatio-temporal trends in the focal receptor (*Clupea harengus*) were obtained from landings data for UK vessels, obtained via Environmental Information Requests submitted to the Marine Management Organisation (MMO). Data on the Thames estuary herring surveys was obtained from the internal Cefas database and discussions with L. Readdy (Cefas) and B. Roel, who were researched and analysed the Thames estuary herring stock, led to additional data and information being obtained. Searches of scientific literature databases (e.g. Scopus) were undertaken to identify peer-reviewed literature pertinent to the case study and which yielded information that provided insight into the availability and suitability of information to complete the steps of the approach. The resulting repository of information and data were then available for evaluation.

To structure the evaluation, an Excel spreadsheet was developed and populated to record what evidence was judged to be relevant to each step and why, the uncertainties identified based on the environmental risk assessment uncertainty typology (Skinner et al., 2014), the sources of the information, and the scores for each of the 6 criteria. Improvements/enabling mechanisms relative to the evidence found and to each step of the CEA pathway were also recorded.

5.4 Results

The output of the evaluation is a graphical representation of the appropriate for task and application scores for each step. A traffic light colour scheme (Figure 22) indicates where existing evidence is sufficient to implement the steps of the CEA pathway (green colours) or where attention is required to improve the data and information available to each step, and/or where investigation is required to clarify how to apply data and information (red and orange colours). Descriptive summaries of the information/data identified, and individual criteria scores are included in Appendix A.1, Evaluation results.

Figure 23 presents the result of evaluating how appropriate is existing evidence to support each step of the CEA pathway in context of the case study and for the North Sea Autumn Spawning Herring (NSAH) and Thames Estuary Herring (TEH). Figure 24 presents the result of evaluating the uncertainties associated with the evidence and whether there is a high level of agreement or if there is a high level of uncertainty about what methodologies or approaches are suitable to process the evidence to complete each step of the CEA pathway. The evaluation results used to derive the scores presented in Figure 23 and Figure 24 are included in Table A-1, Table A-2, Table A-3and Table A-4 in the appendices.

The results of the evaluation relative to each step in the CEA pathway are described in the paragraphs following the two figures.

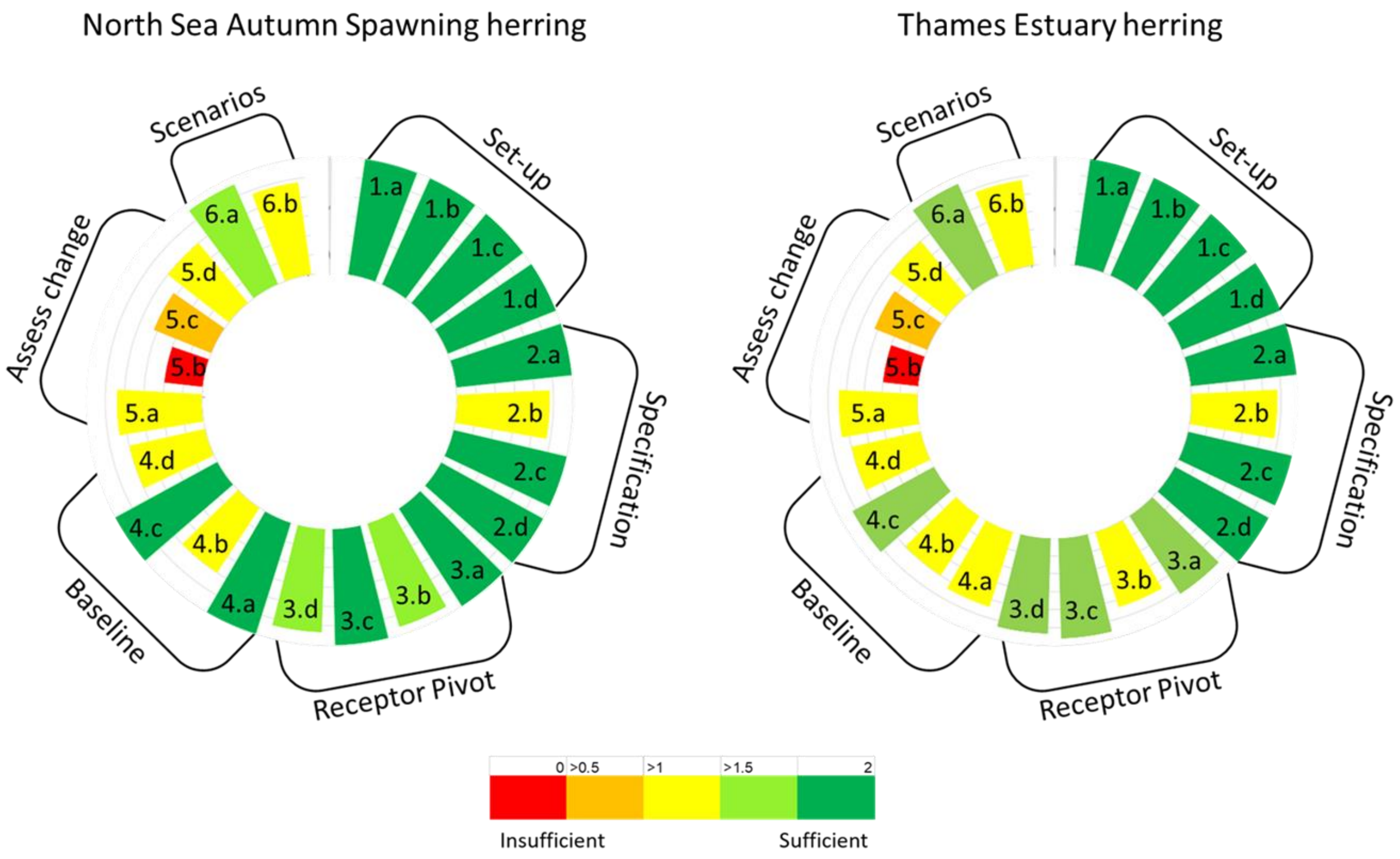


Figure 23. Scoring how appropriate is the evidence identified for each step of the CEA pathway in context of the two herring stocks included in the case study. Green indicates highly appropriate evidence is available for the step and red indicates an absence of evidence. Each column represents a step in the CEA pathway, e.g. 1.a = apply common language.

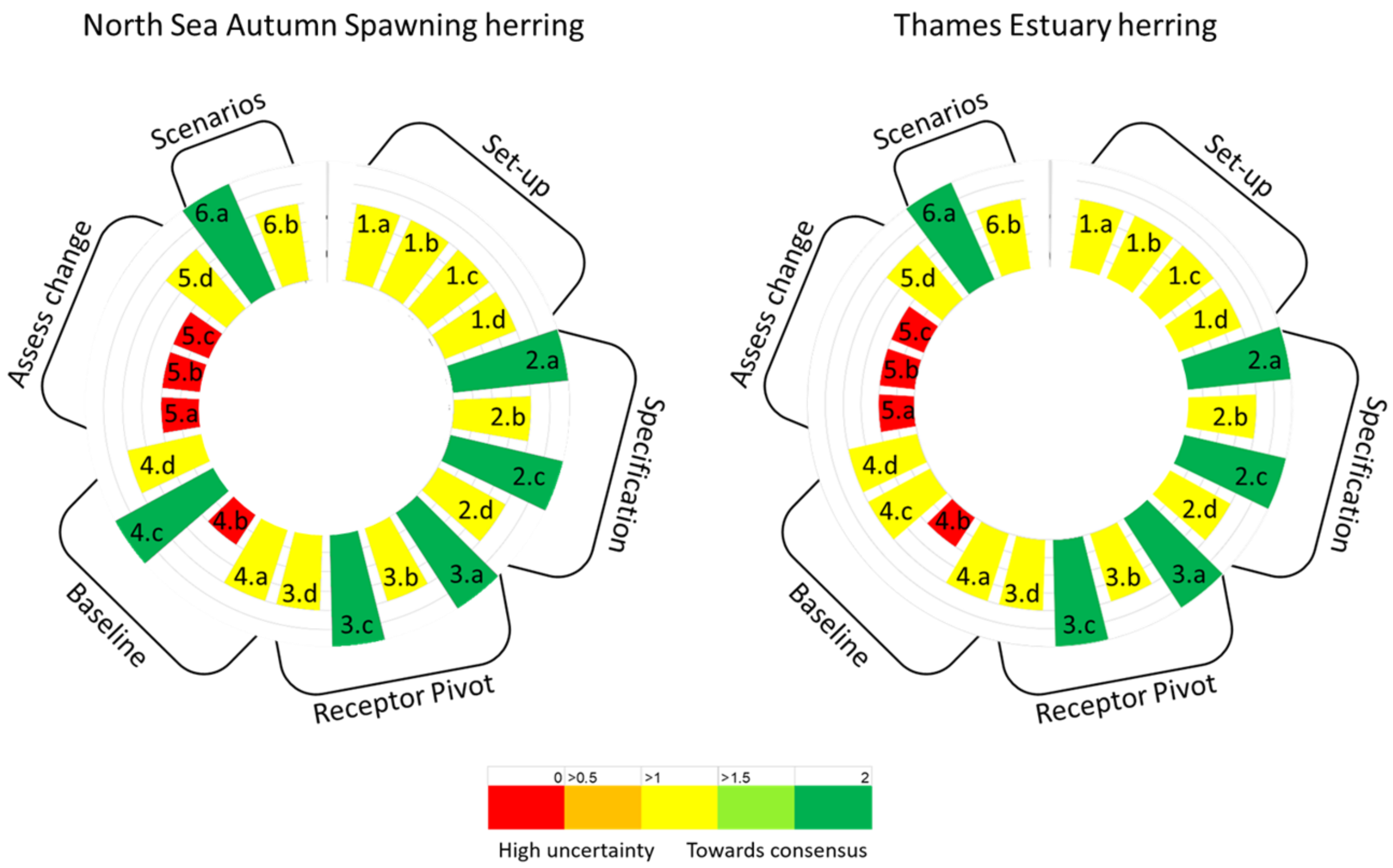


Figure 24. Scoring the level of uncertainty or agreement about how the evidence identified could be applied to complete each step of the CEA pathway for the two herring stocks included in the case study. Green indicates a high level of agreement about how to apply data/information relative to the step, red indicates a high level of uncertainty. Each column represents a step in the CEA pathway, e.g. 1.a = apply common language.

Step 1: Preparation. Evidence is available to support the steps in the preparatory phase, based on a robust literature base, suggesting that coherence between CEAs in terms of appropriate language, structured treatment of uncertainty and risk assessment principles is feasible now. Evaluating the application uncertainties for the preparatory phase steps resulted in lower scores, reflecting the multitude of definitions, typologies and possible approaches that could be applied to each step in this phase.

Step 2: Scoping. Evaluating the available evidence in context of the scoping step points to existing evidence being available that supports a more robust CEA scoping than was observed in EIAs evaluated in Chapter 3. Relative to the case study, the CEA problem can be clearly formulated and a logical process can be applied to progress from identifying the footprint of the effects associated with the focal activity through to the identification and characterisation of focal receptors (explored further in Chapter 6, section 6.3.1). Current Environmental Statements contain sufficient detail about development lifecycle processes to develop spatio-temporal footprints of the stressors generated by the activity (step 2.b). The precision of the information in terms of the temporal and spatial resolution of processes is variable, reflecting an engineering perspective rather than an ecological perspective. Where field or laboratory experiments are lacking, expert judgement is required to translate the processes into ecological effects and thereafter to put these effects into context of focal receptors. As with the preparatory steps, the challenge lies more in determining how to apply the evidence rather than the availability of evidence to support the steps.

Step 3: Receptor Pivot. Step 3 is the first step in the CEA pathway where differences in the ‘appropriate for task’ scores arise between the two receptor populations. Relative to the boundaries of the case study, the biological, ecological and economic characteristics can be derived from existing evidence for both populations. For NSAH, sufficient high quality information is available to characterise the lifecycle of herring, although detail about spatio-temporal patterns is lacking for overwintering adult North Sea herring (Dickey-Collas et al., 2010). There is reduced confidence in the evidence available to characterise

TEH, as specific surveys of this population ceased in 2007/8 and analyses of the health of the TEH stock have subsequently relied on landings data from the fleet targeting this stock. Hence, the lower ‘appropriate for task’ scores for TEH relative to NSAH (Figure 23). The evidence available supports identification of the interactions contributing to the productivity and resilience of the focal receptor populations, supporting the application of approaches to model the structure of system interactions, described in Chapter 6, section 6.3.2. The evidence identified included information about the human activities contributing to the cumulative effect load carried by the receptors. Endogenous and exogenous variables within and outside the system can be identified relative to the case study area, providing a rationale for setting boundaries, providing insights into which interactions and variables to include in the CEA.

Step 4: Baseline. Variations in the evaluation scores for Step 4 for the two herring stocks reflect the stronger evidence available for NSAH, where longitudinal surveys are ongoing and continue to feed into robust assessments of NSAH stock health (reviewed by Simmonds, 2009 and summarised in Table A-1 in the appendices). The availability of a long time-series of data to estimate SSB enables the identification of trends in the NSAH population (step 4.a). The inherent variability of herring populations results in fluctuations from year to year, but the length of period for which SSB data is available permits observation of longer-term trends (discussed further in Chapter 6, section 6.3.3). For TEH, the cessation of directed surveys and the reliance on landings data from the commercial fishing fleet to calculate SSB since 2007 results in a lower appropriate for task score relative to NSAH when establishing a baseline.

The time-series of population data (recruitment and SSB) for NSAH, together with catch data that provide insight into finer resolution spatio-temporal change in herring abundance, provide an evidence base from which to specify measures of resilience and resistance (Step 4.b). This relies on an assumption that SSB is an appropriate proxy that reflects the capacity of the herring population to maintain interactions with connected system components. The evaluation score indicates the need for further research to improve confidence in using SSB as a measure of resilience. Historical maps of spawning habitat and current substrate maps that identify the location and extent of substratum associated with herring spawning (gravel and sandy gravel) are available. No evidence was found, however, to identify which spawning grounds are active and to what extent. Historically, surveys were conducted of TEH spawning grounds (Wood, 1981), however the surveys have long ceased. Insights are limited into the connectivity of herring and spawning habitat, hence insights into how specific spatio-temporal disturbances such as offshore wind construction noise might impact resilience are limited. The uncertainties associated with putting resilience into operation and with applying the evidence results in high uncertainty for step 4.b.

For both herring populations, SSB limits have been identified below which there is a high risk that an abrupt change in the quality, property or state of the ecosystem component will occur, that is, ecological thresholds *sensu* Groffman et al. (2006) exist for the receptor populations to guide CEA. As thresholds are defined (NSAH) or can be inferred (TEH), resilience measures are arguably 'nice to have' rather than critical for the case study. For NSAH, the thresholds are unambiguous for CEA, with robust management reference points established that trigger management responses if the population status becomes precarious. For TEH, different SSB limits were concluded by Roel et al. (2004) and Wood (1981), and no research since 2004 was identified that has investigated how valid the recommended SSB limit remains some 15 years hence. Thus, there is greater uncertainty attached to the inferred TEH thresholds compared with the NSAH thresholds.

Evidence is available to support identification of trends in relevant key variables to include in the CEA (Table A-10, appendices). The key source of information is the MMO license registry that includes data about the location, start and end date of activities associated with licenses from 2002 to the present time, from which effect footprints could be estimated. Many more entries were observed in recent years suggests entries in early years may not capture all license applications in early years. Hence temporal analyses (such as sectoral activity by year) would have reduced confidence unless evidence to the contrary is obtained from MMO. Information about future trends (relevant to steps 4.c and 6.b) can be obtained from grey literature and scientific literature (References included in Table A-11), though the resolution of the latter is much reduced. For example evidence supporting the anticipated increase in rising levels of noise in UK waters (Merchant et al., 2016) is at a scale much greater than the case study area. Multiple sources of information were identified for each activity (Table A-11, appendices), with consistency in predicted trends, such as in shipping based on future scenarios published by the Port of London Authority and Lloyds of London.

Step 5: Assessing cumulative effects. In terms of the existing evidence base and uncertainties, the key weaknesses were identified in step 5. Evaluation scores were the same for both focal receptor populations. Application uncertainties are abundantly clear and stem from multiple levels of inquiry, ranging from conceptual (a lack of agreement about what are cumulative effects and thus what to assess), methodological and practical (how to assess the significance of cumulating stressors, how to assess the significance of an additional stressor). The evaluation identified evidence that could reasonably be applied to Step 5, for example to assess the magnitude and duration of change to cumulative effect load caused by the focal activity effects. However, to gain insight into the relative contribution of the focal activity requires the same CEA approach phases to be applied to other activities contributing to the cumulative effects load. Hence the evidence available to support steps 5.b and 5.c is lacking. Chapter 6 explores this issue further to investigate if specific approaches can make progress relative to the lack of evidence identified.

For both herring populations, evidence is insufficient to appraise multiple stressor effect interactions, whether cumulative effects may result in non-linear effects (step 5.c). Complex adaptive system theory and the complexity of herring and marine ecosystems suggest that non-linearity is the norm rather than the exception, but no information was identified to clarify what non-linear effects may be (such as synergistic or antagonistic, or of a surprise nature).

Step 6: Broader context. For the future scenarios phase, available evidence would support articulation of multiple alternative futures based on qualitative data for variables other than climate change predictions, where robust, peer-reviewed assessments are available to inform trends in variables such as sea surface temperature. As with preceding phases of the CEA approach, application uncertainties are more pronounced in comparison with the availability of evidence that could support the development of scenarios.

5.5 Discussion

The evaluation presented in this chapter set out to determine whether evidence currently exists that could be applied to the steps of the CEA pathway, as a first step to determining if the CEA pathway is practical. The second feature tested was whether there is high level agreement about how to apply the data and information to assess cumulative effects questions. The key result is that, relative to the case study, there is sufficient evidence available that is appropriate for the majority of the steps included in the CEA pathway, but that there is uncertainty regarding how to apply existing data. The hypothesis was thus true in that evidence and approaches current exist. There is, however, ambiguity about how to apply the evidence, including which methodologies for analysis would result in robust outputs.

The evaluation of evidence identified for Step 1, preparation, suggests that there is sufficient, appropriate data and information to produce guidelines for practitioners of environmental assessments of projects and plans. Information exists now that is peer-reviewed in credible scientific journals that could be applied to harmonise the language, characterisation of uncertainty and risk assessment approach to be applied to all CEAs within a management area. The key uncertainty identified relative to the evidence was ambiguity of language, rather than a paucity of sources of information. The challenge would be to decide which definitions from the literature to apply to the guidelines, which, it is suggested here, should be accompanied by a clear analysis of the concepts and values underpinning the definitions adopted.

Similarly, for Steps 2 and 3, scoping the CEA and the receptor pivot, there is sufficient evidence available to populate the steps based on data and information that already exists. The range of uncertainties identified about how to apply the data and information increases, including ambiguity and under-specificity of language, availability and precision of data, and decision uncertainties. Decision uncertainties exist where doubt surrounds the optimal course of action (Skinner et al., 2014). To increase confidence in decisions made where such uncertainties exist, triangulation with additional data sources and/or expert judgement may be warranted. The key point is that evidence was identified that would enable a more 'cumulative effects mindset' approach to scoping an assessment and characterising receptors, in comparison with the equivalent steps observed in the Environmental Statements evaluated in Chapter 3.

Data availability, specifically the lack of data, becomes a noticeable feature when evaluating collated data and information for TEH for Step 4 (baseline). For both herring stocks, evidence is weaker and the application uncertainties more pronounced as the pathway proceeds, notably in Steps 5 and 6. This is not surprising, as the CEA pathway introduces concepts that continue to be debated, including resilience (e.g. Donohue et al., 2016; Gibbs, 2009; Standish et al., 2014), thresholds (e.g. Groffman et al., 2006; Thrush et al., 2014), and the assessment of cumulative effects (e.g. Dibo et al., 2018; Foley et al., 2017; Jones, 2016). The case study included an information-rich receptor, *Clupea harengus*, that has been subject to study for decades and which continues to be researched both in relation to the species and to the ecosystem interactions (ICES, 2014). The uncertainties identified with respect to the CEA pathway and the case study seem likely to be encountered with most receptors and exacerbated with receptors that are less studied.

The differences in the scoring between the two receptors highlighted the importance of up-to-date knowledge about receptors. Differences between the two herring populations arise at Step 3, the receptor pivot, where there is higher confidence in NSAH data due to the ongoing and long-term surveying directed at this population. The loss of perceived value in the TEH population has led to a reduction in resolution in the data available to monitor and manage the population. Maintaining local diversity of fish populations is deemed critical to maintain the resilience of the herring meta-population and there is an extinction precedent from an analogous spring-spawning herring population in the eastern North Sea (ICES HAWG 2018). Given the increasing trend in maritime activities and the push for the blue economy, the shortfall in current data for this depleted stock is a concern. A further observation from the data and information collated was that recent research into the behavioural dynamics of NSAH, a long-studied stock of a much-researched species, point to findings that could have potentially significant effects on impact assessments. For example, decision-making by individual fish within a school may play an important role in determining the use or not of specific spawning grounds (Eggers et al., 2015). What level of detail is required to deliver meaningful CEA is an open question, though the inclusion in the CEA pathway of guidance to apply environmental risk assessment approaches provides an accepted means of dealing with uncertainties (Cormier et al., 2013; IRM, 2018).

Relative to the objective of the CEA pathway, the weaker evidence and greater application uncertainties observed in Step 5, assessing cumulative effects, present a challenge for putting the pathway into practice. Multiple scales of inquiry become relevant, in terms of scales linked to herring ecology, the number of potential interactions between the receptor and the social-ecological system, and the relative footprints of the effects of OWF and MREDs. The evaluation suggests that evidence and approaches exist that could be used to test if the more ambiguous steps could be attempted. This is the subject of the next chapter.

5.6 Conclusion

On the basis of this evaluation, there is a wealth of data and information that could be applied to the CEA pathway, but there is a critical need to reduce uncertainty about how best to apply the evidence to deliver a robust CEA. The challenges of implementing the pathway seem likely to increase as the CEA process moves into the latter steps, with the evidence required relying on robust outputs from preceding steps. Uncertainties therefore compound as the CEA pathway progresses and there is greater ambiguity and less specificity about how to apply the evidence collated in preceding steps. Potential approaches to investigate the more ambiguous steps were identified and are investigated in the next chapter applying the evidence collated for this chapter.

6 Applying the evidence to test the CEA pathway

6.1 Introduction

The previous chapter identified that for several steps in the CEA pathway, application uncertainties rather than a shortage of appropriate evidence were more problematic. Uncertainties were identified about what appropriate scales are for project-level assessments and hence the resolution of data required to create adequate baselines. Uncertainty arising from a lack of specificity about what methods or approaches could or should be used were also recorded. This introduces output uncertainties, where confidence in the outputs is reduced. As outputs are integrated into subsequent steps, as the CEA pathway progresses, there is the potential for uncertainties to compound. This chapter seeks to apply evidence collated to investigate how three procedural uncertainties could be addressed:

i) How to scope effects to include in a project-level CEA;
ii) How to define what receptor-system interactions to include in a project-level CEA; and,
iii) How to define appropriate spatio-temporal boundaries and baselines for a project-level CEA.

The outputs from the three investigations were brought together to support a rapid risk assessment that sought to test the null hypothesis that there is no signal of offshore wind farms in the two herring stocks.

6.2 Methodology

The aim of the research completed for this chapter was to assess whether approaches identified during the evaluation of evidence presented in the previous chapter could support application of the CEA pathway in practice. The two concepts tested include the benthic footprint concept (Miller et al., 2013) to develop activity-receptor footprints, and causal loop diagrams (Lane, 2008) to structure and communicate the interactions between the receptor and the associated social-ecological system. The outputs from these tests were combined with evidence gathered for the previous chapter to then investigate what an appropriate baseline would be, and whether a signal of offshore wind development could be identified in the receptor.

The aim was to deliver a proof of concept, rather than aiming for precision, hence expert judgement was frequently employed and, for the risk assessment section a rapid qualitative approach used. The methodologies used to test the concepts, to investigate appropriate baselines, and to assess the risk of significant cumulative change are described below.

6.2.1 Defining activity effect footprints

One of the key challenges for improving project/activity level CEA is how to communicate and promote focus on the broader spatio-temporal perspectives required to assess and manage cumulative effects. One potential tool is the benthic footprint concept defined by Miller et al. (2013), which could be adapted to create plots of the spatio-temporal footprint of human activities and to put this information into context of sensitive receptors. This approach could in theory be applied consistently across activity sectors to better understand the magnitude and duration of effects introduced into the environment by human activities (Miller et al., 2013).

The footprint concept can aid communication of the temporal and spatial scales of effects in one diagram. This is beneficial as the temporal component of effects relative to receptors is not well addressed in Environmental Statements, as observed in Chapter 3. The footprint concept can also aids a shift in focus away from individual stressors towards the receptor’s perspective of the consequent effects, as each footprint needs to be defined relative to the sensitivity of the receiving environment. A series of effect footprints will be appropriate for a development or activity, as the sensitivity of receptors to stressors and effects will vary. For example, the extent of the spatial footprint of underwater noise effects would vary between those species with physiological traits that increase hearing sensitivity (such as herring) and those without those traits. Clearly, the footprint requires *a priori* knowledge about how stressors are likely to translate into effects in relation to the sensitivity of valued receptors to those effects.

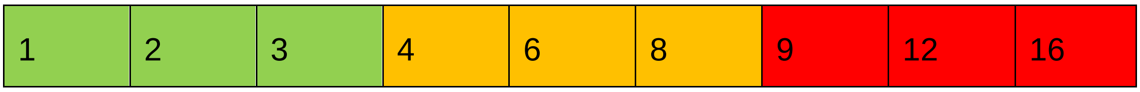
A concern raised by developers and EIA practitioners is proportionality, in the sense that the scope of an assessment should be proportionate to the risk of change (Hawkins et al., 2014). As well as testing the applicability of the footprint concept to the case study, the approach taken also sought to test how onerous the development of effect footprints would be for a development such as an OWF. To answer these questions, an Environmental Statement from those evaluated in Chapter 3 was reviewed, to identify the processes involved in the construction, operation and maintenance, and decommissioning phases of the lifecycle of an OWF. The spatio-temporal characteristics of the processes were estimated using expert judgement and using the information contained in the Environmental Statement. The aim of the test was to prove or disprove the concept, rather than seeking to achieve precision about the footprint generated.

The processes and characteristics identified were tabulated and categorised into lifecycle phases (construction, operation and maintenance, and decommissioning). Each lifecycle process is associated with multiple stressors or outcomes, many of which are analogous across processes. Distinct stressors/outcomes were identified and then categorised into ecological effect categories. Information about the processes and lifecycle stages that generate the stressors/outcomes were retained to enable identification of key processes in the lifecycle of an OWF relative to the receptors. To plot the footprint of OWF stressors/outcomes, the spatio-temporal characteristics of each were classified following a simple qualitative scale (Table 11**Error! Reference source not found.**). To test if the stressor/outcome footprints could be applied in context of receptors, a third dimension was added to the plots, cumulative effect risk, which was calculated by multiplying the estimated sensitivity of receptors to the stressor/outcome by the estimated likelihood that the receptor would be exposed to the stressor/outcome. Expert judgement was applied to classify the sensitivity and likelihood of exposure for the receptors for each of the stressors/outcomes. The criteria for the classification is shown in Table 11. Again, the aim here was to test the concept rather than to seek precision, hence the simplicity and low resolution (4 scales only) applied.

Table 11. Classification scales for variables used to generate the spatio-temporal effects footprint.

Scale	Spatial extent (square metres)	Temporal duration	Sensitivity	Likelihood of exposure
1	1 (highly localised)	Days (very short duration)	Insensitive (no evidence of sensitivity to effect)	None
2	100 (localised)	Weeks (short duration)	low sensitivity (evidence of sensitivity but no significant response)	Short (likely to be exposed but for a very short period)
3	1,000 (dispersed)	Months (long duration)	medium sensitivity (evidence of sensitivity and response)	Medium (likely to be exposed to effect)
4	10,000 (highly dispersed)	Years (very long duration)	high sensitivity (evidence of sensitivity and of strong response)	High (very likely to be exposed to effect)

The 4-point scale and two variables permits 9 potential cumulative effect risk scores, which were classified as low, medium and high risk using a traffic light scheme (Figure 25) to aid presentation of the results.



1	2	3	4	6	8	9	12	16

Figure 25. Range of possible cumulative effect risk scores and traffic light scheme applied to indicate low (green) to high (red) risk.

The cumulative effect risk score was estimated for four receptors: herring, seabirds, benthic productivity, and commercial fishing. Seabirds and commercial fishing are aggregated receptors, potentially including multiple species and fleet metiers respectively, and benthic productivity is an ecological function. Hence the additional receptors included may not be directly comparable to herring, herring being an individual species, but the intention was to test how the footprint approach performs when applied to a range of receptors that differ in terms of sensitivity to specific effects and likelihood of exposure.

6.2.2 Mapping system interactions and scales

The critical intent behind Step 3, the receptor pivot, is to shift away from the typical project and plan assessment approach of considering individual stressors acting on receptors, towards more comprehensive consideration of multiple factors contributing to the cumulative effects load carried by a receptor. This is intended to enable insight into how changes or additions to the cumulative effect load may influence the resilience and trajectory of receptors. Tools are therefore needed that aid management by integrating consideration of the structure and dynamics of the system associated with receptors into assessments, and hence to support identification of fragile interactions.

Causal Loop Diagrams (CLDs) are one potential tool that can be applied to define the system structure and variables relevant to a CEA. CLDs are a visual method that convey the variables and feedback structure in a model of a system (Lane, 2008). CLDs can act simply to articulate systems thinking and to examine the logic behind causal links by showing clearly the structure of assumptions describing a problematic situation (Lane, 2000). This is attractive for the CEA approach, to address the challenge of communicating cumulative effects acting on a system and to aid communication of assumptions about causal links between system components and the receptor.

Causal Loop Diagrams can also act as a framework to enable theoretical changes of interventions or disturbances to be examined and to see how the persistence of interactions within a system may be affected. CLDs indicate the (assumed) network of causes and effects between variables and, by specifying link polarities (the direction of effect that the influencing variable has on the influenced variable; Lane, 2008), the direct and indirect consequences of change can be considered (Lane, 2008).

To investigate whether CLDs can support mapping and definition of the system relevant to the receptor and to the CEA, evidence collated was used to characterise the receptor, *Clupea harengus*. Pertinent cause-effect interactions were identified and documented using the literature identified when collating evidence, which covered the receptor's lifecycle and relationships with human activities. This information was then used to develop a CLD using Vensim PLE (Ventana Systems, 2015). Vensim PLE is designed to develop causal loop diagrams and dynamic stock and flow simulations, and is also useful for identifying causal trees and feedback loops within CLDs. The aim was to investigate whether CLDs can function as decision-making support tools, by making explicit the structure, dynamics and assumptions relating to the focal receptor and its associated social-ecological system.

The CLD was also tested as a tool to aid the justification of the baseline and of the assessment of cumulative effects, by investigating if CLDs can aid qualification of which human activities and changing future conditions are influential for the receptor, and which are feasible to include in a project-level assessment. To this end, the characteristics of the interactions between variables included in the CLD were described. The description of spatial scale recorded whether the influencing and influenced 'ends' of the interactions were exogenic or endogenic relative to the case study area. The temporal characteristics were described as the temporal lag expected between an effect being experienced and the result manifesting in the metric used to measure the status of the receptor. The confidence in the evidence behind the interaction and characteristics were recorded along with supporting references. Finally, expert judgement was applied to estimate how influential the effects of identified receptor-system interactions are relative to the persistence of the receptor within the social-ecological system, to investigate the potential for CLDs to aid insights into impacts on resilience.

6.2.3 Justifying a baseline and boundaries

Defining appropriate spatial and temporal boundaries is a persistent challenge for CEAs, particularly EIA-led CEAs that typically define boundaries in context of the extent and duration of stressors generated by a development or activities. CEAs must better characterise receptors to justify what are appropriate spatial and temporal scales for the assessment. Datasets identified for the two receptors were combined with information identified about the processes and periods of offshore wind farm development in the case study area to investigate what boundaries and baselines could be deemed appropriate for project-level CEA.

For the spatial boundaries, the aim was to test how different sources of information could be combined to gain insight into the relative footprints of the activity and receptors being assessed and hence to investigate the difference between project-scales and receptor-scales. A GIS was used to display data on the locations of offshore wind farms in the study area, and areas known to be important to the herring stocks. 37km buffers around the offshore wind farms were created to represent the area ensonified by impulsive piling of wind turbine foundations. The extent of noise pollution will vary depending on how noise propagates away from the source, which is affected by, *inter alia*, pile diameter, hammer force, substratum and bathymetry (Hawkins et al., 2013). The sensitivity of receptors to noise and sound particle motion would also influence the spatial extent of a noise effect footprint. Empirical data of herring reactions to seismic surveying identified significantly reduced abundances of herring 37 km from the sound source (Slotte et al., 2004) and modelled data indicates piling can be heard by herring up to 80 km from the sound source (Thomsen et al., 2008). For the test, a 37km buffer was felt to be a reasonable spatial extent within which herring could be assumed to flee.

For the temporal boundaries, the aim was to test how evidence collated for the case study could be applied to gain insight into changes in the condition or status of the receptor and hence to infer how resistant and resilient the receptor would be to additional disturbances. Where data permits, CEAs must include an appropriate temporal period that enables identification of patterns and trends in the receptor, which covers the time over which effects would be expected to manifest in focal receptors, and which should inform monitoring and validation planning. The evidence collated for the previous chapter was used to create a time-series that indicates change over time in a suitable metric to infer changes in the condition of the receptor population, and which was of an appropriate spatial and temporal resolution for the case study.

For NSAH and TEH, data were obtained from the ICES species stock assessment database and from Cefas respectively. ICES data extend back to 1947. TEH SSB estimates were originally derived from annual stock-specific surveys conducted by Cefas from 1981 to 2007. The surveys ceased in 2007 due to a decline in the economic and political value of TEH (B. Roel, *pers. com*). Cefas developed a stock assessment tool based on landings data from sentinel fisheries (fleet metier: herring driftnet vessels) dotted around the study area (B. Roel, *pers. com*). SAS code was developed to correlate landings and spawning stock biomass for the years when SSB was estimated from fishery-independent surveys, and then used to predict SSB based on reported landings in years following the cessation of surveying (L. Readdy, Cefas, *pers. com*). SSB data for TEH was thus available for each year between 1981 and 2016. A caveat regarding confidence in the derived SSB data is the potential influence of the herring market price on fishing effort, whereby depressed prices reduce the cost-benefit of expending effort catching herring.

Spawning stock biomass time-series for the two herring stocks were created for the period 1981-2016. To see if a clear pattern was present, trend lines were added to the SSB time-series. To test for notable changes in variance, the percentage change in SSB on the preceding year was plotted. A second percentage change in SSB was calculated to investigate the effect of a 3-year time lag (% change year 4 in comparison with year 1), to see if any signals of disturbance to spawning herring were identifiable in the SSB time-series. All *Clupea harengus* are mature in their third year, hence a significant reduction in spawning success due to disturbance could be reflected in reduced recruitment into the spawning stock three years later. As a final test of variation in SSB time-series, percent coefficient of variation was calculated for the two herring stocks, for different periods that covered the whole time-series and periods when construction noise from offshore wind farms was identified to have occurred. Percent coefficient of variation (%CV) was used as different datasets can be compared by calculating a relative measure of variation, expressed as the percentage of the mean represented by the standard deviation.

The final stage in the baseline/boundary investigation was to combine the estimated spatial and temporal footprints of the noise effects of offshore wind construction and of the herring stocks, and the examination of SSB time-series to reach a conclusion on what a reasonable baseline and boundaries would be for a project-level CEA of offshore wind farm effects.

6.2.4 Assessing the risk of significant cumulative effects

A simplified environmental risk assessment approach was applied to assess the risk of significant cumulative effects to herring being caused by the development and expansion of offshore wind farms. The approach was adapted from the processes detailed in the ICES marine and coastal ecosystem-based risk management handbook (Cormier et al., 2013) and Defra’s guidelines for environmental risk assessment and management (Gormley et al., 2011). A complete risk assessment process would include additional components for identifying and appraising management options and designed an appropriate management strategy (Gormley et al., 2011). These components were not included here, as the aim was to investigate potential progress relative to step 5 of the CEA pathway and due to time constraints. Thus, a reduced risk assessment process was developed (Figure 26).

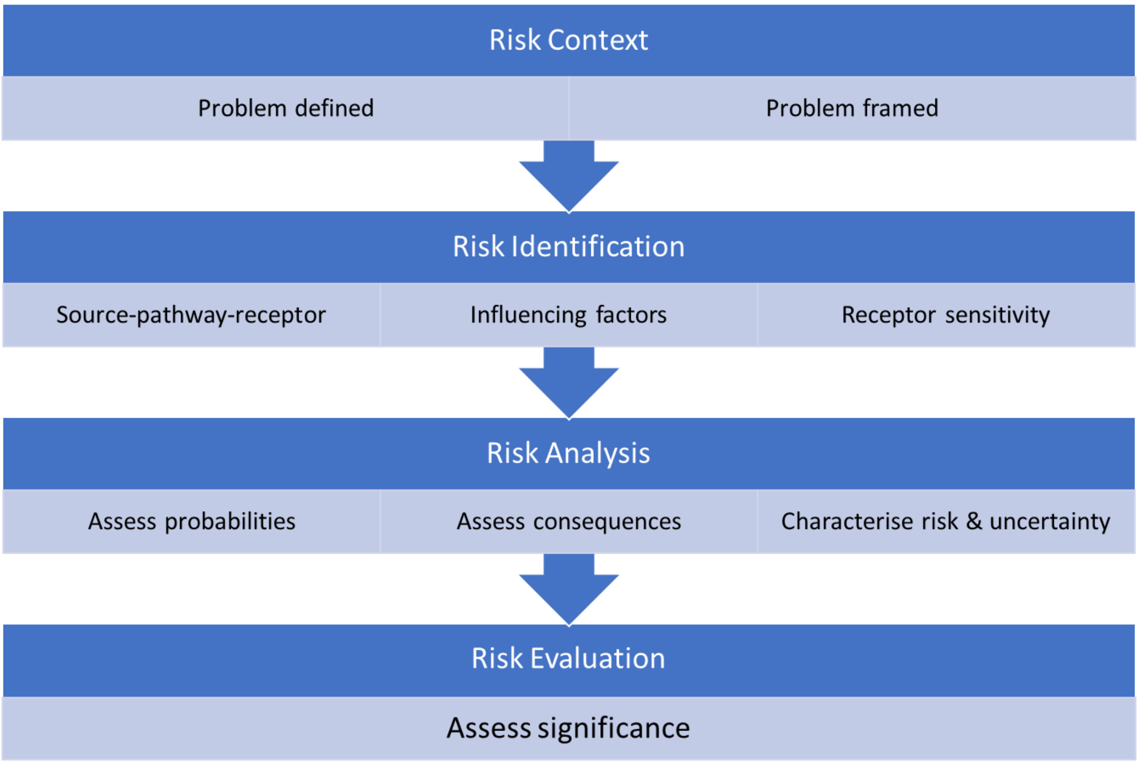


Figure 26. Risk assessment process applied to the case study evidence to assess the risk of significant cumulative effects to herring being caused by the development and expansion of offshore wind farms. Risk assessment process adapted from Cormier et al. (2013) and Gormley et al. (2011).

Application of the risk assessment process for this chapter built on the outputs of the investigations described in sections 6.2.1, 6.2.2 and 6.2.3. In keeping with these preceding sections, proof of concept was the aim, that is, to establish sound logic from which to gauge the value of more detailed analysis, thus a rapid qualitative approach to risk analysis was applied.

Risk probabilities were estimated and scored between 0 and 1, with probabilities close to 0 being highly unlikely, and probabilities close to 1 being highly likely. Three probability estimates were combined: 1) the probability of the hazard occurring; 2) the probability of the receptor being exposed to the hazard; and 3) the probability of the receptors being affected. No weighting based on strength of evidence or uncertainty was included to limit the scope of the risk assessment, however this would be useful analysis to included to further investigate the sensitivity of the approach to assessing cumulative effects.

Consequences in a systems sense were estimated and the risks characterised by pulling together the preceding information to derive a qualified statement of the likelihood that the known impacts would occur if the receptor is exposed to the effect. Thereafter, a statement of significance was derived to conclude the assessment.

6.3 Results

6.3.1 The effect footprint concept

Reviewing the Round 3 offshore wind farm Environmental Statements resulted in 25 marine processes being identified that are associated with the lifecycle of a generic offshore wind farm. A total of 81 stressors and outcomes were identified, but numerous processes result in the same stressors/outcomes. The construction phase included 9 processes associated with 18 distinct stressors/outcomes (Table A-5, appendices). The operation and maintenance phase included 8 processes associated with 8 distinct stressors/outcomes (Table A-6, appendices). The decommissioning phase included 8 processes associated with 14 distinct stressors/outcomes (Table A-7, appendices). Accounting for repetition of stressors/outcomes across the lifecycle phases, a total of 25 distinct stressors/outcomes were identified, with distinct temporal and spatial characteristics.

Aggregating stressors/outcomes into distinct effect categories led to five effect categories being identified: (1) suspended sediment change; (2) short-term habitat disturbance; (3) underwater noise and vibration; (4) hydrological change; and (5) long-term habitat change (Table 12). Each category contained sub-categories that reflected distinct temporal and spatial characteristics of the stressors/outcomes identified from the list of processes associated with the lifecycle of an offshore wind farm.

Table 12. Distinct stressor/outcomes categorised into effect categories and assigned a classification number (Class.). Offshore wind farm lifecycle processes that generate the stressors/outcomes and lifecycle phases are recorded.

Category	Class.#	Stressor/outcome	Spatial characteristics	Temporal characteristics	Associated lifecycle processes	Lifecycle phase
Suspended sediment change	1.a	Increased suspended sediment concentrations	localised seabed contact – discrete point source	duration measured in days	Site investigation surveys; Installation of met mast infrastructure; Installation of offshore collector station infrastructure; Installation of offshore converter station infrastructure; Cable repair; Removal of met mast infrastructure; Removal of offshore collector station infrastructure; Removal of offshore converter station infrastructure; Site inspection surveys	Construction; O&M; Decommissioning
	1.b	Increased suspended sediment concentrations	multiple discrete point sources spread over the extent of OWF	duration of each point measured in days	Site investigation surveys; Installation of met mast infrastructure; Installation of offshore collector station infrastructure; Installation of offshore converter station infrastructure; Cable repair; Removal of met mast infrastructure; Removal of offshore collector station infrastructure; Removal of offshore converter station infrastructure; Site inspection surveys	Construction; O&M; Decommissioning
	1.c	Increased suspended sediment concentrations	discrete source over an extended spatial line	duration measured in weeks	Site investigation surveys; Site inspection surveys	Construction; Decommissioning

Category	Class.#	Stressor/outcome	Spatial characteristics	Temporal characteristics	Associated lifecycle processes	Lifecycle phase
Short-term habitat disturbance	2.a	Structural disturbance to habitat	localised seabed contact - discrete point source,	duration measured in days	Site investigation surveys; Installation of wind turbines; Turbine inspections; Offshore converter stations & collector stations inspections; Turbine replacement; Cable inspections; Removal of met mast infrastructure; Removal of wind turbines; Removal of offshore collector station infrastructure; Removal of offshore converter station infrastructure; Site inspection surveys	Construction; O&M; Decommissioning
	2.b	Structural disturbance to habitat	multiple discrete point source spread over the extent of OWF	duration of each point measured in days	Installation of met mast infrastructure; Installation of offshore collector station infrastructure; Installation of offshore converter station infrastructure	Construction
	2.c	Structural disturbance to habitat	discrete source over an extended spatial line	duration measured in weeks	Installation of met mast infrastructure; Installation of offshore collector station infrastructure; Installation of offshore converter station infrastructure; Stations operation	Construction; O&M
Underwater noise & vibration	3.a	Underwater noise & vibration – seismic surveys	discrete point source, strong impulsive noise signal	duration measured in hours	Installation of met mast infrastructure; Installation of offshore collector station infrastructure; Installation of offshore converter station infrastructure	Construction; O&M
	3.b	Underwater noise & vibration – vessel movements	discrete point source, localised noise and vibration	duration measured in days	Installation of wind turbine foundations; Installation of scour protection material; Removal of wind turbine foundations and scour protection	Construction; Decommissioning

Category	Class.#	Stressor/outcome	Spatial characteristics	Temporal characteristics	Associated lifecycle processes	Lifecycle phase
	3.c	Underwater noise & vibration	discrete point source, strong, repetitive impulsive noise signal	duration measured in hours	Installation of wind turbine foundations; Installation of scour protection material; Removal of wind turbine foundations and scour protection	Construction; Decommissioning
	3.d	Underwater noise & vibration	multiple discrete point sources spread over the extent of OWF, strong impulsive noise signal	duration spread over the extent of foundation installation period	Installation of wind turbine foundations	Construction
	3.e	Underwater noise & vibration – vessel movements	multiple discrete point sources spread over the extent of OWF	duration of each point measured in days	Installation of wind turbine foundations; Installation of scour protection material; Removal of wind turbine foundations and scour protection	Construction
	3.f	Underwater noise & vibration	multiple discrete point sources spread over the extent of OWF, localised noise and vibration	duration spread over the extent of foundation installation period	Installation of wind turbine foundations; Installation of scour protection material	Construction; O&M

Category	Class.#	Stressor/outcome	Spatial characteristics	Temporal characteristics	Associated lifecycle processes	Lifecycle phase
	3.g	Underwater noise & vibration - discrete point source	discrete point source, localised noise and vibration	duration measured in weeks	Installation of wind turbine foundations; Installation of scour protection material	Construction; O&M
	3.h	Underwater noise & vibration	multiple discrete point sources spread over the extent of OWF	duration spans operational life of OWF	Installation of scour protection material	Construction; O&M
Hydrological change	4.a	Hydrological change	discrete point source	duration spans operational life of OWF	Installation of wind turbines	Construction; O&M
	4.b	Hydrological change	multiple discrete point sources spread over the extent of OWF	duration spans operational life of OWF	Installation of inter-array cabling; Installation of export cabling; Removal of inter-array cabling; Removal of export cabling	Construction; Decommissioning
	4.c	Hydrological change	discrete point source	duration spans foreseeable future	Installation of inter-array cabling; Installation of export cabling; Removal of inter-array cabling; Removal of export cabling	Construction; Decommissioning
	4.d	Hydrological change	multiple discrete point sources	duration spans foreseeable future	Installation of inter-array cabling; Installation of export cabling; Cable repair; Removal of inter-array cabling; Removal of export cabling	Construction; O&M; Decommissioning

Category	Class.#	Stressor/outcome	Spatial characteristics	Temporal characteristics	Associated lifecycle processes	Lifecycle phase
Long-term habitat change	5.a	Presence of novel substrate	discrete spatial point	duration spans operational life of OWF	Turbine operation; Stations operation	O&M
	5.b	Presence of novel substrate	multiple discrete spatial points	duration spans operational life of OWF	Turbine operation	O&M
	5.c	Presence of novel aerial structure	multiple discrete spatial points	duration spans operational life of OWF	Cable operation	O&M
	5.d	Moving turbine blades	multiple discrete spatial points	duration spans operational life of OWF	Removal of met mast infrastructure; Removal of offshore collector station infrastructure; Removal of offshore converter station infrastructure	Decommissioning
	5.e	Presence of electro-magnetic fields	discrete sources over multiple extended spatial lines	duration spans operational life of OWF	Removal of met mast infrastructure; Removal of offshore collector station infrastructure; Removal of offshore converter station infrastructure	Decommissioning
	5.f	Removal of established substrate	discrete point source	duration spans foreseeable future	Removal of wind turbine foundations and scour protection	Decommissioning

Category	Class.#	Stressor/outcome	Spatial characteristics	Temporal characteristics	Associated lifecycle processes	Lifecycle phase
	5.g	Removal of established substrate	multiple discrete point sources	duration spans foreseeable future	Removal of wind turbine foundations and scour protection	Decommissioning

Applying the classification scale (Table 11) to the spatial and temporal characteristics of the effect categories enabled a plot to be developed of the effects footprint of a large-scale offshore wind farm (Figure 27).

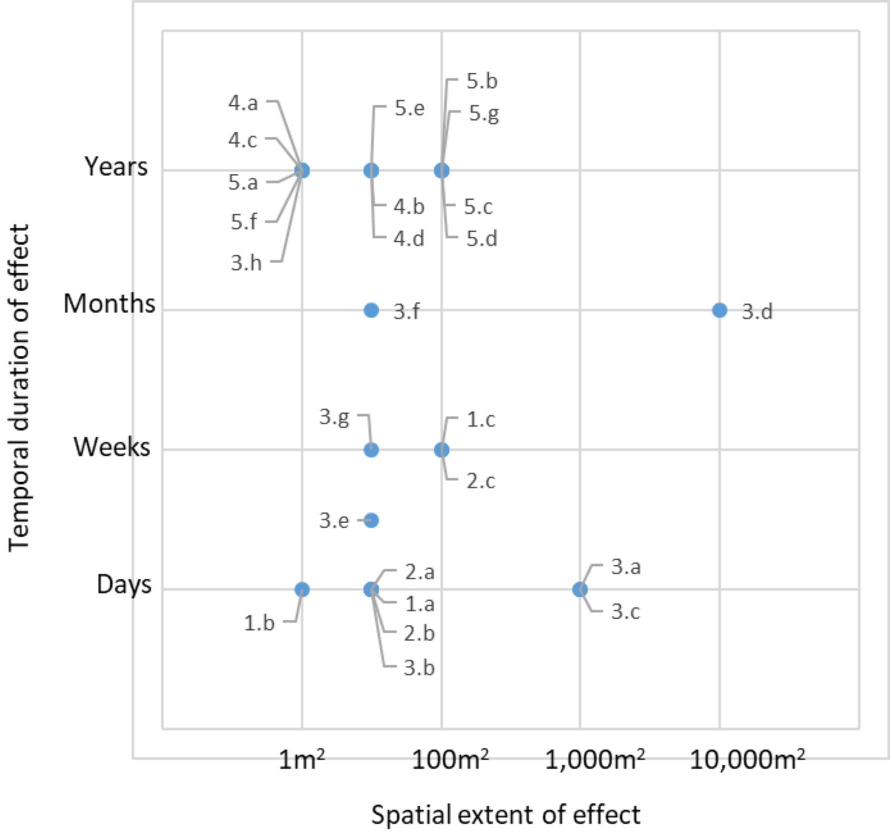


Figure 27. Plot of the spatial and temporal characteristics of the ecological effects associated with a large-scale offshore wind farm. The numerals (e.g. 3.d) correlate with the stressor/outcome classification number in Table 12.

An assumption was made that herring, seabirds, benthic productivity and commercial fishing overlap with the effects generated by the OWF. This is a reasonable assumption in the case study area, where all four receptors are present and widely distributed across the region. The sensitivity of receptors and the likelihood of exposure were classified according to the scale shown in Table 11, and the cumulative effect risk calculated (Table 13)

Table 13. Estimated sensitivity and likelihood of exposure scores for receptors affected by the development of a modelled offshore wind farm. The cumulative effect risk score (CE_risk) is calculated by sensitivity*exposure. Stressor classification numbers correspond to those listed in Table 12.

	Herring			**Seabirds**			**Benthic productivity**			**Commercial fishing**		
Stressor Class.#	Sensitivity	Exposure	CE_risk	Sensitivity	Exposure	CE_risk	Sensitivity	Exposure	CE_risk	Sensitivity	Exposure	CE_risk
1.a	1	2	2	1	2	2	3	4	12	1	1	1
1.b	1	2	2	1	2	2	3	4	12	1	1	1
1.c	1	2	2	1	2	2	3	4	12	1	1	1
2.a	1	1	1	2	2	4	4	4	16	3	2	6
2.b	1	1	1	2	2	4	4	4	16	3	4	12
2.c	1	1	1	2	2	4	4	4	16	4	3	12
3.a	4	2	8	2	2	4	2	2	4	4	2	8
3.b	3	2	6	4	2	8	1	1	1	2	2	4
3.c	4	2	8	2	2	4	2	1	2	4	2	8
3.d	4	4	16	2	3	6	2	4	8	4	4	16
3.e	3	2	6	4	2	8	1	1	1	3	3	9
3.f	3	2	6	2	2	4	1	2	2	2	2	4
3.g	3	2	6	4	2	8	2	2	4	3	3	9

	Herring			**Seabirds**			**Benthic productivity**			**Commercial fishing**		
Stressor Class.#	Sensitivity	Exposure	CE_risk	Sensitivity	Exposure	CE_risk	Sensitivity	Exposure	CE_risk	Sensitivity	Exposure	CE_risk
3.h	3	2	6	1	4	4	1	1	1	2	2	4
4.a	1	1	1	1	4	4	3	4	12	1	1	1
4.b	1	1	1	1	4	4	3	4	12	1	1	1
4.c	1	1	1	1	4	4	3	4	12	1	1	1
4.d	1	1	1	1	4	4	3	4	12	1	1	1
5.a	1	1	1	1	4	4	4	4	16	4	4	16
5.b	1	1	1	1	4	4	4	4	16	4	4	16
5.c	1	1	1	4	4	16	1	1	1	1	1	1
5.d	1	1	1	4	4	16	1	1	1	1	1	1
5.e	1	1	1	1	1	1	1	4	4	3	4	12
5.f	1	1	1	1	1	1	4	4	16	3	4	12
5.g	1	1	1	1	1	1	4	4	16	4	4	16

The cumulative effect risk scores were plotted as the third dimension in the OWF effects footprint. Bubble charts were created for each receptor, where the receptor risk score defined the size of the bubble. The result was a modified receptor-effects footprint plot that aids identification of which stressors and processes are predicted to carry the highest risk of having a significant cumulative effect on the receptor (Figure 28).

The cumulative effect risk plots in Figure 28 show that the activity-receptor footprint concept can distinguish different levels of risk for different receptors. The risk of significant cumulative effects to herring is shown to stem primarily from stressor/outcome 3.d, which, using Table 12, is associated with the installation of wind turbine pilings, that is, impulsive piling.

The cumulative effect risk plots for the remaining three receptors show a greater range of high-risk stressor/outcomes, indicating that CEAs to investigate OWF-receptor interactions would warrant a greater number of stressors/outcomes. A further observation is that high cumulative effect risks were shown for stressors/outcomes where the duration or extent were limited. For example, benthic productivity was estimated to be highly sensitive to site investigation surveys and the installation of the met mast (processes associated with stressor/outcome 1.b), but these are point events that are of very short duration and very limited extent relative to the extent of the benthos, assuming in this case that there is an equal distribution of benthic productivity across the site of an OWF. Taken in a regional perspective, the risk of significant cumulative effects to the benthos due to stressor 1.b could be negligible. An iteration of the activity-receptor plots was completed to emphasise where high cumulative effects risks were associated with stressors/outcomes with a longer duration and/or greater spatial extent Figure 29. Relative to the case study, the most significant effect is identified as underwater noise and vibration, which stems from impulsive piling during the construction phase (stressor/outcome 3.d).

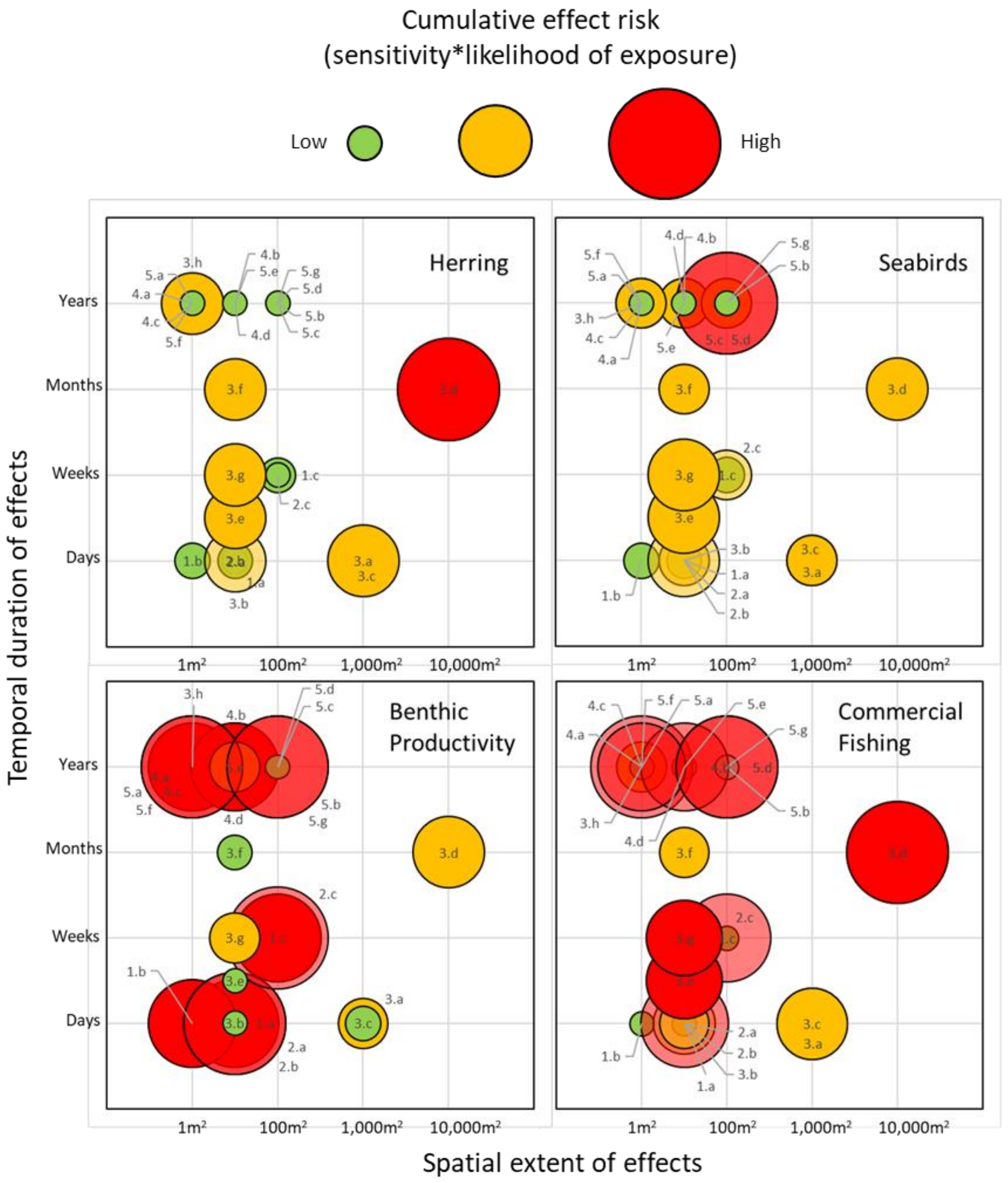


Figure 28. Bubble charts of the risk that offshore wind farm stressors and outcomes will have a significant cumulative effect on four receptors. The numerals correspond to the stressor/outcome classification numbers listed in Table 12. Note that a high cumulative effect risk may be offset by a short duration and/or small extent of the effects. Also note that the objective was to test the concept, not to develop a precise output. Plots should not be used for purposes other than as a generic representation of varying risk of cumulative effects caused by human activities.

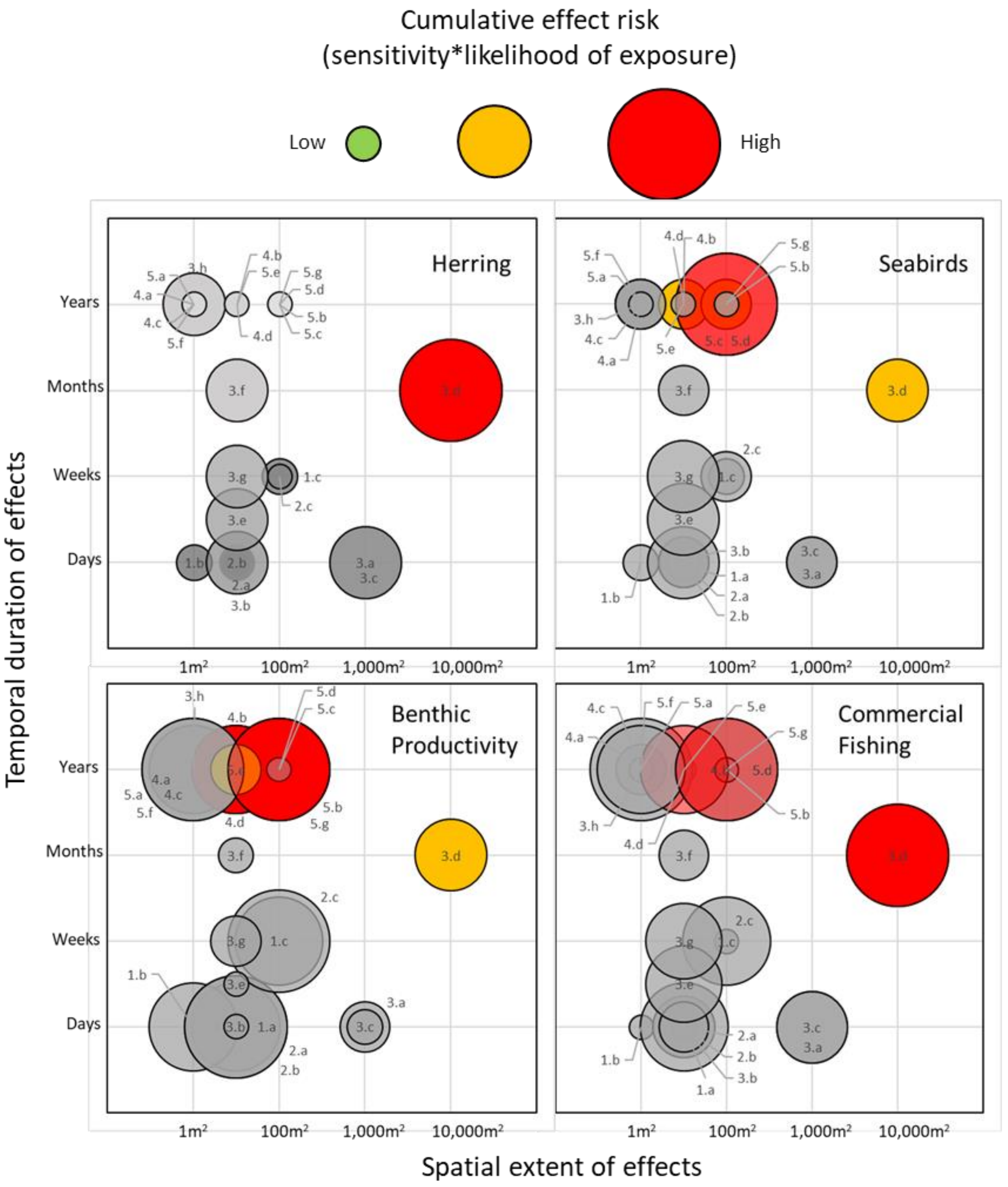


Figure 29. Iteration of Figure 28 with emphasis (coloured bubbles) on the medium and high cumulative effect risks that are associated with stressors/outcomes with a longer duration and a greater spatial extent, indicating how the footprint concept could be used to support CEA scoping. Again, the objective was to test the concept rather than precision. More accurate sensitivity/exposure criteria could result in markedly different results and the risk score could be more precautionary for endangered species. The numerals correspond to the stressor/outcome classification numbers listed in Table 12.

As was stressed in the methodology and in the captions above, the objective was to develop and test the activity-receptor footprint concept. Confidence in the specific for the receptors other than herring would be markedly increased if the process were repeated with a more refined set of stressors/outcomes relative to the receptors, and an evidence base about the sensitivity and likelihood of exposure of other receptors to the stressors identified. The key result relative to the activity-effect footprint concept can support the scoping process, and can provide an evidenced justification for a focus on particular receptors and stressors originating from human activities.

6.3.2 Structuring assessments and boundaries

The evaluation of available evidence for the CEA pathway presented in Chapter 5 resulted in the identification of literature about the lifecycle of herring that was evaluated as being robust evidence from which to complete step 3 of the pathway (the receptor pivot; evidence summarised in Table 14).

Reviewing the information led to the identification of system variables and cause-effect interactions relevant to the condition and resilience of the case study herring stocks (Table 15). The polarity of the interactions were noted as positive or negative, where positive relationships indicate that an increase in the causal variable leads to an increase in the effected variable, and negative relationships indicate that an increase in the causal variable leads to a decrease in the effected variable.

The spatial scales of the interactions were recorded as being either exogenic or endogenic at the scale of the case study system. The temporal lag for the effect to manifest was estimated using expert judgement and the confidence in the rationale behind each interaction noted with reference to the quality of the underlying evidence available (Table 15).

Table 14. Summary of the information gathered for the case study and for Step 3 (receptor pivot), and which was used as evidence to support the development of the causal loop diagram. Extracted from Table 9A.1 (appendices).

CEA pathway step	Description of data/information available to herring case study
4.A. Use current evidence base to characterise receptor/s	(NSAH) A substantial knowledge base grounded in current and historical science is available to support characterisation of the North Sea herring population. Sufficient peer-reviewed literature is accessible, notably from the ICES Herring Assessment Working Group (HAWG) that supports a robust characterisation of the biological, ecological and economic aspects of herring lifecycles, demographics and productivity. The quality of ICES HAWG outputs has been favourably evaluated (Simmonds, 2009) indicating sufficient certainty about the quality and application of data and information used to characterise and monitor the autumn spawning herring metapopulation and subpopulations. Additional useful information, though rough in terms of spatial resolution, is available via Fishbase (for fishes), where species envelopes are available for herring based on minimum, preferred minimum, preferred maximum and maximum envelopes, comprising depth, temperature, salinity, primary production and distance to shore. Spring spawning herring spawn significantly closer to shore than the listed preferred minimum distance to shore (6 km), highlighting the approximate nature of the generalised envelopes. Recent literature emphasises that uncertainties exist in all areas (Geffen, 2009; Hufnagl et al., 2015; Petitgas et al., 2013). Uncertainties emerge in relation to the relative importance of environmental drivers regulating lifecycle processes (Hufnagl et al., 2015), in relation to ecosystem interactions (Heikinheimo, 2011; Rockmann et al., 2011), and at population and individual behaviour levels where evidence of the plasticity and adaptability of herring populations is emerging (Geffen, 2009). However, for the purposes of the assessment, sufficient, high-quality information is available to document and characterise the herring lifecycle including reproductive strategy and potential bottlenecks relative to resilience and resistance.
	(TEH) As above, with the caveat that knowledge about the Thames herring life cycle is based on historical studies. TEH is excluded from the ICES HAWG assessments and the most recent dedicated peer-reviewed study specific to this population is from 2004 (Roel et al., 2004).

CEA pathway step	Description of data/information available to herring case study
4.B. Specify temporal and spatial lifecycle and key ecosystem interactions	(NSAH) Sufficient historical and current data and information is available to characterise the temporal and spatial variability of North Sea herring. Information is available about spawning grounds (Dickey-Collas et al., 2010; Rockmann et al., 2011) (including of larval distribution via ICES IHLS dataset). Spatial resolution of ICES data is good for areas surveyed, however these do not include the areas closest to shore in the study area, which are associated with the spring spawning population (not NSAH). Catch statistics provide good spatial cover relative to the study area for mature herring (ICES statistical rectangle) and can be used to glean insights into temporal (monthly and annual) and spatial distribution. Caveats about fishery dependent data apply (Pecoraro et al., 2017). For the over-10 metre fleet, consistency over time is likely to be higher, as the current data collection system has been established for longer, although specific to herring, misreporting and issues with fishery dependent data have been noted in the past (ICES HAWG 2007) but are currently considered to be a minor issues in the North Sea herring fishery (ICES HAWG 2018). Changes in the catch reporting system for 10-metre and under vessels in 2006 result in low confidence prior to 2006 (MMO pers. comm). A priori relationships between herring and the environment are known based on the literature available for and specific to herring, notably ICES HAWG 2015. Key processes influencing herring populations includes access to spawning habitats (potential for noise barriers), hence ICES HAWG advising no aggregate extraction at likely spawning sites (ICES HAWG 2007, though this has been contested by the aggregates industry) The data/information available about herring is sufficient for the purposes of improving CEA. Environmental forcing and density-dependent effects play key roles in herring productivity and population dynamics, though underlying mechanisms are not well understood (ICES HAWG 2018). A caveat regarding confidence in existing knowledge is the consequence of new research, which has previously required accepted thinking to be revised (Geffen, 2009). In terms of ecosystem relationships, Fauchald et al. (2011) point to herring in the North Sea occupying an intermediate trophic level where diversity is lower than higher and lower levels, pointing to a wasp-waist system with herring a critical component influencing the abundance of seabird populations and zooplankton. Small pelagics, including herring, thus have an important role in controlling ecosystem relationships (Fauchald et al., 2011). This presents an alternative view to that often presented, that the North Sea ecosystem is a bottom-up regulated system. Research also points to the “prey to predator” feedback loop (Bakun and

CEA pathway step	**Description of data/information available to herring case study**
	Weeks, 2006) being applicable, whereby decreased predator abundance (such as cod due to overfishing) reduces predation pressure on herring, that in turn predate on cod larvae (Heikinheimo, 2011).
	(TEH) Past information is available for the sub-population of the Thames estuary, but is not up to date, with populations surveys stopped in 2007/8 (data can be obtained via Cefas via a request for information). Some research is available relating to specific periods (such as localised plankton surveys 1993-1997; Fox, 2001). Important temporal periods relate to the observed spatial distribution of adult herring returning to the coastal waters in the study area prior to spawning, from November onwards, finally moving into spawning aggregation prior to spawning from February through to April/May (Wood, 1981) depending on water temperature, with temperatures above 5 degrees celcius thought to be a spawning cue (Power et al., 2000). Related to key relationships, Power et al (2000) discuss some of the concomitant importance of herring (and sprat) abundance in the Thames estuary, as important components of the community structure. The Thames herring larvae hatch within 2-4 weeks after spawning (March to mid-May), depending on water temperature and appear to remain close to the coast (Wood 1981). Metamorphosis occurs in July-August (Wood 1981). Juveniles are found in the Thames estuary in large numbers in August with peaks in November to March, and then declining, perhaps following a cue to migrate offshore once water temperatures exceed 10 degrees celcius (Power et al., 2000). This is a notably different pattern than the herring populations spawning further offshore (Banks and Downs populations) where the water flow takes larvae and juveniles around to the eastern reaches of the Southern North Sea (ICES HAWG 2014 or 15?). Greater reliance on historical information hence limited knowledge of changes in fecundity, spawning site usage, potential for allee effect. The sub-population in the Thames estuary is subject to greater uncertainty, as directed surveying ceased in 2008 and abundance information (SSB) is reliant on CPUE calculations with fishing effort also influenced by the market for herring at the time. Fishery-dependent data is also subject to other potential biases (Geehand and Pierre 2015, in Pecoraro et al., 2017).
4.C. Identify key human activities	(NSAH) Knowledge about the lifecycle of herring is sufficient to determine direct sensitivities (fishing mortality, spawning habitat disturbance, noise) and hence human activities directly contributing to the cumulative effects load. The role of indirect, exogenous

CEA pathway step	Description of data/information available to herring case study
contributing to cumulative effect load	factors (pollution, eutrophication, water quality, sedimentation, climate change) are less clear, and knowledge about how activities interact to cumulatively influence herring populations is minimal. Pollution has been a major issue in the North Sea for decades (Ducrotoy et al., 2000). However, in context of this assessment (which seeks to be proportional for practitioners associated with assessments of the cumulative effects of individual developments) an argument can be made that the current 'good' status of North Sea herring (ICES 2014; ICES 2018) indicates herring have not been significantly impacted by historical pollution. For this assessment, The Crown Estate provides open access spatial data that indicates where maritime industries required a lease to occupy the seabed. This information can be entered into a GIS to identify which are present in the study area and which to include in the assessment based on potential interactions with herring (e.g. overlap with potential spawning habitat). Information available points to key endogenic activities (relative to the study area) contributing to the status of the herring population including offshore wind farms (noise and vibration), ports and shipping (noise and vibration), aggregate extraction (spawning habitat disturbance), wind export cable routes (spawning habitat disturbance) and commercial fishing (mortality). Good spatial data is available from reliable sources (OSPAR, TCE, MMO, Cefas) to apply GIS to identify the proximity of fixed infrastructure or license areas to sensitive herring habitat
	(TEH) human activities as above, with additional mortality experienced due to power station water intakes in the Thames estuary (Power et al., 2000) and a small-scale whitebait fishery operated by a handful of vessels in winter months (pair-trawling from Southend) that can take juvenile herring (Roel et al., 2004; Wood, 1981). Good spatial data is also available (as per NSAH) to apply GIS to identify the proximity of fixed infrastructure or license areas to sensitive herring habitat.

Table 15. Characteristics of the interactions between variables included in the Causal Loop Diagram (Figure 30). Note footnotes that specify where there is ambiguity about spatial scale of the variables depending on the focal receptor population and/or resolution applied to the variables (e.g. discrete fishing fleet metier).

Interaction (cause to effect)		Polarity (+/-)	Rationale	Spatial scale relative to system	Temporal lag for effect to manifest	Confidence	Notes	References
1	Herring population productivity - Egg production[7]	+	Increased population numbers increases total egg production	Exogenic - Exogenic	Annual	High	Stock fecundity variability through change in relative abundance of different spawning components. One unit of SSB of Autumn Spawning herring produces 30% more eggs than spring spawners but potentially lower survival rates.	Dickey-Collas et al., 2010; Kell et al., 2016; Dutil & Brander, 2003
2	Herring population productivity - Prey availability	-	Increased population numbers decreases abundance of prey through predation by herring	Exogenic - Exogenic	Within year	High	Different prey at different life stages. Also potential for cannibalism of larvae by adults if preferred prey availability low.	Bakun & Weeks, 2006

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[7] Potential for TEH productivity to be classified as endogenous to CEA boundaries, as spawning grounds endogenous to CEA boundaries. NSAH potentially partially endogenous on same basis, with some potential spawning grounds based on substrate presence lying within CEA boundaries.

Interaction (cause to effect)		Polarity (+/-)	Rationale	Spatial scale relative to system	Temporal lag for effect to manifest	Confidence	Notes	References
3	Herring population productivity - Density dependent regulation of growth	+	Increased population size increases the likelihood of density dependent growth regulation	Exogenic - Exogenic	Within year	Medium		Brunel & Dickey-Collas, 2010
4	Density dependent regulation of growth - Growth of surviving fish	-	Decreased growth rate caused by the increased competition for food when population size is high	Exogenic - Exogenic	Within year	Medium		Brunel & Dickey-Collas, 2010
5	Growth of surviving fish - Herring population productivity	+	Larger fish are more fecund contributing to increased herring population productivity	Exogenic - Exogenic	2-3 years	High		ICES HAWG; Dutil & Brander, 2003
6	Herring population productivity - Pelagic fishing[8]	+	Increased herring population productivity supports higher quotas increasing the level of fishing	Exogenic - Exogenic	2-3 years	High		ICES HAWG

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[8] Potential for TEH productivity and fishery to be classified as endogenous to CEA boundaries, and NSAH to be partially endogenous.

Interaction (cause to effect)		Polarity (+/-)	Rationale	Spatial scale relative to system	Temporal lag for effect to manifest	Confidence	Notes	References
7	Herring population productivity - Predation	-	High herring population size may reduce predation by cod (key predator) as herring adults feed on gadoid eggs	Exogenic - Exogenic	3+ years	Medium	Introduces numerous other system components, e.g. mackerel and horse mackerel (key predators of juvenile herring) and in turn the factors affecting the abundance of those predators.	(Bakun, 2006; Bakun et al., 2009; Dickey-Collas et al., 2010)
8	Pelagic fishing - Fishing mortality[9]	+	Increased fishing increases fishing mortality	Exogenic - Exogenic	Within year	High		ICES HAWG
9	Fishing mortality - Recruitment of new fish	-	Increased fishing mortality decreases the number of fish available to contribute to recruitment	Exogenic - Exogenic	Within year	High	Local interaction stems from discrete fisheries targeting aggregating stocks at or around spawning periods. Herring stock collapse in the 1960s/1970s attributed at least in part to targeting juvenile herring, indicating potential bottleneck risk.	ICES HAWG

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[9] Potential for TEH fishery and associated fishing mortality to be classified as endogenous to CEA boundaries.

Interaction (cause to effect)		Polarity (+/-)	Rationale	Spatial scale relative to system	Temporal lag for effect to manifest	Confidence	Notes	References
10	Predation - Recruitment of new fish	-	Increased predation decreases the number of fish available to contribute to recruitment	Exogenic - Exogenic	Within year	High		ICES HAWG
11	Natural mortality - Recruitment of new fish	-	Increased natural mortality decreases the number of fish available to contribute to recruitment	Exogenic - Exogenic	Within year	High	Source of increased mortality from parasitic fungus Ichthyophonus spp. that is lethal to herring and could have a significant effect on natural mortality in the stock and ultimately on spawning stock biomass	ICES HAWG
12	Recruitment of new fish - Herring population productivity	+	Increased recruitment increases the size of the herring population, increasing population productivity	Exogenic - Exogenic	Within year	High	Productivity is a function of recruitment and growth	Dutil & Brander, 2003
13	Egg production - Recruitment of new fish	+	Increased egg production increases the level of recruitment of new fish	Exogenic - Exogenic	2-3 years	High		ICES HAWG

Interaction (cause to effect)		Polarity (+/-)	Rationale	Spatial scale relative to system	Temporal lag for effect to manifest	Confidence	Notes	References
14	Prey availability - Favourable over-wintering phase for larvae	+	Increased prey availability increases the favourability of the over-wintering phase for herring larvae	Exogenic - Exogenic	Within year	Medium	The over-wintering phase is a key factor influencing year-class strength	(Nash et al., 2009)
15	Prey availability - Growth of surviving fish	+	Increased prey availability increases the growth rates of surviving herring	Exogenic - Exogenic	Within year	Medium		ICES HAWG
16	Favourable over-wintering phase for larvae - Recruitment of new fish	+	A favourable over-wintering phase increases the survival rate of larvae increasing the level of recruitment of new fish	Exogenic - Exogenic	2-3 years	Medium	The over-wintering phase is a key factor influencing year-class strength	(Nash et al., 2009)
17	Climate change - Growth of surviving fish	+	Increasing water temperatures increase growth rates of surviving herring	Exogenic - Exogenic	10+ years	Low	Higher waters temperatures may result in faster growth rates, but potentially lower egg quality.	ICES HAWG

Interaction (cause to effect)		Polarity (+/-)	Rationale	Spatial scale relative to system	Temporal lag for effect to manifest	Confidence	Notes	References
18	Climate change - Regime shifts	+	Increasing climate change increases the likelihood of regime shifts	Exogenic - Exogenic	10+ years	High		Dickey-Collas et al., 2010
19	Climate change - Predation	+	Increasing water temperatures increase the abundance of predators of herring larvae	Exogenic - Exogenic	10+ years	Low	Increasing sea temperatures are associated with the observed increases in sardines and anchovies in the North Sea, which are predators of herring larvae. Increasing sea bottom temperatures are thought to be an environmental cue for spawning. A sharp decline in herring abundance above 10 degrees Celsius water temperature has been observed, which may be a cue for offshore migration by herring juveniles.	(Payne et al., 2009; Power et al., 2000)
20	Climate change - Quality and	-	Increasing water temperatures reduce the attractiveness of	Exogenic - Endogenic	10+ years	Low	There is evidence of plasticity of reproductive activity in herring in response to environmental	(Winters and Wheeler, 1996)

Interaction (cause to effect)		Polarity (+/-)	Rationale	Spatial scale relative to system	Temporal lag for effect to manifest	Confidence	Notes	References
	availability of spawning grounds		spawning grounds where temperature cues are exceeded				conditions. Spring-spawning herring in the West Atlantic have been observed to adjust spawning times to reflect sea temperatures, with spawning times matching expected environmental conditions in 4 months' time. January sea temperatures control fecundity, egg size and reproductive output of this population and are thus a major factor influencing year-class strength. The reason posited for this plasticity is to coincide the emergence of herring larvae with spring plankton blooms.	
21	Regime shifts - Prey availability	-	Regime shifts reduce the availability of preferred prey for herring juveniles and adults	Exogenic - Exogenic	Within year	High		(Dickey-Collas et al., 2010)

Interaction (cause to effect)		Polarity (+/-)	Rationale	Spatial scale relative to system	Temporal lag for effect to manifest	Confidence	Notes	References
22	Quality and availability of spawning grounds - Recruitment of new fish	+	Increasing quality and availability of spawning grounds increases the chance of spawning success increasing the recruitment of new fish	Endogenic - Exogenic	2-3 years	High	Herring display complex spawning behaviour, including use of spawning grounds. Spawning shoals change during the spawning season, with fish leaving and arriving. The natal homing instinct is not proven, authors suggest that individuals return to the same spawning ground in the same season where and when the fish first spawned, hence juveniles may be recruited to different populations. There is an open question whether repeated disturbances to spawning grounds and reduced numbers of returning fish increases the likelihood that spawning grounds become defunct, reducing the diversity of the	(Dickey-Collas et al., 2010; Geffen, 2009; Schmidt et al., 2009)

Interaction (cause to effect)		Polarity (+/-)	Rationale	Spatial scale relative to system	Temporal lag for effect to manifest	Confidence	Notes	References
							metapopulation. There is, however, evidence of repopulation of abandoned grounds if suitable sites are available and if the metapopulation is growing.	
23	Structural disturbance to benthic habitat - Quality and availability of spawning grounds	-	Increasing disturbance of the benthic habitat at spawning grounds decreases the quality and availability of spawning grounds	Endogenic - Endogenic	Within year	High		ICES HAWG
24	Noise and vibration - Quality and availability of spawning grounds	-	Increasing noise and vibration in the vicinity of spawning grounds decreases the quality and availability of spawning grounds	Endogenic - Endogenic	Within year	High		ICES HAWG
25	Offshore wind farm construction - Noise and vibration	+	Increasing offshore wind farm construction	Endogenic - Endogenic	Within year	High		MMO online spatial database

Interaction (cause to effect)		Polarity (+/-)	Rationale	Spatial scale relative to system	Temporal lag for effect to manifest	Confidence	Notes	References
			increases the level of noise and vibration					
26	Ports and shipping - Noise and vibration	+	Increasing shipping activity increases the level of noise and vibration	Endogenic - Endogenic	Within year	Medium		MMO online spatial database
27	Aggregate extraction - Noise and vibration	+	Increasing aggregate extraction increases the level of noise and vibration	Endogenic - Endogenic	Within year	Medium		MMO online spatial database
28	Aggregate extraction - Structural disturbance to benthic habitat	+	Increasing aggregate extraction increases structural disturbance to benthic habitat	Endogenic - Endogenic	Within year	High		MMO online spatial database
29	Demersal trawling - Structural disturbance to benthic habitat	+	Increasing demersal trawling increases structural disturbance to benthic habitat	Endogenic - Endogenic	Within year	High		MMO online spatial database

Interaction (cause to effect)		Polarity (+/-)	Rationale	Spatial scale relative to system	Temporal lag for effect to manifest	Confidence	Notes	References
30	Offshore cables - Structural disturbance to benthic habitat	+	Increasing numbers of offshore cables increases structural disturbance to benthic habitat	Endogenic - Endogenic	Within year	High		MMO online spatial database

The characterisation of cause-effect interactions was used to estimate how strong an effect the interaction has on the persistence of the receptor (Table 16). The importance of the interaction relative to the case study period (2000-2015) was noted and a rationale provided for both judgements. An additional column was added identifying whether the interaction was associated with a ‘bottleneck’, that is herring productivity is linked to density-dependent processes or association with specific habitat at specific times. Such interactions should be included in a CEA to investigate: i) whether the activity in question could impact critical interactions; and, ii) whether other activities/changes are increasing the risk of critical interactions being affected, and therefore influencing how significant additions to the cumulative effects load may be. A useful concept that could be adopted in future research is assimilative capacity, defined here as the capacity a receptor has to absorb additional effects without the persistence of the receptor in the social-ecological system being adversely affected (adapted from Elliott et al., 2018). Such an approach may prove useful at identifying where minor effects could have a significant impact.

The speed at which variables change influences whether interactions that have a strong effect on herring persistence were judged to be important for the case study period. For example the productivity of herring, while varying over time, is likely to be most strongly influenced by environmental conditions (Dickey-Collas et al., 2010), which have been assumed to be exogenous to the case-study area and hence beyond the reasonable scope of a project-level CEA. Table 16 highlights that the key interactions that should be included in a project-level CEA, with the exception of interaction 12, all stem from human activities. In theory, information should be available to support more detailed assessment of these key interactions, as the activities are licensed, managed activities in the case-study area, which could be investigated at a later date. The key human activities contributing to the herring cumulative effects load are offshore wind farm construction, ports and shipping, and aggregate extraction (noise and vibration), and aggregate extraction, demersal trawling, and offshore cable laying (structural disturbance to spawning grounds).

Table 16. Estimating the importance of cause-effect interactions on the persistence of herring as a critical social-ecological system component and the importance relative to the case study reference period (2000-2015). Bottleneck risks are identified, where there is a risk that one of the driver behind the causal variable could disrupt discrete spatial and/or temporal characteristics of the herring lifecycle with potential consequences for the resilience of herring. Colour coding reflects the importance of the interaction to project-level CEA – 3 violet cells in a row, for example, indicates a critical interaction to include in a CEA.

Interaction (cause to effect)		Assumed effect on persistence	Importance for CEA (2000-2015)	Rationale	Bottleneck risk
1	Herring population productivity - Egg production	Strong	Low	Egg production fundamental to persistence of species. Part of positive reinforcing loop. Assume constant over period of CEA. Exogenous relative to case study area.	No
2	Herring population productivity - Prey availability	Weak	Low	Ecological interaction that has persisted over long period of time; Part of a balancing loop, assume self-organising. Assume constant over period of CEA. Exogenous relative to case study area.	No
3	Herring population productivity - Density dependent regulation of growth	Weak	Low	Ecological interaction that has persisted over long period of time; Part of a balancing loop, assume self-organising. Assume constant over period of CEA. Exogenous relative to case study area.	No
4	Density dependent regulation of growth - Growth of surviving fish	Weak	Low	Ecological interaction that has persisted over long period of time; Part of a balancing loop, assume self-organising. Assume constant over period of CEA. Exogenous relative to case study area.	No
5	Growth of surviving fish - Herring population productivity	Strong	Low	Growth of surviving fish fundamental to persistence of species. Forms component of a balancing loop, but is influenced by other variables/interactions. No direct relationships with managed human activities, however, changes to growth could be influential. Exogenous relative to case study area.	No

Interaction (cause to effect)		Assumed effect on persistence	Importance for CEA (2000-2015)	Rationale	Bottleneck risk
6	Herring population productivity - Pelagic fishing	Strong	Low	Productivity determines fishing quotas, which in turn are a key factor influencing recruitment and hence persistence of the species; Low importance to CEA due to high level of management, with quotas reflecting assessed productivity. Assume managed balancing loop. Exogenous relative to case study area.	No
7	Herring population productivity - Predation	Weak	Low	Ecological interaction that has persisted over long period of time; Part of a balancing loop, assume self-organising. Assume constant over period of CEA. Exogenous relative to case study area.	No
8	Pelagic fishing - Fishing mortality	Strong	Low	Pelagic fishing efforts determines fishing mortality, which is a key factor influencing recruitment and hence persistence of the species. Exogenous relative to case study area.	Yes
9	Fishing mortality - Recruitment of new fish	Strong	Low	Fishing mortality is a key factor influencing recruitment and hence persistence of the species. Low importance to CEA due to high level of management, with quotas reflecting assessed productivity. Assume managed balancing loop. Exogenous relative to case study area.	Yes/No
10	Predation - Recruitment of new fish	Strong	Low	Ecological interaction that has persisted over long period of time; Part of a balancing loop, assume self-organising. Assume constant over period of CEA. Exogenous relative to case study area.	No
11	Natural mortality - Recruitment of new fish	Medium	Low	Ecological interaction that has persisted over long period of time. Assume self-organising. Assume constant over period of CEA. Exogenous relative to case study area.	No
12	Recruitment of new fish - Herring population productivity	Strong	High	Recruitment fundamental to persistence of species. Influenced by other variables/interactions, including direct relationships with managed human activities including endogenous relative to case study area. Changes to recruitment could be influential, hence high importance.	No
13	Egg production - Recruitment of new fish	Strong	NSAH-Low TEH-High	Egg production fundamental to persistence of species. Part of positive reinforcing loop. Assume constant over period of CEA. Exogenous relative to case study area for NSAH, endogenous relative to case study area for TEH.	No

Interaction (cause to effect)		Assumed effect on persistence	Importance for CEA (2000-2015)	Rationale	Bottleneck risk
14	Prey availability - Favourable over-wintering phase for larvae	Strong	Low	Overwintering phase is key for larval survival, potential for a strong link with prey availability. Exogenic environmental influences. Assume constant over period of CEA.	No
15	Prey availability - Growth of surviving fish	Strong	Low	Prey availability a key factor influencing growth rates. Subject to environmental influences at exogenic scales and temporal periods outside CEA boundaries. Assume constant over period of CEA	No
16	Favourable over-wintering phase for larvae - Recruitment of new fish	Strong	Low	Overwintering phase is key for larval survival, potential for a strong link with prey availability. Exogenic environmental influences. Assume constant over period of CEA.	No
17	Climate change - Growth of surviving fish	Weak	Low	Climate change a slow variable. Herring has a wide temperature tolerance. Assume constant over period of CEA. Exogenous relative to case study area.	No
18	Climate change - Regime shifts	Strong	Low	Evidence that shift from cold water to warm water *Calanus* spp. has occurred due to climate change in North Sea, with deleterious effects on herring. As climate change a slow variable, assume constant over period of CEA. Exogenous relative to case study area.	No
19	Climate change - Predation	Unknown	Low	Unknown effect of increased presence of species that predate on herring larvae. As climate change a slow variable, assume constant over period of CEA. Exogenous relative to case study area.	No
20	Climate change - Quality and availability of spawning grounds	Unknown	Low	Unknown effect of changing climate on quality of spawning grounds for herring. As climate change a slow variable, assume constant over period of CEA. Exogenous relative to case study area.	Yes
21	Regime shifts - Prey availability	Strong	Low	Evidence that shift from cold water to warm water *Calanus* spp. has occurred due to climate change in North Sea, with deleterious effects on herring. As climate change a slow variable, assume constant over period of CEA. Exogenous relative to case study area.	No

Interaction (cause to effect)		Assumed effect on persistence	Importance for CEA (2000-2015)	Rationale	Bottleneck risk
22	Quality and availability of spawning grounds - Recruitment of new fish	Strong	High	Persistence of species fundamentally linked to access to spawning grounds of suitable quality at specific periods of time. Influenced by other variables/interactions, including direct relationships with managed human activities including endogenous relative to case study area.	Yes
23	Structural disturbance to benthic habitat - Quality and availability of spawning grounds	Strong	High	Persistence of species fundamentally linked to access to spawning grounds of suitable quality at specific periods of time. Influenced by other variables/interactions, including direct relationships with managed human activities including endogenous relative to case study area.	Yes
24	Noise and vibration - Quality and availability of spawning grounds	Strong	High	Persistence of species fundamentally linked to access to spawning grounds of suitable quality at specific periods of time. Influenced by other variables/interactions, including direct relationships with managed human activities including endogenous relative to case study area.	Yes
25	Offshore wind farm construction - Noise and vibration	Strong	High	Strong evidence that strong underwater noise can interrupt interaction between herring and spawning grounds. Influenced by other variables/interactions, including direct relationships with managed human activities including endogenous relative to case study area.	Yes
26	Ports and shipping - Noise and vibration	Medium	Medium	Strong evidence that strong underwater noise can interrupt interaction between herring and spawning grounds. Shipping has existed for a long period of time in the CEA area and herring has persisted. Shipping noise forecast to increase contributing to chronic noise levels, hence medium importance. Influenced by other variables/interactions, including direct relationships with managed human activities including endogenous relative to case study area.	Yes
27	Aggregate extraction - Noise and vibration	Medium	Medium	Strong evidence that strong underwater noise can interrupt interaction between herring and spawning grounds. Aggregate extraction has existed for a long period of time in the CEA area and herring has persisted. Plans to expand aggregate dredging, contributing to chronic noise levels, hence medium importance. Influenced by other variables/interactions, including direct relationships with managed human activities including endogenous relative to case study area.	Yes
28	Aggregate extraction - Structural disturbance to benthic habitat	Strong	High	Strong evidence that aggregate extraction overlapping with spawning habitat has a long-term damaging effect. Aggregate extraction has	Yes

Interaction (cause to effect)		Assumed effect on persistence	Importance for CEA (2000-2015)	Rationale	Bottleneck risk
				existed for a long period of time in the CEA area and herring has persisted. Plans to expand aggregate dredging, potential to incrementally reduce available spawning habitat, hence high importance. Influenced by other variables/interactions, including direct relationships with managed human activities including endogenous relative to case study area.	
29	Demersal trawling - Structural disturbance to benthic habitat	Strong	High	Strong evidence that demersal fishing with heavy gear has a medium-term damaging effect. Beam-trawling and Otter trawling have existed for a long period of time in the CEA area and herring has persisted. Potential to incrementally impact available spawning habitat, hence high importance. Influenced by other variables/interactions, including direct relationships with managed human activities including endogenous relative to case study area.	Yes
30	Offshore cables - Structural disturbance to benthic habitat	Medium	Medium	Cable laying/trenching overlapping with spawning habitat will have a long-term damaging effect. Plans to increase the number of power cables. Potential to incrementally reduce or disturb available spawning habitat, hence high importance. Influenced by other variables/interactions, including direct relationships with managed human activities including endogenous relative to case study area.	Yes

The preceding results were plotting in Vensim to generate the causal loop diagram (CLD), which depicts the variables and feedback structures influencing the productivity of the receptor population (Figure 30). The productivity of the herring stocks is placed at the centre of the CLD and variables are organised around herring productivity. The different strengths of the effect of interactions on persistence are represented using different arrow widths, with wider arrows indicating a stronger effect. Climate change is represented as a slow variable, in that the changes are gradual relative to the speed of change associated with human activities. How appropriate such an assumption is given the pace of climate change (Brodie et al., 2014; Raimonet and Cloern, 2017) is open to debate.

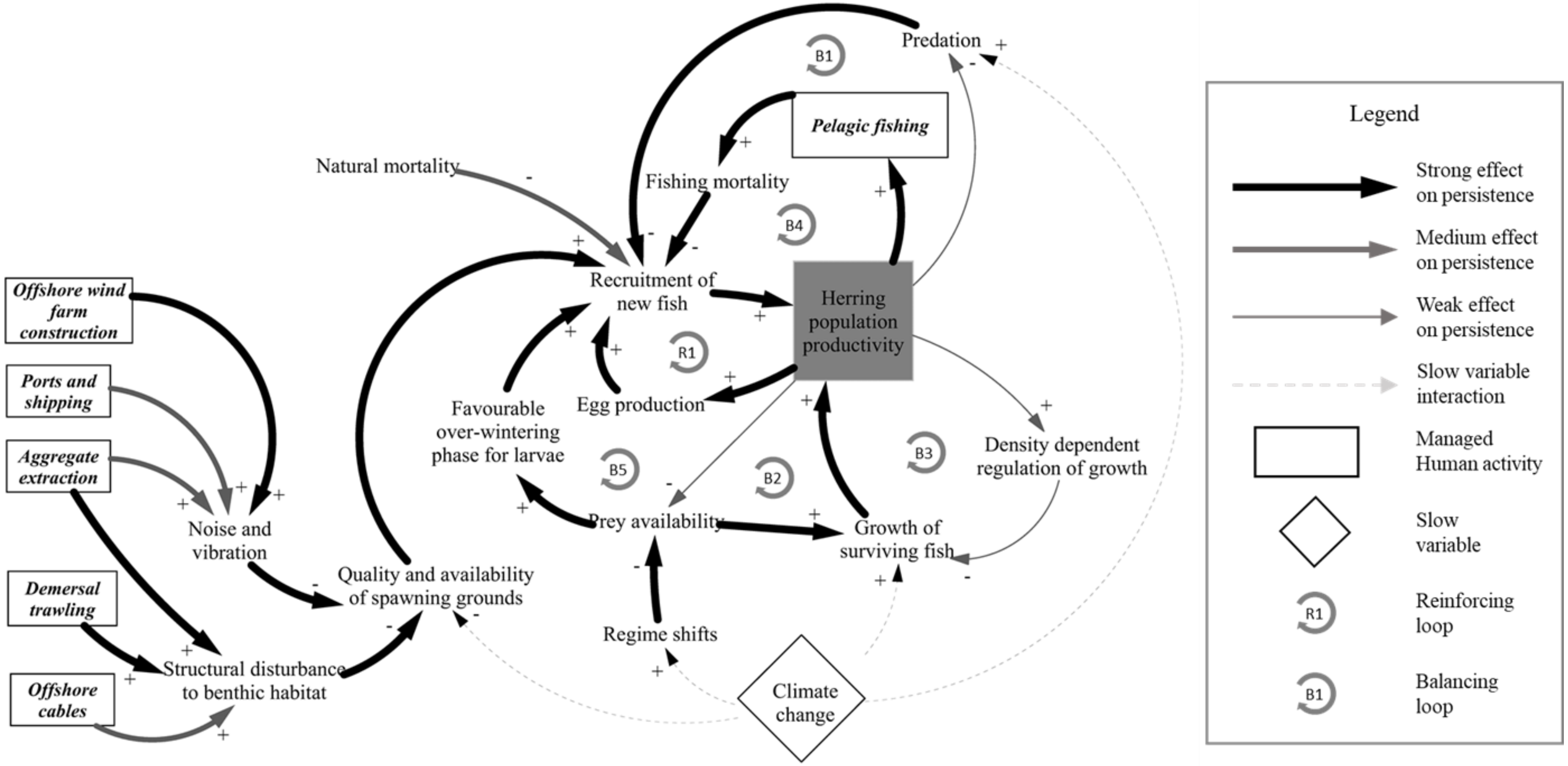

Figure 30. Causal Loop Diagram of the variable and interactions between variables influencing the productivity of the focal receptor. Arrows represent a causal direction from cause to effect. The weight of the arrows indicates the assumed effect of the interaction on the resilience of herring. Polarity signs denote the relationship between the influencing variables and the influenced variable, e.g. '+' denotes that an increase in the influencing variable causes an increase in the influenced variable. R indicate reinforcing feedback loops and B indicates a balancing feedback loop (Table 17).

By specifying the polarities of interactions, the CLD can be used to identify where feedback loops exist (Table 17). Balancing feedback loops tend to have a stabilising, regulating effect on a system, and are a source of resistance within a system to change (Meadows, 2008). Reinforcing feedback loops are self-enhancing, leading to exponential growth or runaway collapses over time (Meadows, 2008).

If the CLD identified that OWFs interacted with a feedback loop, this would suggest that assessing the effects of OWF on the receptor would require an assessment of interactions associated with the loop. However, other than loop B4, which includes pelagic fishing (Table 17), the remaining loops do not include human activities variables. For NSAH, pelagic fisheries are exogenic relative to the case study system scale, while for TEH, fishing mortality was thought to be confined to the case study system scale (Wood, 1981).

Table 17. Reinforcing and balancing feedback loops contributing to the productivity of the focal receptor population.

Variable	Loop number	Loop	Reinforcing/ balancing
Herring population productivity	B1	Herring population productivity - Predation - Recruitment of new fish	Balancing
	B2	Herring population productivity - Prey availability - Growth of surviving fish	Balancing
	B3	Herring population productivity - Density dependent regulation of growth - Growth of surviving fish	Balancing
	B4	Herring population productivity - Pelagic fishing - Fishing mortality - Recruitment of new fish	Balancing
	B5	Herring population productivity - Prey availability - Favourable over-wintering phase for larvae - Recruitment of new fish	Balancing
	R1	Herring population productivity - Egg production - Recruitment of new fish	Reinforcing (positive)

The CLD makes explicit the interactions, including the influencing and influenced variables, and feedback loops assumed to contribute to the resilience of the receptor, where the productivity of the receptor is assumed to be an appropriate proxy for resilience. Extracting a causal tree from the CLD enables the variables and hence interactions contributing to productivity/resilience to be identified, and thereafter the variables amenable to management based on the boundaries of the CEA (Figure 31).

The majority of variables in the causal tree that influence herring dynamics are environmental, such as advection, prey availability, regime shifts and egg production. These variables are exogenic relative to the scale of the case study system boundaries and hence only the consequences can be managed in the case-study area. These interactions and variables can be argued to be not reasonable for inclusion in a project-level CEA, unless there is evidence of rapid change or unusual variability.

The focus can therefore shift to the variables that are endogenous relative to the case study system scale, particularly the human activities where the causes are endogenic relative to the CEA boundaries, hence are amenable to management. These include fishing mortality and activities impacting the quality and availability of spawning grounds. The dependence of herring on spatially discrete patches of spawning ground accessed at discrete periods of time, presents a bottleneck risk. Interruption of access to the spawning grounds in the period preceding and during spawning and structural disturbance of spawning grounds present a high risk of impact to associated herring populations or sub-populations reliant on those spawning grounds. The Thames estuary herring population is a good example of this bottleneck, as three highly localised spawning grounds are known and herring congregate and spawn during a narrow window of time (Roel et al., 2004; Wood, 1981). As well as fishing mortality, monitoring and protection of spawning grounds is a logical management objective to conserve local herring populations. Any activity that disturbs spawning grounds should be considered high-risk, particularly for a locally constrained stock such as the Thames estuary herring.

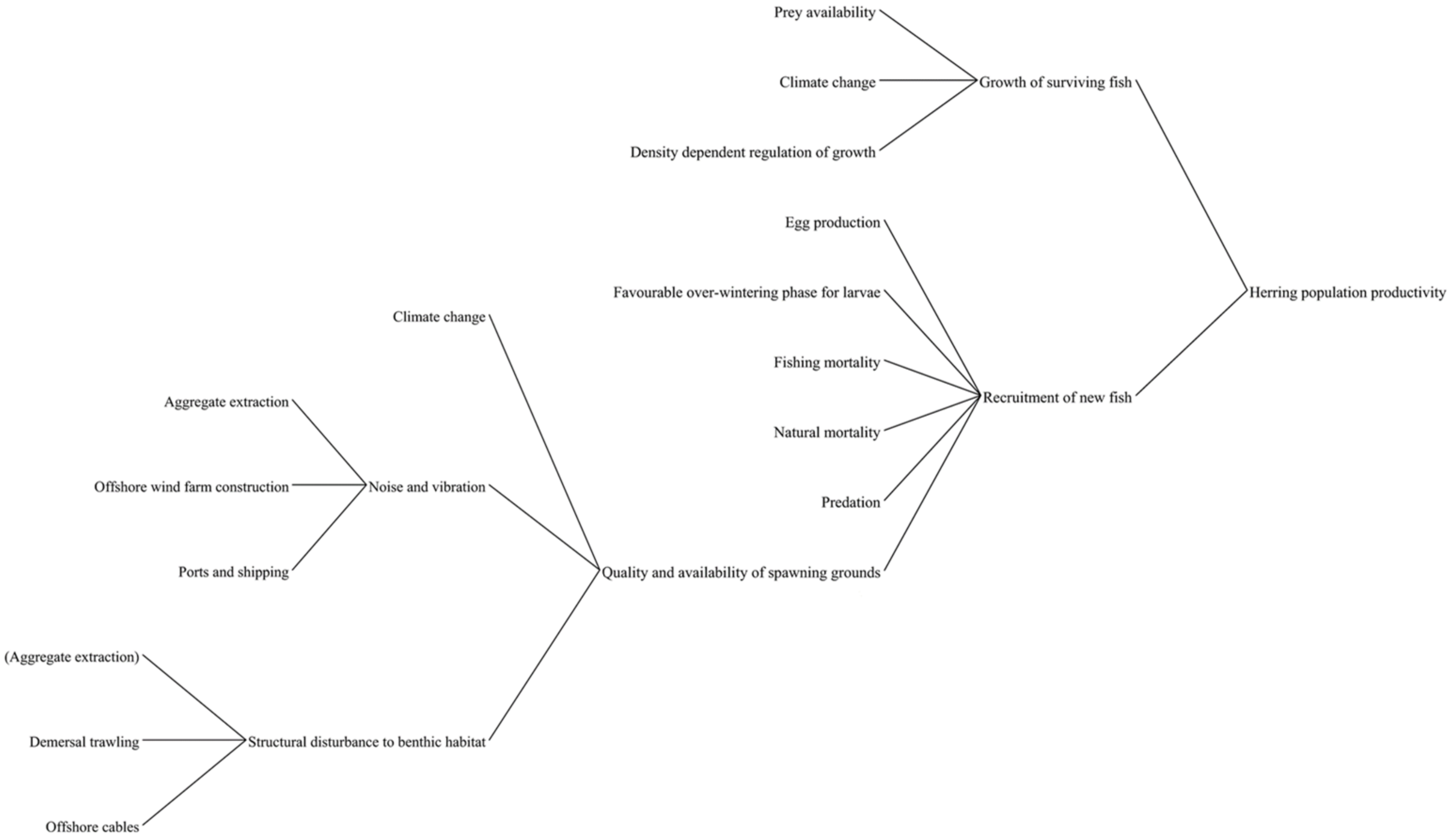

Figure 31. Causal tree of variables and interactions influencing herring population productivity. Other than fishing mortality, human activities directly affecting herring are those that can change the quality and availability of spawning grounds.

In combination with the evidence collated about the receptor lifecycle, the CLD and causal trees support qualitative identification of interactions that are relevant to the CEA and, in combination with a GIS, identification of those interactions that are endogenous to the management area. These interactions and variables are associated with spatial characteristics (endogenic or exogenic relative to the case study area) and temporal lag characteristics (how long it takes for the effect to manifest within the receptor population). Interactions can be identified with spatial and temporal characteristics that suggest a disturbance may influence the resilience of the receptor through disturbing connectivity with discrete spawning grounds for example. The quality of the outputs would likely improve with weightings applied, however the rapid test carried out here suggests CLDs can aid CEA scoping and the receptor pivot steps with evidenced rationales for the conceptual system structure and the interactions to include in a CEA.

6.3.3 Appropriate baselines and boundaries

Offshore wind farm construction commenced in the case study area in October 2003 and additional developments under the Round 1 and Round 2 programmes were constructed periodically resulting in a total of 8 developments during the case study period of 2000-2015 (Table 18). From no offshore wind farms being present in 2003, by 2015 a cumulative total of 344 km^2 of seabed was occupied by offshore wind farms comprising 540 turbines producing 1818.3 MW of electricity. Turbine installation periods were identified from the 4cOffshore website[10].

A challenge identifying the likelihood of temporal exposure arose as there is conflicting evidence about license conditions restricting when piling was permitted for Kentish Flats, Gunfleet Sands and Greater Gabbard wind farms. A report by the MMO suggests piling windows were in place for these wind farms, (Marine Management Organisation, 2014) although detail about the period of the window was not identified. A review by Cefas of monitoring data associated with

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[10] https://www.4coffshore.com

license conditions related to noise does not mention piling restriction and noted that the Thanet restriction was lifted before piling following additional surveys by the developer that reported low herring abundances (Cefas, 2009b). Telephone and email conversations with the MMO were unable to clarify where and for which offshore wind farms piling timing restrictions were enforced. The MMO was contacted to clarify this uncertainty, but the MMO were unable to provide information about which developments had license conditions attached to limit when piling could occur, or about the dates and duration of piling operations. As all 8 offshore wind farms piled turbine foundations, an assumption was made that piling occurred during the periods identified.

Table 18. Expansion of offshore wind farms in the case study area between 2003 and 2015 and turbine installation periods (Data source: www.4coffshore.com).

Offshore wind farm	Recorded start date of installation	Recorded end date of Installation	Number of turbines	Cumulative number of turbines installed	Area occupied (KM2)	Cumulative area of seabed occupied (KM2)	Capacity (MW)	Cumulative capacity (MW)
Scroby Sands	01/10/2003	30/03/2004	30	30	4	4	60	60
Kentish Flats	22/08/2004	19/10/2004	30	60	10	14	90	150
Gunfleet Sands	14/10/2008	30/04/2009	48	108	16	30	172.8	322.8
Greater Gabbard	02/08/2009	31/08/2010	140	248	146	176	504	826.8
Thanet	09/12/2009	28/06/2010	100	348	35	211	300	1126.8
London Array	08/03/2011	19/10/2012	175	523	122	333	630	1756.8
Gunfleet Sands 3	19/09/2012	24/09/2012	2	525	3	336	12	1768.8
Kentish Flats Extension	02/05/2015	25/05/2015	15	540	8	344	49.5	1818.3

The temporal period of the case study covers a series of year-classes of herring, which mature after 3 years (Dickey-Collas et al., 2010). If construction noise disturbs spawning behaviour in one year and if the disturbance has a significant effect on the spawning population, a signal of interrupted spawning would be expected to manifest in 3-4 years after the disturbance. This highlights a complicating factor when setting boundaries for a project-level CEA, as the temporal footprints of noise effects from different developments overlap relative to herring lifecycles. The Downs stock of the NSAH spawns between November and January, and TEH spawns between February and early May. Put into context of the noise effect footprint periods identified and using a GIS to taking into account the spatial footprints of noise effects, 5 of the 8 offshore wind farms would be expected to impact the localised abundance of herring (Table 19).

Table 19. Temporal and spatial overlaps between offshore wind farm noise effect footprints and herring spawning grounds, and % overlap with spawning grounds. Highlighted orange cells indicate where a potential barrier effect could occur (Figure 32). NSAH – North Sea Autumn Spawning Herring (Downs sub-stock); TEH – Thame estuary herring

	Temporal overlap		Spatial overlap		% overlap	
	NSAH	TEH	NSAH	TEH	NSAH[11]	TEH
Scroby Sands	Y	Y	Y	N	11.37%	N/A
Kentish Flats	N	N	N/A	N/A	N/A	N/A
Gunfleet Sands	Y	Y	N	Y	N/A	40.05%
Greater Gabbard	Y	Y	Y	N	21.37%	N/A
Thanet	Y	Y	Y	N	18.09%	N/A
London Array	Y	Y	Y	Y	2.04%	6.92%

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[11] The Downs sub-stock spawning grounds include the two areas shown in Figure 32, and a distinct area in the English Channel, which has been excluded from the calculations here, as it is about 100km southwest of the larger spawning area shown in Figure 32 and the use of spawning grounds may be influenced by natal homing (Dickey-Collas, 2010; cited in Petitgas, 2010).

Gunfleet Sands 3	N	N	N/A	N/A	N/A	N/A
Kentish Flats Extension	N	N	N/A	N/A	N/A	N/A

The GIS was used to calculate the area of overlap between the noise effect footprints from each development and the herring spawning grounds where a spatio-temporal overlap was identified (Table 19). This is represented graphically in Figure 32, which also highlights developments where due to the geography of the bay leading to the Thames estuary, a potential barrier effect could occur and which are highlighted in (Table 19).

The overlaps suggest that five developments would need to investigate effects on herring: Scroby Sands, Gunfleet Sands, Greater Gabbard, Thanet and London Array. The spatial dimension of the effect footprint included in the environmental assessment for these developments should include the extent of the noise pollution calculated by a noise propagation model and put into context of herring. This was the approach observed in the Environmental Statements of Round 3 offshore wind farms evaluated in Chapter 3. The evaluated Environmental Statements did not, however, then include the noise effect footprints of other human activities, or the effects of other human activities on the receptor (i.e. a CEA of herring was not completed.

The temporal dimension of the effect footprint would logically extend to cover the period of turbine foundation installation. When determining appropriate temporal boundaries for the associated CEA, the lifecycle of herring suggests a period of at least 3 years in either direction should be included in an assessment to capture significant noise effects from other offshore wind farms, or indeed from other human activities.

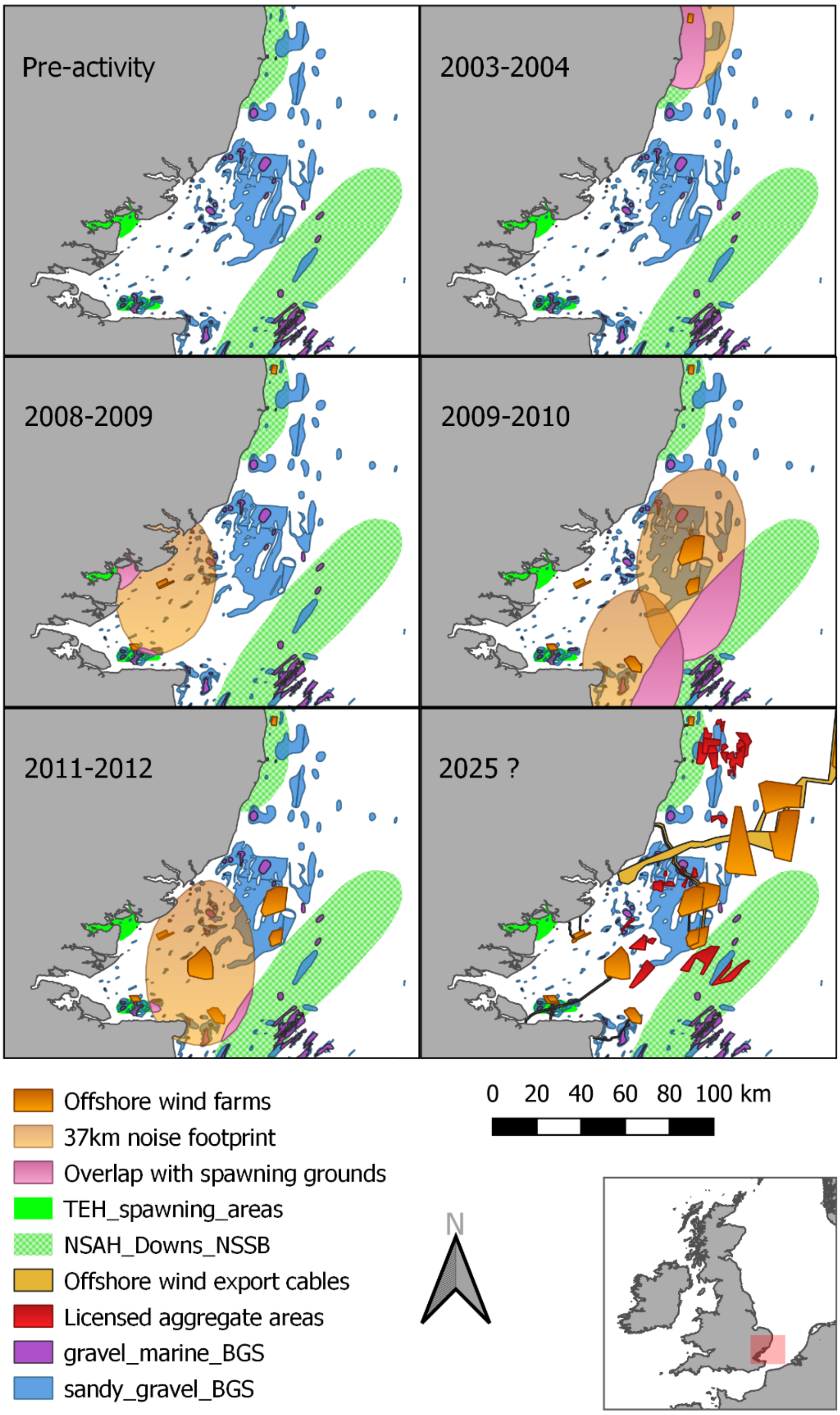

Figure 32. Development of offshore wind in the case study area between 2000-2015 in context of the Downs sub-stock of the North Sea Autumn Spawning herring stock and the Thames estuary herring stock. The final pane in the series (2025?) includes Round 3 offshore wind farms, export cables and all possible aggregate extraction areas (Data sources: Cefas, BGS, The Crown Estate).

At this point the results of the time-series analysis become relevant to investigate what baseline, what reference condition, becomes appropriate. The SSB of NSAH shows a repeated pattern of rising and falling SSB, underpinned by a general increasing trend in stock biomass (Figure 33). SSB has remained above the SSB biomass limit reference point (B_{LIM}) of 800,000 tonnes (ICES HAWG, 2018) since about 1984.

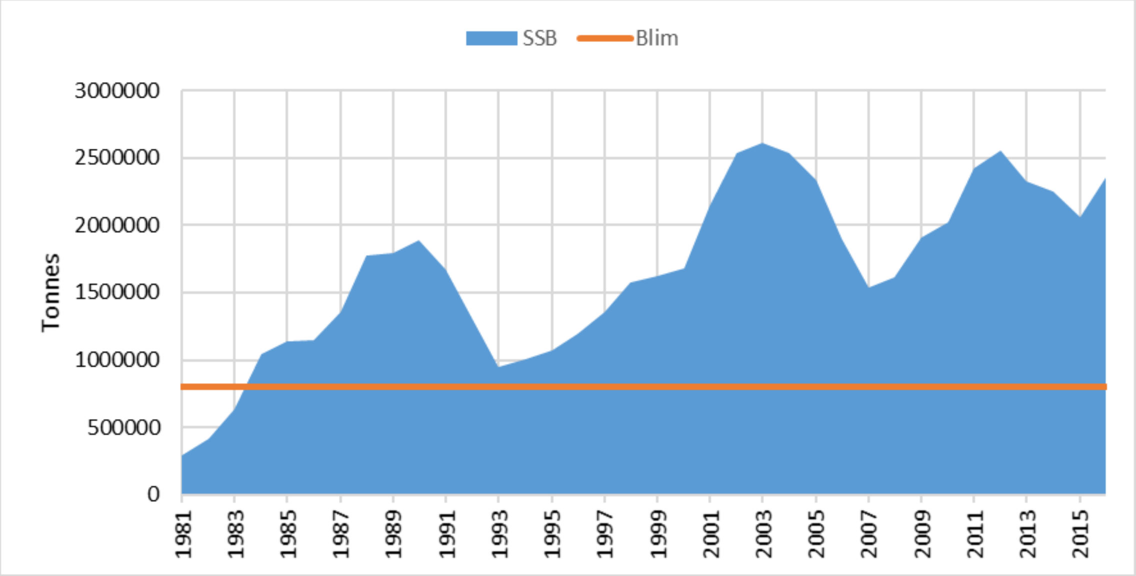

Figure 33. Time-series of spawning stock biomass (SSB) of North Sea Autumn Spawning herring. SSB B_{LIM} is set at 800,000 tonnes as per the latest ICES advice (ICES HAWG, 2018).

Thames estuary herring, by contrast, shows an increasing trend between 1981 and 1992, a period of steep decline between 1992 and 1997, and then a period of gradual decline until 2009. Thereafter there is a period of high variability between 2010 and 2015 (Figure 34). SSB has been below SSB B_{LIM} since 2004.

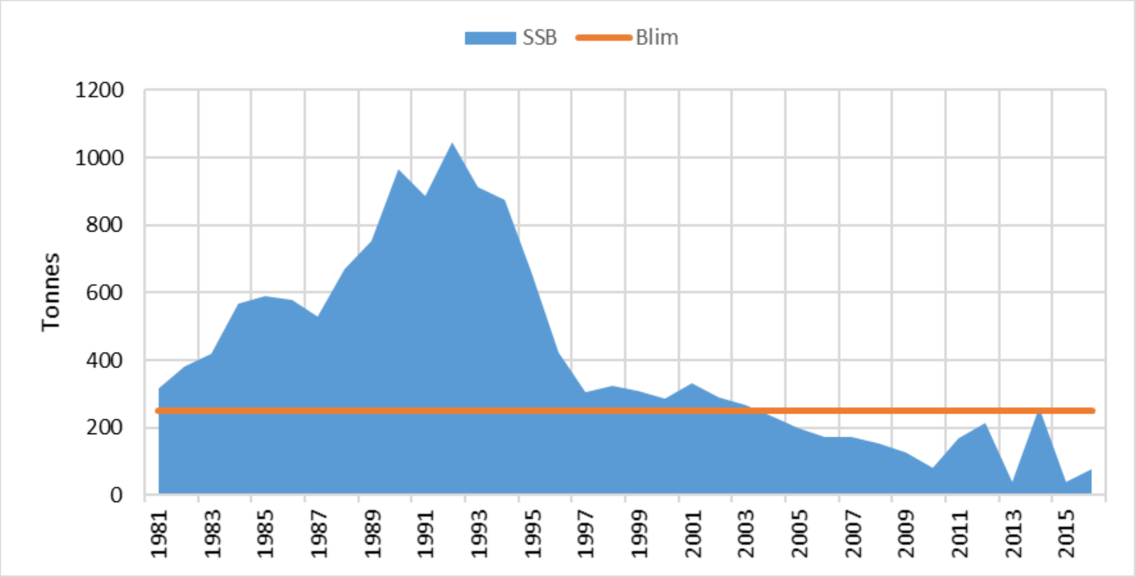

Figure 34. Time-series of spawning stock biomass (SSB) of Thames estuary herring. SSB B_{LIM} is set at 250 tonnes as advised by Roel et al. (2004).

Plots of the percentage change in SSB compared to the preceding year, and the percentage change in SSB compared with 3 years previously provide insight into variation in SSB over the time-series of NSAH and TEH stocks (Figure 35 and Figure 36 respectively). An Order 4 polynomial trend line was fitted to the SSB time-series to reflect the 3 hills and valleys in the two time-series.

While the R^2 indicates a relatively poor fit to the NSAH data (R^2 = 0.67), the increasing trend in SSB is apparent. The % change time-series suggests that since the recovery of the NSAH stock to levels above SSB B_{LIM} in 1984, variance from year to year is reduced, and the cyclical increase-decrease pattern in SSB in visible in the lag time-series (Figure 35). Based on this analysis, there is a clear rationale for using the current SSB as the reference condition (baseline). Sensitivity to changes in the cumulative effects load are likely to be the same as in recent years.

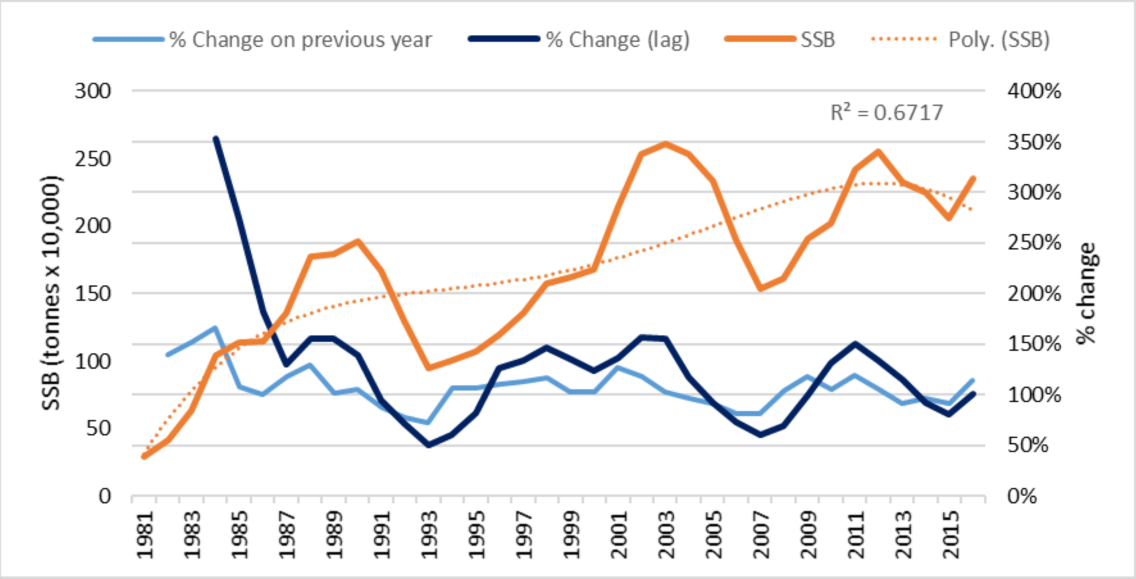

Figure 35. Time-series of North Sea Autumn Spawning herring SSB and the % change in SSB from preceding year (% change on previous year) and from 3-years previously (% change lag). An Order 4 polynomial trend line is fitted to SSB. The very high % change (lag) in the first years is a legacy of the collapse of the NSAH stock caused by overfishing in the 1960s and 1970s, and the recovery of the stock through the 1980s.

The trend in TEH is clear, with an increasing and then decreasing trend in SSB (R^2 = 0.81). The % change time-series show that variation from year-to-year and over the lag time-series did not vary significantly (though the declining trend in SSB is visible) until 2010. Thereafter annual and lag variability increases. The particularly high variability since 2010 may be a feature of the underlying data, as the SSB model has been reliant on landings data from a sentinel fishery since 2007 and can therefore be influenced by factors influencing the behaviour of the vessels in the sentinel fishery (B. Roel, *pers. com*). Nevertheless, there are strong signals that the reference condition for TEH should be derived from an analysis of trends and variation in SSB, and not be based on the current SSB alone.

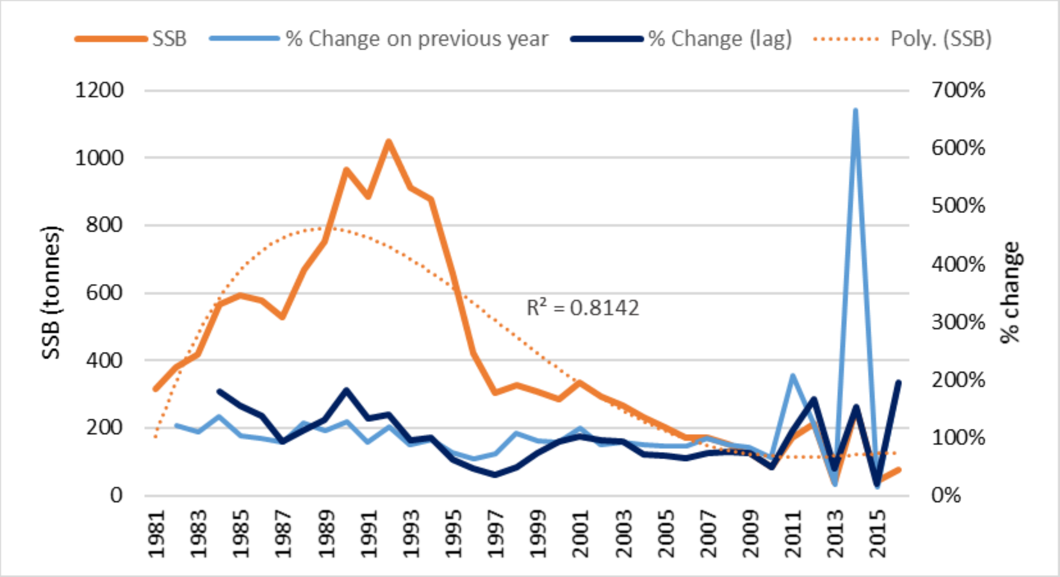

Figure 36. Time-series of Thames estuary herring SSB and the % change in SSB from preceding year (% change on previous year) and from 3-years previously (% change lag). An Order 4 polynomial trend line is fitted to SSB.

Given the small population size and the attendant genetic and demographic risks (Hutchings and Reynolds, 2004; Reynolds et al., 2005), the declining population trend observed between 2001-2010 and the high variability thereafter, there is a rationale to conclude that TEH has been progressively less resilient in the last 15 years. Since SSB dropped below SSB B_{LIM} in 2004, the capacity of the TEH to absorb perturbations and to recover and reorganise has been reduced.

Combining the SSB time-series with the temporal footprints of turbine installation for those developments where a spatio-temporal overlap was identified (Figure 37) does not show a discernible signal in NSAH taking into account the pattern of repeating increasing/decreasing SSB and the underlying increasing trend in SSB over time. For TEH, there is no clear signal of impulsive piling and changes in SSB, however there is much increased variability in SSB from 2010 onwards, which coincides with the period of repeated impulsive sound footprints.

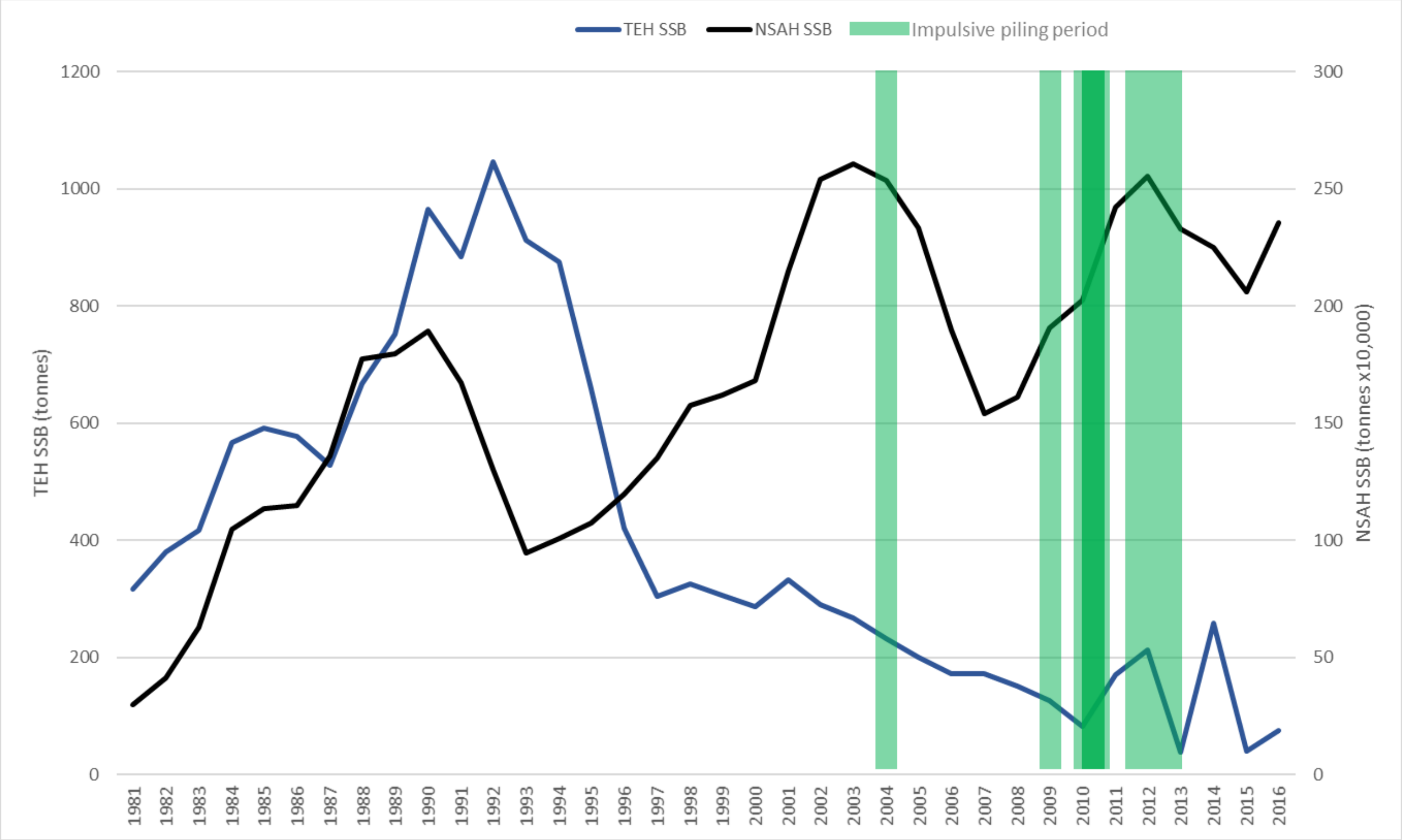

Figure 37. Time-series of spawning stock biomass for North Sea Autumn Spawning herring (NSAH) and Thames estuary herring (TEH) overlaid with the temporal footprints of impulsive noise generated by turbine installation activities for developments identified as have a spatio-temporal overlap with herring stocks in the case-study area. Note the two vertical axes.

The variability in SSB was investigated further to see if there was a correlation between periods of impulsive piling and variation in SSB. The percent coefficient of variation was calculated for the time-series to provide a further indication of the variability of herring SSB over different time-periods (Table 20) where %CV = mean/standard deviation. Four different scenarios were included for NSAH and three for TEH, to reflect the period of time over which SSB data is available for the two stocks, to cover the comparable period over which data is available for both stocks, the period of the case-study, and the period over which noise effects from offshore wind farms have contributed to the cumulative effects load acting on the two stocks.

The variation in the NSAH is high (%CV = 66.9) over the whole period for which data is available, which includes the collapse and recovery of the stock. The variation is less over the period 1981-2016 (%CV = 37.22) and further reduces over the period 2000-2016 (%CV = 15.87). The variation is very similar over the period since offshore wind noise effects have been present in the case-study area (%CV = 15.43).

Table 20. Variation within and between spawning stock biomass time-series for the North Sea Autumn Spawning herring (NSAH) and Thames estuary herring (TEH) covering different periods. Variation is expressed as the percent coefficient of variance (%CV).

Scenario	Stock and period	MEAN (SSB)	SD (SSB)	%CV (SSB)
Period of available data	NSAH 1947 - 2016	1,884,885	1261927	66.95%
Period of available data for TEH	NSAH 1981 - 2016	1,667,956	620751.3	37.22%
Period of case-study	NSAH 2000 - 2016	2,164,520	343559.3	15.87%
Period since OWF noise effects	NSAH 2004 - 2016	2,140,128	330277.9	15.43%

Scenario	Stock and period	MEAN (SSB)	SD (SSB)	%CV (SSB)
Period of available data for TEH	TEH 1981 - 2016	405.9613	282.6936	69.64%
Period of case-study	TEH 2000 - 2016	183.0945	89.6046	48.94%
Period since OWF noise effects	TEH 2009 - 2016	125.7008	81.41459	64.77%

For TEH, variation in SSB is noticeably higher than NSAH in the two directly comparable scenarios (1981-2016 and 2000-16). Over the case study period 2000-2016 variation is TEH SSB is much higher (%CV = 48.97) than NSAH (%CV = 15.87). Over the period since offshore wind noise effects contributed to the cumulative effects load acting on herring, variation in TEH SSB is much higher (%CV = 64.77) compared with NSAH (%CV = 15.43).

This section highlights how an analysis of the relationship between the activity being assessed and the receptors is required before appropriate boundaries and baselines can be identified. The spatial extent of the effect-receptor footprint will be set by the characteristics of the stressor/outcome put in context of the receptor. This should be considered together with other effect-receptor footprints within the management area that are known to influence receptor condition.

For NSAH, there is a rationale for using the current SSB as the reference condition, while for TEH, the precariousness of the stock calls for greater precaution and for the reference condition to be linked to previous changes in SSB. The lifecycle of herring suggests that impacts caused by noise pollution may not manifest in the population for 3 years, although for receptors reliant on the receptor as prey, for example, could be impacted immediately. Monitoring should continue for at least 3 years, although the results presented here also point to the need for a strategic perspective to provide context, as effect footprints overlap to cumulatively affect the receptors.

6.3.4 Assessing the risk of cumulative effects to herring stocks caused by offshore wind farms

Table 21. Rapid risk assessment completed using qualitative approach outlined in Section 6.2.4 and bringing together the evidence collated and analysis completed in Chapters 5 and 6.

Step		Output	Weight of evidence
What is the risk of noise footprints caused by offshore wind farm construction adversely affecting fish stocks? What areas are affected and for how long?			
Risk identification	Source-pathway-receptor	Impulsive piling – noise propagation – herring stocks	Strong: Footprint concept (Section 6.3.1); Case study background (Section 5.2)
	Receptor sensitivity	Herring highly sensitive to noise	Strong: Footprint concept (Section 6.3.1); Case study background (Section 5.2)
		Herring sensitive to disturbance during spawning phase	Strong: Case study background (Section 5.2)
		Indirect receptor sensitivity: predators sensitive to reduced herring abundance, small-scale fishers sensitive to reduced earnings during winter months	Medium: Case study background (Section 5.2)

Step		Output	Weight of evidence
Risk analysis	Assess probabilities	Probability of hazard occurring during construction phase: 1	Strong: Chapter 3 evaluation; Footprint concept (Section 6.3.1)
		Probability of herring being exposed if hazard overlaps with spawning phase: 1	Strong: Spatio-temporal analysis (Section 6.3.3); Footprint concept (Section 6.3.1); Case study background (Section 5.2)
		Probability of herring being strongly affected if within 37km: 0.7	Medium: Analogy from case study background (Section 5.2)
	Assess consequences	Poor recruitment into herring stock from proportion of spawning grounds affected reduces resilience of herring stock	Medium: Analogy from extinction in spring-spawning population; NSAH collapse caused in part by targeting spawning fish and juveniles (Section 5.2); system interactions analysis (Section 6.3.2)
		Disturbance to trophic system for the period of disturbance results in poor recruitment for predator species reliant on seasonal herring abundance	Medium: Analogy from case study background (Section 5.2); system interactions analysis (Section 6.3.2)

Step		Output	Weight of evidence
		Reduced abundance of herring decreases catch per unit effort for small-scale vessels resulting in reduced earnings	Weak: known small-scale fishery reliant on herring during winter months, old references (Section 5.2)
	Characterise risk	Within 37km of impulsive piling, exposure-effect evidence suggests herring likely to avoid noise effect footprint	Medium: Analogy from case study background (Section 5.2)
		If spawning disturbed, duration of effect likely to last one year until following spawning season (if no further disturbances in following year)	Medium: Analogy from case study background (Section 5.2)
		Likelihood of risk of significant impact influenced by percentage of overlap with spawning grounds and/or barrier effects preventing access to spawning grounds or disturbing spawning	Weak: assumption based on analysis in sections 6.3.2 and 6.3.3

<table>
<tr><th>Step</th><th>Output</th><th>Weight of evidence</th></tr>
<tr><td>Risk evaluation</td><td colspan="2">There is good evidence that offshore wind farm construction noise can adversely impact herring. The risk is high in areas where there is a spatio-temporal overlap with spawning activity. There is evidence that adverse impacts to social-ecological components linked to herring can occur. The significance of the risk is influenced by the extent and duration of overlapping effect-receptor footprints, and by the strength and timing of interactions with social-ecological system components linked to herring. The significance of the risk is also influenced by the reference condition of the herring, which for TEH is poor and for NSAH is good. Where exposure criteria are met, the risk of offshore wind farms adversely impacting TEH is high. Where exposure criteria are met AND the effect footprint is of the scale assessed in this chapter, the risk of offshore wind farms adversely impacting NSAH is low.</td></tr>
</table>

6.4 Discussion

6.4.1 Reflections on the case-study

The key conclusion from the analyses completed for this chapter is that it was not possible to identify a signal of offshore wind development in the two herring stocks using the methods applied. Therefore, the hypothesis was shown to be true. However, for Thames estuary herring, the analyses also show that not identifying a signal of offshore wind development does not equate to offshore wind farms having no adverse impact on this stock.

There is strong empirical and modelled evidence that noise effects will disturb herring over a large spatial extent. Analysing whether an impact *sensu* Gill (2005) has occurred or is likely to occur is complicated by the range of influences acting on herring. In context of the case study, the key concern relates to offshore wind farm construction noise interfering with spawning aggregations and spawning behaviour, and potentially the abundance of herring for predators (Perrow et al., 2011; Skeate et al., 2012). The persistence of species associated with a specific habitat is influenced by the structure of the habitat being maintained (Chambers et al., 2017). Herring is a good example of this, with its evolutionary bottleneck created by the relationship with spatially distinct substratum that is accessed at distinct times of the year (but which can vary; Winters and Wheeler, 1996). This is particularly true for TEH, where the stock is intrinsically linked to a very small extent of spawning grounds relative to NSAH.

Applying the CEA pathway to the cumulative effects question set, albeit in a largely quantitative way, provided more context from which to guide a CEA of the effects of offshore wind on receptors. The footprint concept supported identified of which stressors and processes to focus on and clearly communicated the rationale for including/omitting stressors from a CEA. More detailed quantitative approaches to developing effect-receptor footprints would enable the approach to be refined and for the applicability of the approach across social-ecological system components to be tested. The analysis presented in this chapter contributes a test of the approach and it is straightforward to conceive how the footprint concept could be applied consistently across receptors and activities. It is a useful tool to aid communication of the spatio-temporal characteristics of effects arising from human activities, and also supports to communicate the rationale for focussing on specific effects in relation to specific receptors.

The CLD makes it clear that management and protection of essential habitat for herring depends on coherent management and monitoring of the range of activities that perturb herring spawning behaviour and habitat. The identification of this bottleneck provides a clear rationale for CEAs to put effort into assessing how the effects of the activity in question interact with other endogenous effects to change access to and the structure of the spawning grounds. The CLD as applied in this chapter also strongly supports the rationale for project-level CEA to be supported by an overarching CEA process, the strategic CEA proposed in Chapter 4. This strategic perspective is essential to counter the risk that apparently minor, transient effects, such as noise pollution, accumulate with other effects, such as incremental loss of habitat from aggregate extraction or abrasion by heavy fishing gear, resulting in non-linear effects. Such a scenario could occur if herring retreat to key spawning grounds, as has been observed when the population is in decline (Dickey-Collas et al., 2010) and concentrating spawning increases egg mortality by successive spawning waves suffocating eggs laid previously (Wood 1981). Restoring and maintaining the spatial diversity of spawning grounds would infer greater resilience to changes in exploitation, environment and fish behaviour (McPherson et al., 2001, cited in Dickey-Collas et al., 2010). The consequences of resistance being overwhelmed at local scales require research, and into the consequences of local depletions in herring on connected social-ecological system components.

Based on the analysis of the SSB time-series, there is strong justification why the sensitivity of the two herring stocks to noise effect footprints should be considered to be different. There is a question whether time-series of SSB are appropriate to use as a proxy for resilience is an area for future research. There is high confidence in the quality of SSB data for herring (Simmonds, 2009). However, Kell et al. (2016) point to the variability of stock reproductive potential over time as being related to more than only SSB. For reasons yet to be determined, herring recruitment has fallen significantly since 2002 despite the SSB remaining above management reference points (Corten, 2013; Payne et al., 2009). The risk, therefore, is that SSB can underestimate uncertainties associated with reproductive potential (Kell et al., 2016). A further issue arises from the stochastic traits of herring populations and predictions of future productivity from year-to-year are of limited use as changes in environmental variables and linked ecosystem components can have a profound effect of recruitment, but we are not able to fully understanding the interactions and implications of change (Dickey-Collas et al., 2010). Nevertheless, SSB has operated well as a proxy for stock reproductive potential (Dickey-Collas et al., 2010) and in the interests of pragmatism, SSB can be an appropriate metric to investigate reference conditions and the resilience of receptors.

More complex statistical analysis of time-series could improve the exploration of relationships and interactions between trends of multiple time-series (Sonderblohm et al., 2014). This requires comparable time-series of the variables identified as important to the productivity of the receptor, and multifactorial time-series analyses have been completed for herring (see for example: Dickey-Collas et al., 2010; Payne, 2010; Rockmann et al., 2011). Dickey-Collas et al. (2010) point out that searching for one critical variable driving changes in recruitment may be naïve unless the spatial and temporal differences between spawning grounds (or between nursery grounds) is accounted for (Dickey-Collas et al., 2010). This could be argued to be beyond what is reasonable to expect of a project- or activity-level assessment, but there evidence collated and the use of GIS suggest that more refined assessments of herring are possible than were encountered in the Fish and Shellfish chapter of Environmental Statements evaluated in Chapter 3.

Returning to the case study, the conclusion of the risk assessment was that the TEH stock is likely to be adversely affected if there is an overlap between noise effect footprints and TEH spawning aggregations, spawning grounds, or migration to spawning grounds. The noise effect footprint will vary depending on the characteristics of the noise generated and the environment transmitting the noise and vibration. The duration and frequency of the noise created will also influence the response in herring, but there is evidence that herring may abandon spawning if stressed (Eggers et al., 2015; Geffen, 2009) suggesting that a precautionary approach is justifiable. Hence, in the absence of information to the contrary, it is reasonable to assume that if there is an overlap between TEH during the spawning phase, including aggregation, and noise-herring effect footprints, recruitment will be impacted. Responding to the ICES herring advice (ICES HAWG, 2018) there is a risk that the turbine foundation installation phase of offshore wind farm lifecycles would be detrimental to the Thames estuary herring stock, where exposure criteria are met.

For NSAH, the low variance in SSB since 1981 and the underlying increasing trend in SSB, and the distance between current SSB and SSB B_{LIM} suggests that offshore wind farms of the scale included in this assessment are unlikely to be detrimental to the Downs sub-stock of the North Sea Autumn Spawning herring stock. A caveat is that changes in other human activities may reduce the resilience of NSAH to future impacts, as may climate change. Here, causal loop diagrams (CLDs) in combination with the CEA pathway can help prioritise uncertainties for research by identifying bottlenecks, endogenic (i.e. amenable to management) versus exogenic variables, and supporting structured investigation of the strength and importance of interactions.

There are two relevant precedents when considering the trajectory of the Thames estuary stock. The autumn spawning herring meta-stock collapsed and then recovered once the principal pressure, fishing, was effectively managed (Hutchings and Reynolds, 2004), suggesting that the TEH stock could rebuild if the negative effects of endogenous human activities can be managed. The second precedent is the recorded extinction of a spring-spawning herring stock in Norwegian waters (ICES 2018), indicating a very real possibility of a similar fate for TEH with consequent impacts on associated social-ecological system components.

6.4.2 Reflections on applying evidence and approaches to the CEA pathway

While the approaches tested are useful, there is a clear problem isolating the contribution of one particular activity to the cumulative effects load. More advanced statistical and quantitative approaches may prove more fruitful, but problematic evidence gaps were identified. Little evidence was found that validated predicted effects on herring. Information about how to scale effects up to the regional level was very limited and no multi-stressor response studies were identified. Evidence for non-linear effects typically stems from experimental research and, for ecosystems, from statistical analysis of suitable survey data to identify stressor interactions. Such information was not identified for herring. Proxies such as measuring change in the pressures may be a solution in combination with the assumption of additive responses in the absence of information to the contrary (Judd et al., 2015). One direction for future research would be to populate the CLD with available data to create a stock-flow model to appraise how changes to interactions propagate through the modelled system, combined with information about disturbance and recovery rates.

The key benefit of the CEA pathway is the robust context developed that supports a risk assessment approach. A robust scoping step can be completed, the receptor pivot phase provides insights into relevant endogenous interactions relative to the system defined, and the boundaries and baseline can be justified in context of a project-level CEA. At least in the case-study area over the period examined, however, the range of influences on herring points to the need for coherent CEAs that can collectively contribute to better understanding the consequences of changes to the cumulative effects load acting on the receptor.

To support practitioners and to reduce variability, guidelines are required that defines how to specify and monitor trends over time. Coordination between management objectives and survey/monitoring objectives (requiring coordination between regulators and industries) is critical to establish and maintain data collection that supports appropriate statistical analysis of temporal trends over an appropriate period of time (Wagner et al., 2013), pointing to the value of coherent CEAs nested within a strategic CEA process.

6.5 Conclusion

This chapter presents the results of applying the evidence to the project-level steps of the CEA pathway (from 2-5). The broader intention was to generate evidence to reach a conclusion whether the CEA pathway is more effective than a typical CEA applied to offshore wind farm environmental uncertainties, or not. The key weakness identified was the difficulty ascribing a change to a specific activity, in the absence of a clear signal. The key strength identified was the improved context from which a risk assessment can be completed, including a more robust characterisation of the receptor reference condition, and a robust rationale for where spatial and temporal boundaries are set.

The process applied to identify evidence and to evaluate it in context of the case study indicates that the data and approaches exist that would result in more robust risk assessments than are currently submitted in support of license applications. This supports an interim statement that the CEA pathway could result in improved CEA relative to project-level CEAs currently completed, if supported by an overarching strategic process. Further, that qualitatively better CEA is possible now, though whether qualitative approaches would meet the evidence requirements of decision-makers requires research.

The next chapter brings the findings from Chapters 5 and 6 together with the research from the preceding chapters and discusses how the CEA pathway performed, where and how improvements may happen. The broader question, whether CEA is distinct from EIA and SEA, and whether the pathway offers any prospects for progress, is also discussed.

7 Bringing it all together

7.1 What is cumulative effects assessment?

Over the course of the research completed, the comprehension of what is CEA has evolved, notably in light of the realisation that assessing and managing cumulative effects benefits from systems thinking. There is no shortage of definitions of CEA but the lack of a universal definition has been suggested to be a hindrance (Cooper and Sheate, 2004). However, the breadth of fields where cumulative effects are relevant arguably precludes a single, appropriate definition for all scenarios (Duinker et al., 2012; Judd et al., 2015).

In seeking to provide a concluding definition of CEA for the thesis, it is useful to heed the advice of Duinker et al. (2012) that the complexity of the topic means that comprehensive definitions should be welcomed and simple definitions treated with caution. One of the first points of clarification is the discipline within which CEA sits. Jones (2016) states that CEA is a sub-discipline of EIA and that the operational steps of CEA are agreed, meaning that the main obstacles to improved CEA are not scientific. However, as discussed in Chapter 2, CEAs encompass a broader field than EIA alone, and as noted by Judd et al. (2015) many drivers lie behind the variety of CEA observed today. This thesis argues that CEA is not a sub-discipline of EIA. Research into how to assess the cumulative effects of human activities, including individual developments, has expanded beyond the remit of EIA alone. EIA should be a sub-discipline of CEA.

The CEA pathway developed and proposed in this thesis focuses on CEA driven by the legal requirement to assess the cumulative effects of human activities. As stated above, the thesis proposes that CEA should be the overarching discipline guiding the practice of project-level and plan-level environmental assessments. Jones (2016) concludes that CEA should be undertaken regionally and not project-by-project. This is the conception of CEA applied by much of the scientific literature on CEA theory, reviewed in Chapter 2, and the research presented in this thesis concurs that regional CEA is necessary. However, there are pragmatic and scientific reasons why effects to improve project-level assessments should continue. The roles and responsibilities, and the legal infrastructure underpinning EIA (and to a lesser extent SEA) is established and functions. Evolving this system to serve CEA information needs would seem a less challenging task establishing a new legal, technical and bureaucratic infrastructure. The critical caveat is that project-level CEA will only be effective if underpinned by a strategic process that provides the necessary regional context to assess and manage cumulative effects.

Jones raises a point that the main obstacles to improved CEA are not scientific, as there are sufficient robust methodologies to conduct meaningful CEA (Jones, 2016). The research completed for this thesis partially agrees, as better practice than that found by reviews of CEA (Chapter 3 and, e.g. Foley et al., 2017) is clearly possible using existing techniques and data (Chapters 5 and 6). However, the conception of CEA that is advocated here requires the integration of concepts that are not well defined, including sustainable development (the roots and ambiguities are well discussed in Du Pisani, 2006, and Wu, 2013), social-ecological systems (Levin et al., 2013; Österblom et al., 2016) and resilience (Gibbs, 2009; Standish et al., 2014). For CEA to progress to deliver meaningful assessments relative to these concepts will require further research.

Perhaps the clearest conclusion from the research, from the literature review through to the results of testing the CEA pathway, are that multiple CEAs will always be necessary and to assess and manage cumulative effects, an ongoing CEA process is required that is focussed on system structures and dynamics. The thesis recommends that CEA be reconceived as a strategic process into which multiple tractable CEAs feed, and which use the strategic CEA as a source of information to guide the setting of baselines and boundaries. Not only does this require consistency across CEAs, it requires a fundamental change in environmental assessment systems, to evolve from “a shallow adversarial process to a technically rigorous and collaborative one” (Greig and Duinker, 2014; pg 24).

Sinclair et al. (2017) cogently argue that better practice will follow when “CEA becomes a mindset that guides all facets of Environmental Assessment” (Sinclair et al., 2017; pg 183). As a contribution to implementing this mindset, a definition of CEA is proposed that includes CEA as a practice and CEA as a process:

> *The practice of CEA is the delivery of assessments of the risk that changes to the cumulative effects load experienced by receptors and caused by human activities will adversely affect the structure and functioning of social-ecological systems.*
>
> *The process of CEA is the regional context required to make strategic decisions about the significance of the risk assessments supplied by the practice of CEA.*

Human activities create spatio-temporal effects footprints that accumulate over the spatio-temporal footprint of receptors, resulting in incremental and sometime sudden changes in receptor species, communities and habitats. Changing the number and extent of activity-effect-receptor footprints acting on receptors will change the cumulative effects load experienced by receptors, for better or worse. The consequences of the change will depend on how the effects accumulate, and the response to the change will reflect the resistance and resilience of the receptors and of the system, which changes over time. Hence, regional management of cumulative effects requires a CEA process.

This thesis also argues that to make efficient progress with marine planning and management it is essential to benefit from the legal requirement to assess the cumulative effects of projects and plans. To date, project-level and plan-level environmental assessments do not adequately assess cumulative effects (Chapter 3, and (Dibo et al., 2018; Foley et al., 2017; Noble et al., 2019; Sinclair et al., 2017) although legal obligations to do so exist in most countries with EIA and SEA legislation. The key question, which the main hypothesis sought to test, is whether it is possible to improve project-level CEA to meaningfully support regional marine management and planning. As discussed in Chapters 2 and 4, and established in Chapters 5 and 6, the implications of ‘meaningful’ in an age of ecosystem management require a holistic perspective far beyond that feasible for reductionist assessments of project-level effects. Whether the CEA pathway proposed in this thesis is a feasible tool to improve project-level CEA is discussed later in this chapter.

The point of expending time and resources assessing the effects of human activities is to transition to sustainability *sensu strictu* Wu (2013). While the specifics of reaching sustainability are ambiguous, there are numerous precedents where human activities have overwhelmed social-ecological systems with catastrophic consequences for the humans therein (Cumming and Peterson, 2017). The nature of complex adaptive systems (Levin et al., 2013; Levin and Lubchenco, 2008) demands that marine management and planning is supported by meaningful CEAs, and that CEAs are heavily weighted in contemporary decision-making (Sinclair et al., 2017). Progress in the practice and process of CEA is critical.

7.2 In context of MREDs

The research for this thesis was originally conceived to investigate how to assess the cumulative effects of expanding MREDs in UK waters. It soon became apparent that uncertainties about MRED effects also stem from uncertainties about the effects of other activities, of the dynamics of receptors, and of the structure and functioning of social-ecological systems. Further, that uncertainties about how to assess cumulative effects of any activity hindered efforts to reduce uncertainties specific to MREDs. This led to a deeper investigation into CEA and into the nature of cumulative effects, which led to systems thinking as a means of structuring the holistic perspective demanded if cumulative effects are to be assessed and managed. Literature on CEA in the 1980s (e.g. Preston and Bedford, 1988) and in recent years (e.g. Foley et al., 2017; Noble et al., 2017; Sinclair et al., 2017) highlights the need for a holistic, broader perspective to assess and manage cumulative effects. The advance here has been to investigate how to link explicitly CEA theory and systems thinking, where the latter provides various methods, such as causal loop diagrams, to investigate the interactions between components of social-ecological systems.

The influence of perspectives on CEA, notably on determinations of significance, also became apparent as the research progressed. Different perspectives can result in different interpretations of the significance of permitting a MRED; local versus regional, species conservation versus global climate change, economic growth versus degrowth. One of the evident challenges for marine management and planning with respect to MREDs is how to accommodate different scales when determining significance of effects. At a local scale, an effect can be significant, but when viewed from a regional perspective, the significance appears reduced (Therivel and Ross, 2007). This has influenced project-level assessments, where the anticipated cumulative effects of developments and activities are concluded to be insignificant and can be ignored (Duinker, 2013; cited in Sinclair et al., 2017). This clearly conflicts with CEA theory, which states that individually minor effects can accumulate over broad spatial and temporal scales, resulting in significant effects (Harriman and Noble, 2008; Therivel and Ross, 2007).

The transition to low carbon energy generation requires that MREDs be installed and operated in greater numbers (Sithole et al., 2016). Mitigation measures and license conditions will reduce some effects, but adverse impacts are inevitable, hence trade-offs are too, including for human communities (Friedman et al., 2018). There is also the scenario that permitting one MRED may preclude future developments in the same region, which leads to questions about the impartiality of project-level assessments that are developer-led (Sinclair et al., 2017). These uncertainties and the knowledge gaps about MRED (and other human activity) cumulative effects suggest that the values underlying efforts to streamline EIA processes should be scrutinised in a broad, inclusive forum. Perhaps the most important recommendation from this research, which involves the least systemic change, is to urgently develop and implement CEA standards for all maritime industries and activities in management areas.

7.3 Revisiting the key CEA considerations

The literature on CEA theory points to considerations that must be accounted for to improve CEA, as discussed in Chapter 2. The key considerations identified included ecological connectivity, temporal and spatial accumulation of effects, endogenous and exogenous sources of pressures, placing receptors at the centre of assessments, and clarity about the purpose of each CEA. The research completed for this thesis led to a revision of these considerations to better reflect the evolved conception of CEA.

How effects accumulate: The nature of cumulative effects requires broader spatial and temporal perspectives than are typically applied in project-level assessments. The scales over which effects accumulate and the uncertainties about how receptors respond to cumulative effects emphasises the need for a strategic process to provide the context required to put the localised, higher resolution outputs from project-level assessments to better use. Integrating the receptor's perspective of effects is critical to advance CEA and to appropriate considerations of the scales of effect accumulation (Beanlands and Duinker, 1984; Segner et al., 2014; Sinclair et al., 2017). The receptor perspective naturally leads to consideration of the connectivity between ecosystem components and hence on to social-ecological systems.

Social-ecological systems and connectivity: Human activities and ecological resources are embedded in an intertwined system (Österblom et al., 2016). Reductionist approaches to assessments are necessary given the complexity of social-ecological systems, but significance determinations, management interventions and policies that do not account for the broader systems perspective risk undesirable outcomes (Levin et al., 2013). To be effective, project-level CEAs must be able to refer to a strategic, broader perspective that is based in social-ecological systems thinking. This will require increased interdisciplinary efforts and an emphasis on establishing systematic structuring of assessments to enable knowledge to accumulate.

Enabling common ground: The range of activities and scenarios that require CEAs, and the interdisciplinary research required to investigate social-ecological system structure and functioning, precludes a single methodology being defined. Assessing and managing cumulative effects requires collaboration and interdisciplinary research to link the outputs of CEAs to accrue knowledge. Commonalities between CEAs independent of drivers are possible; the overarching purpose of CEAs should be to support sustainable development.

Agreeing a high-level intent, basic principles and a common language would aid coherence and at the very least, CEAs should be transparent in terms of purpose, definitions, treatment of data, and interpretations of significance, including underlying values.

Proportionality of boundaries and baselines: Appropriate boundaries and baselines should be defined on a case-by-case basis. The footprints of the effects being assessed, the distribution, lifecycle and connectivity of receptors, and the extent of pertinent management areas will shape what is proportionate to include in a CEA. Defining appropriate boundaries and baselines is likely to be iterative, with revisions made in light of investigation into the nature of system interactions associated with the activity-effect-receptor footprints, whether system interactions are exogenous or endogenous to the management area, and whether variables are fast or slow relative to the temporal extent of the CEA.

7.4 Reflections on the CEA pathway

The research completed for Chapters 5 and 6 provided important first steps in testing whether the CEA pathway is logical and practical. The main finding was that where data exists the steps are viable and the outputs from preceding steps support the completion of subsequent steps. That is, the CEA pathway appears to follow a logical route. Where data do not exist or are not appropriate to deliver the intended output, qualitative approaches enable progress. In comparison with typical EIAs, the approach provides a more complete foundation from which to assess the risk that human activities will adversely impact receptors within social-ecological systems. The graphical and analytical outputs presented in Chapter 6 contribute to understanding the broader perspective required to assess and manage cumulative effects. The outputs also support communication of cumulative effects scenarios and could be used to create a boundary object, a “collaborative product that is adaptable to multiple viewpoints and robust enough to maintain identity across those viewpoints” (Thornton and Hebert, 2015; pg.372). Such an object would support dialogue between stakeholders, including maritime industries, regulators and conservation agencies to explore the consequences of permitting or not permitting certain activities, and the scales at which such consequences might apply.

The principal benefit of the CEA pathway over the approaches to assessing cumulative effects observed in Chapter 3 (that are typical of project-level environmental assessments), is that the pathway is grounded in CEA theory. The CEA pathway was developed with the key CEA considerations identified in Chapter 2 and refined in section 7.3 in mind. It therefore stems from a different conceptual starting point than EIA, where EIA seeks to inform decision-makers about the consequences of individual developments or activities (Glasson et al., 2012). The argument in this thesis and by other researchers (e.g. Duinker et al., 2012; Dube et al., 2013; Sinclair et al., 2016) is that EIAs are fundamentally unable to adequately assess cumulative effects, because of the conceptual starting point of EIA. This is important because social-ecological systems are shaped by cumulative effects, yet the principal tool for CEA used in contemporary decision-making is not fit for purpose.

The institutionalisation of SEA stemmed from the recognition that EIAs alone were not providing sufficient information to manage the effects of human activities over the timescales and spatial extents that affecting the wellbeing of societies. SEAs should assess cumulative effects (Lobos and Partidario, 2014; Tetlow and Hanusch, 2012) but practice applies project-level assessment principles (Noble et al., 2019). SEAs also suffer from an overly reductionist perspective that limits insights into how human activities affect systems (Gasparatos et al., 2008). SEAs, then, also struggle to assess cumulative effects in a meaningful way. There is a reasonable argument that the CEA pathway, with a grounding in CEA theory that requires a more holistic perspective, is conceptually stronger than EIA or SEA as a tool to support sustainable development.

A second advantage the CEA pathway has over EIA and SEA is that it was developed with ecosystem management in mind from the outset, where the effects of human activities need to be put into context of the dynamic and multi-scalar characteristics of social-ecological systems. In the European Union, EIA has been part of the legal landscape protecting the environment since 1988, and

SEA since 2001 (and transposed into national law by 2004, Cooper and Sheate, 2004). By contrast, the Marine Strategy Framework Directive (2008/56/EC), which stipulates implementation of ecosystem management was adopted in 2008. EIA and SEA predate ecosystem management and lack a systems perspective (Gunn and Noble, 2009). Revising the EIA and SEA systems to address this shortcoming is possible; in the European Union the revised EIA Directive (2014/52/EU) establishes the conditions to better integrate systems thinking (Lonsdale et al., 2017), though this is not routinely done in current practice (Lonsdale et al., 2017). However, the conceptual shortcomings of EIA and SEA relative to assessing cumulative effects remain. In this regard, the CEA pathway is more than a simple evolution of EIA thinking, as it stems from consideration of the information needs required for ecosystem management.

Turning to the practicalities of the CEA pathway, strengths and weaknesses emerged from the tests applied for Chapters 5 and 6. Recognising that consistency between CEAs of maritime activities is necessary to achieve coherent practice, the CEA pathway was structured to first establish the conditions for consistency (Step 1) and then to guide the application of evidence to address cumulative effects uncertainties that stem from human activities in multi-activity environments. Chapter 5 identified that there is sufficient robust information to enable consistency of language, treatment of uncertainty and the approach to risk assessment. The conditions required to enable consistency across CEAs, and hence coherence at a strategic level, already exist. This thesis argues that the directed accumulation of knowledge from multiple CEAs is the most urgent improvement for CEA practice relative to ecosystem management. The information exists to make progress in this regard, providing support to Jone’s statement that the main obstacles to improved CEA are procedural rather than scientific (Jones, 2016).

The focus on receptors from Step 3 onwards supports the development of a more comprehensive characterisation of the cumulative effects load acting on a receptor. The steps completed to derive the Causal Loop Diagram (CLD) for herring should be familiar to EIA practitioners with the difference being the extended characterisation of the variables and interactions influencing the condition of a receptor. The integration of a systems perspective using the CLD aided identification of the interactions critical to the condition of a receptor (Chapter 6, section 6.3.2) and hence supported a risk assessment that has a less reductionist perspective than typical EIAs and SEAs (Chapter 6, section 6.3.4). The application of evidence in Chapter 6 was focused on testing the concept rather than precision of outputs, but the semi-qualitative approach applied suggests that the exploration of interactions, via expert judgement and weighting, or by integration with empirical or modelled results, would be worthwhile.

In the baseline step (Step 4), the need to specify resilience requires identification of a receptor reference condition, which was achieved in Chapter 6 by developing time-series for the case-study receptor and identifying trends and variability over time. This provided a more robust baseline than is typically observed in EIAs and, in the case of the North Sea Autumn Spawning herring, provided evidence that using the current stock size as the reference condition is justifiable. This is preferable to the assumption observed in the Environmental Statement chapters evaluated in Chapter 3 where there is an absence of evidence justifying the reference condition applied. The application of evidence in Chapter 6 indicates that significance can vary at different points in time, and adequate characterisation of the receptor population is necessary to gauge how resistant and resilient to change the receptor may be.

An obvious question to ask is whether the CEA pathway is generic or case-study specific. The wealth of evidence collated reflects the case-study receptor, herring, being a data-rich example, which is subject to annual monitoring and assessment under the coordination of the ICES Herring Assessment Working Group. This level of focus is not consistent across receptors in the Southern North Sea and ecosystems and receptors in less developed regions will be data deficient. Even for a data-rich receptor, the case study highlighted remaining uncertainties, such as the unknown driver behind the depressed recruitment of herring, and the influence of individual behaviour on the choice of spawning grounds (Eggers et al., 2015; Geffen, 2009). Testing whether the CEA pathway can be transferred to other receptors and scenarios would be straightforward, given the documentation included in this thesis, and the evidence gathering and application suggest that the CEA pathway is logical and hence repeatable.

The key limitation observed was the inability of the approaches tested in Chapter 6 to quantify the contribution of specific human activities on the herring stocks. No specific signal of offshore wind farm development could be distinguished from background noise. For the large, regionally dispersed stock, this is not a surprise given the current extent of offshore wind farms relative to the extent of North Sea Autumn Spawning herring grounds. For the Thames estuary population, however, the CEA pathway was effective at providing evidence of a much greater risk of disturbance to the stock and hence a greater need for precautionary licensing and license conditions. The CEA pathway provides a transparent justification why human activities that disturb this receptor should be subject to increased scrutiny. In the absence of evidence or methodologies that quantify the significance of individual activities relative to receptors, the CEA pathway enables an improved assessment of the risk that changes to the cumulative effects load acting on receptors, relative to Environmental Statements evaluated in Chapter 3.

Knowledge gaps about how effects accumulate and whether changes in the receptors may be additive, synergistic, antagonistic or of a ‘surprise’ nature (Harriman and Noble, 2008) are a challenge for CEAs in general and for the CEA pathway. As noted in Chapter 6, multi-stressor studies for herring, a data-rich receptor, are very limited. Judd et al. (2015) advise that in the absence of evidence to the contrary, an additive relationship is assumed. The CEA pathway is beneficial in establishing when the risk of non-linear responses to additional effects is increased, as with Thames estuary herring.

The test of boundaries and baselines led to the suggestion in Chapter 6 that project-level assessment could define boundaries by including the interactions that have a time signature that is proportionate to the lifecycle of the project, and of the effects relative to identified receptors. In the case-study, where underwater noise and vibration were identified as the critical activity-effect-receptor footprint, the temporal component of the footprint was limited to the construction period. Hence, by the logic suggested, slow variables such as climate change would be excluded from the analysis of the risk the activity poses to the receptor. However, slow variables can be critical in determining how precarious or resilient a system or system component is (Hossain et al., 2017; Levin et al., 2013). Climate change-driven change may occur over a longer period of time than would reasonably be included in a project-level CEA (although climate change effects may manifest suddenly and unexpectedly - Harris et al., 2006). This again points to the need for a strategic perspective to oversee project-level CEA. While change in slow variables may be thought of as a future issue not to be included in a project-level CEA, areas such as the North Sea have already experienced regime shifts that have had and are having profound effects on, for example, herring resilience (Payne et al., 2009).

A further limitation observed was the challenge translating CEA and systems theory into practice, as concepts such as the cumulative effects load, systems interactions and resilience remain ambiguous. The need for extended boundaries to capture cumulative effects is conceptually sound, but is practically difficult where receptors migrate over vast distances and migratory routes differ at different life stages, as with herring. While the CEA pathway case study provides a rationale for setting boundaries, determining how appropriate these boundaries are requires discussion and further testing.

The ambiguity encountered raises a question about the degree of precision necessary for decision-makers to fulfil their legal obligations to account for cumulative effects. Quantifying change in cumulative effects loads due to specific activities or stressors is challenging, due the number of interactions that may be relevant to one receptor (Chapter 6, section 6.3.2). Confidence in transferring experimental results into real-world scenarios is tempered by the nature of complex adaptive systems (Levin et al., 2013). There are numerous examples of data-rich situations being mined for statistically significant correlations that are in fact coincidental (Kupschus et al., 2016). The approaches tested in Chapter 6 are visually useful in terms of appreciating the interactions between activities and receptors, but they are at this stage qualitative or semi-qualitative. There is a tendency in environmental management to aim for precision and certainty, which in context of complex systems risk management interventions having counter-productive outcomes (Levin et al., 2013). How acceptable non-quantitative approaches are to decision-makers requires investigation.

The role of the expert and the reliance on knowledge are evident from the evaluation. An observation from the CEA session at the ICES Annual Science Conference (2018) was that researchers have less confidence in qualitative methods and a desire to move away from expert judgement towards quantitative methods. Qualitative methods are criticised for producing results that rely on subjective inputs and conclusions, rather than using data to link inputs and conclusions (Hegmann et al., 1999) and hence are difficult to replicate (Lawrence, 1993). Yet qualitative methods, including expert judgement, underpin models of cumulative effects that are categorised as quantitative (Halpern and Fujita, 2013). Where data allow, quantitative methods are preferable, but if the subjective judgements behind quantitative methods are not substantiated, it risks masking results behind a façade of precision and objectivity (Lawrence, 1993; Wandall, 2004). The lack of validation of CEA predictions (and of EIAs and SEAs) is also problematic, as the accuracy of observed results can differ substantially from modelled results (Clark et al., 2016; Stock and Micheli, 2016). Given the range of uncertainties and the shortage of quantitative data, qualitative methods will continue to play a key role in advancing CEA. Where data are limited, novel techniques are emerging that support identification of the status of populations based on limited data, such as those generated by baseline studies. Examples applicable to data-deficient situations include methodologies to estimate stock status from length frequency data (Froese et al., 2018) and a toolkit to interpret the trends and health of valued receptors (McDonald et al., 2018).

In summary, the CEA pathway is a guiding process that structures the application of evidence to deliver CEA. The gathering of evidence reported in Chapter 5 and the application of evidence in Chapter 6 demonstrate that the CEA pathway is feasible and generates more robust CEAs that were observed in Chapter 3. In theory, the steps could be completed using quantitative, semi-quantitative and/or qualitative methodologies to reflect available evidence or methodological advances, but this is untested. The key strength of the CEA pathway is the formalisation of a conception of CEA that is rooted in CEA theory and that explicitly integrates systems thinking. The preparation step and the structured process from steps 2-5 should lead to CEAs that are coherent independent of methodologies applied to deliver the steps. The CEA pathway should, therefore, better support the assessment and management of cumulative effects at a strategic, regional level. Iterations of the CEA pathway with different receptors and activities to further test the CEA pathway and to test how coherent different outputs are in a regional, multi-activity sense are needed to draw conclusions about strategic effectiveness.

7.5 Feedback on the CEA pathway

To obtain feedback on the CEA pathway, an expert panel was convened composed of core members of the Cefas Regulatory Advice and Assessment Group. Panel members regularly review project-level and plan-level environmental assessments for UK government agencies and are advisors to the Marine Management Organisation and OSPAR. The discussion commenced with a presentation of the CEA pathway and the results of collating evidence presented in Chapter 5. Strengths and weaknesses of the CEA pathway and opportunities for improvement were discussed (Table 22).

Table 22. Strengths and weaknesses of the CEA pathway relative to current EIA and SEA practice.

Strengths	Designed specifically to assess cumulative effects
	Straightforward to apply being based on making use of existing data and approaches
	Question-led rather than undirected or process-led and focussed on legal obligations

	Includes a resilience perspective, which is lacking from current project- and plan-level assessments
Weaknesses	Differences in language, important to reflect common terminology from EIA/SEA systems
	Level of uncertainty in assigning significance of specific activities to change in receptors
	Challenges accessing data in UK scenarios where commercial confidentiality is cited by developers and practitioners, and which

The expert panel agreed with the contention that CEA is the most meaningful component of project- and plan-level assessments in relation to contemporary management objectives. A strength of the CEA pathway was thus identified to be the focus of the CEA pathway to deliver CEA, rather than for CEA to be a sub-component of an environmental assessment.

The CEA pathway seeks to answer a specific question (the activity-receptor interaction), which was perceived as a strength in comparison with other CEA methodologies that are driven by scientific inquiry and with project- and plan-level assessments. CEAs driven by scientific inquiry have tended to combine large volumes of data without being guided by a specific question, and hence tend not to be specific enough to aid practical management and planning. Project- and plan-level assessments, by contrast, are process driven and led by legal obligations rather than seeking to resolve scientific uncertainties, hence tend not to meaningfully reduce cumulative effect uncertainties.

The inclusion of a resilience focus in the approach was also well received, as this is entirely absent from existing EIAs despite being an important consideration for the ecosystem approach. The challenges of implementing resilience in practice were commented on, with the expert panel noting that research to find suitable indicators that can be applied across human activities is ongoing.

Steps to improve the CEA pathway were discussed. The CEA pathway would be more recognisable to practitioners if the language and terminology matched that used in EIA and SEA systems. Step 2 as presented to the expert panel was called ‘Specification’, rather than ‘Scoping’, as is typically used in EIAs and SEAs. The CEA pathway in Figure 16 reflects this recommendation and integrates the term Scoping for Step 2.

Relative to the need to plan for and manage individual activities, the difficulty identifying a signal of specific developments over background noise was a weakness. Recognising the difficulty in ascribing significance to the consequences of discrete effects adding to the cumulative effects load, a recommendation was given that guidance should be provided to specify how to deal with the uncertainties that arise.

The expert panel commented on the value of the CEA pathway as providing a more complete characterisation of cumulative effect scenarios relative to receptors and providing the conditions for improved cumulative effects risk assessments. Access to existing data was also flagged as a major challenge for practitioners as well as researchers. The aggregates industry share data collected by survey and monitoring programmes, whereas the offshore wind industry does not. Practitioners undertaking CEA are reliant on publically available information and do not have access to the underlying data, hampering efforts to include past data in CEAs.

Notable quotes recorded during the feedback session included that the CEA pathway “demonstrates the power of thinking about things from a CEA perspective rather than a more traditional EIA perspective”. In context of contributing to the evidence base from which to drive change, the CEA pathway “helps inform why you’d want to think differently and the benefits of doing things differently”. The panel felt that the CEA pathway would be transferable to SEA scenarios, where CEA practice is also reported to be weak. There was consensus that a strategic perspective is necessary, whether SCEA or another regional mechanism. The logic behind a strategic process is accepted at a scientific level in international fora such as OSPAR, but that there is substantial pushback when mooted change encounters procedure-led mentalities (Judd, Cefas, *pers. com*). Feedback from the expert panel points to the main obstacle to improved CEA being procedural, rather than scientific.

7.6 Does the CEA pathway improve project-level CEA?

The CEA pathway integrates CEA science (summarised in Chapter 2 under the key CEA considerations) with social-ecological systems thinking, as was the aim of the research. The CEA pathway sought to address key shortcomings in project-level environmental assessments (Chapter 3), which are summarised in Table 23 together with a comment on the strengths and weaknesses of the CEA pathway relative to the shortcomings.

Table 23. Shortcomings in project-level CEA practice identified in Chapter 3 and the relative strengths and weaknesses of the CEA pathway.

Short-coming	CEA pathway strengths	CEA pathway weaknesses
Unsubstantiated reference conditions applied and no consideration of trends	Following the pathway resulted in evidence being structured to provide a more complete characterisation of receptors and an evidenced reference condition being identified (Chapter 6).	Performance in data-poor scenarios untested.
Inadequate consideration of cumulative effects relative to receptors	The integration of systems-thinking and the receptor-pivot step enabled identification of the human activities that contribute to the cumulative effects load acting on the receptor (Chapter 6).	Identifying the contribution of individual activities or developments to the receptor. Uncertainty about receptor responses to additional cumulative effects (linear/non-linear responses).
Lack of analysis of effects of development on	The Causal-Loop-Diagram and identification of the scales and strengths of receptor-system interactions	Low precision and a lack of quantitative methods applied to test how changes in

Short-coming	CEA pathway strengths	CEA pathway weaknesses
activity-receptor-system interactions	permitted qualitative inferences into how activity-effects-receptor interactions could influence receptor condition (Chapter 6).	interactions may influence resilience.
Lack of confidence in significance determinations	The CEA pathway provides a robust, transparent position from which risk assessments of cumulative effect consequences can be carried out. Uncertainties are dealt with in a structured, consistent format, providing transparency about the where uncertainties influence confidence in significance determinations (Chapter 6).	Lack of validation data and preceding ambiguities limit the precision of significance determinations.
Inconsistency	The preparation step (Step 1) requires the CEA to define the conception of CEA, terminology and approaches to uncertainty and risk assessment. Repetition with the same conditions is therefore possible.	A common conception of CEA, common language and the approaches to uncertainty and risk assessment are not formalised.

The need to repeat the pathway for other cumulative effect uncertainties means there is insufficient evidence to state with certainty that the CEA pathway improves project-level CEA. However, the CEA pathway does result in outputs are better at addressing the key shortcomings in project-level assessments, summarised in Table 23 relative to the Environmental Statements evaluated in Chapter 3. The shortcomings are similar to those highlighted in other evaluations of CEA practice (e.g. Canter and Ross, 2010; Foley et al., 2017). The interpretation of the shortcomings is slightly different in this thesis due to the integration of systems thinking, for example specifying one shortcomings as the lack of insight into system interactions. The preliminary conclusion is therefore that the CEA pathway improves project-level CEA.

The research completed suggests that the hypothesis is true: project-level CEA could meaningfully support contemporary marine management and planning. There are substantial caveats to this statement. As argued in this thesis, project-level CEA must be supported by a regional, strategic process. CEA practice could meaningfully support contemporary marine management and planning if supported by a strategic CEA process. A second caveat is that the CEA pathway, which preliminary testing suggests improves CEA practice, was not able to identify the contribution of specific developments to the cumulative effects load. In the format tested here, the CEA pathway resulted in a robust reference condition being identified from which a cumulative effects risk assessment could be completed. This is a substantially different output from the more definite (though dubious) significance determinations presented with development consent applications. Whether the CEA pathway can practically support contemporary marine management and planning therefore requires testing with regulators and developers, to identify how legal obligations to assess cumulative effects could be achieved with an emphasis on assessing risk.

7.7 Is project-level CEA useful?

There are compelling reasons why the EIA system should be adapted to focus on delivering fit-for-purpose CEAs, rather than scrapped and replaced. The EIA system is established, accepted and has resulted in profound benefits for environmental protection (Glasson et al., 2012). Most nations are signed up to ‘do’ EIA (Glasson et al., 2012) and international agencies and financial lenders are increasingly requiring EIAs to be completed as a condition of lending (Bond and Pope, 2012). The legal and procedural infrastructure of EIA systems tend to be strong relative to other systems of environmental assessment (Glasson et al., 2012). In the UK alone, about 800 EIAs are undertaken each year (Jha-Thakur and Fischer, 2016) pointing to an enormous potential source of data, if available.

At a scientific level, the EIA system has helped to develop the theoretical understanding of environmental change and has fostered analytical methods for predicting and assessing environmental change as a result of human activities (Smit and Spaling, 1995). However, scientific understanding has greatly advanced about how effects propagate and accumulate, and how the interactions in complex adaptive systems influence resilience. The legal requirement to assess the cumulative effects of projects and plans are not met by the standard EIA and SEA approaches (Canter and Ross, 2010; Duinker and Greig, 2006; Foley et al., 2017; Noble et al., 2017). There is therefore a legal obligation to challenge the primacy of EIA as a decision-making tool in environmental planning and management.

Recent reviews of EIA effectiveness and future directions (Jha-Thakur and Fischer, 2016; Loomis and Dziedzic, 2018; Morgan, 2012; Pope et al., 2013) demonstrate the depth of thinking being applied to improve the EIA system. What is missing from these reviews is an analysis of whether EIA and SEA are able to serve their respective purposes as evidence mounts that overly reductionist assessments may be counterproductive (Levin et al., 2013; Levin and Lubchenco, 2008). Ulrich (2001) states that once something is established as a process and answers have been found that serve the given purpose, there is an absence of questioning whether we are seeking answers to the correct question, or not. EIA is an established process that is familiar to policy-makers, regulators and practitioners. There are known procedures to follow that result in outputs that have been successful in the past, where success is defined as achieving consent for a project or activity to proceed (Figure 38).

Figure 38. An illustration of the emphasis within the EIA industry on achieving consent for project and activity proponents, rather than seeking to reduce environmental risk uncertainties (source: www.royalhaskoningdhv.com).

Duinker and colleagues have long cautioned against the reliance on EIAs as a tool to inform environmental management, in large part due to the proponent-dominated process that is adversarial and consequently fraught with obstacles to efficiency (Duinker and Greig, 2006; Greig and Duinker, 2014). Having worked for a decade in environmental consultancy, this author is aware that the motivations of individual practitioners of EIAs and SEAs are generally positive. However, there is a rationale for considering whether the processes of EIA and SEA result in answers to the right question.

One final question to raise is whether the CEA pathway and the conception of CEA as elaborated in this thesis are simply EIA or SEA done properly. The argument here is that CEA is distinct, that EIA and SEA should be delivering consistent CEAs that support coherent regional assessment and management of cumulative effects. EIA and SEA if done ‘properly’ (see Chapter 4) could result in fit for purpose CEA. However, the conceptual underpinnings of EIA and SEA are not focussed on CEA, even though the achievement of the purpose of EIA and SEA demands that cumulative effects are assessed well. This thesis argues that there are good reasons to co-opt the EIA and SEA systems to deliver fit for purpose CEA at project- and plan-level, but that the systems should be redirected to support the practice and process of CEA.

8 Research needs and recommendations

The research completed and the discussion about how to move away from highly reductionist environmental assessments to more holistic, systems structured assessments highlights areas where additional research is required to fill knowledge gaps. This chapter summarises the research needs relative to the CEA pathway (Table 24) and relative to efforts to improve project-level CEA (Table 25). The chapter concludes with key recommendations for improved CEA practice and process.

8.1 Research needs

Table 24. Areas for future research to develop the CEA pathway and the supporting rationale

Research need	Rationale
Repeat the CEA pathway with other scenarios and receptors across different scales, management areas, and social-ecological system components.	Iterations of the CEA pathway across a range of spatial and temporal scales would increase confidence in the findings discussed here. One means of testing the approach would be to extend the case study to other receptors, from species to ecosystem services, within the same geographic region, and to test applicability to other sectors.
Build on evidence base for the case-study to investigate scale and boundaries, if scaling up and down may influence significance determinations, and how effects propagate across scales relative to receptors.	The evidence base for the case-study is well established and there is more than could be gleaned from it to investigate human activity-effects-receptors footprints, and to populate the pathway with different scales in mind. Investigate the spatio-temporal characteristics of interactions, and how these scale up and down and interact, to gain insights into the relationships and hierarchies between scales.
Stakeholder consultation using CEA pathway outputs as objects	Extended testing and evolution of the CEA pathway in conjunction with stakeholders,

Research need	Rationale
to advance participatory CEA, discuss consequences and trade-offs at different scales, from different perspectives.	including regulators and representatives of the maritime industries, would be necessary to investigate further if the CEA pathway is practical and appropriate as a means of structuring project-level assessments and/or plan-level assessments. Developing case-studies into boundary objects *sensu* Thornton and Hebert (2015) is an avenue of research that could bring CEA into the public domain for discussions between competing stakeholders about consequences and trade-offs as a result of different development/conservation scenarios. Game theory could be included in outreach efforts, to structure research into the motivations, conditions and decisions that need to be considered to achieve cooperation between disparate players (Wood, 2011).
Investigate if/how outputs from different scenarios using different methodologies can be combined to support knowledge accumulation.	Testing how outputs and knowledge from different CEA approaches is required to explore compatibility and the potential for knowledge accumulation. Whether tiered frameworks from social-ecological systems analysis may be suitable for CEA is an avenue for future research, as a means of enabling regional coherence between assessments.
Expand CLD models with network analysis techniques to identify which network traits best explain network structure and functioning.	The causal loop diagrams can be expanded to enable dynamic systems analysis that can explore interaction weightings, time-lags and effect interactions. Network theory can be integrated into the CEA pathway to link two dimensional spatial, structural characteristics with the dynamics associated with

Research need	Rationale
	ecosystem services or specific receptors to investigate the effects of changing network relationships (Dee et al., 2017). Network analysis can also be used to identify which traits in ecological networks best explain network structure (Eklöf et al., 2013), potentially supporting improved identification of key receptors or interactions to assess and monitor.
Integrating more complex methodologies into the CEA pathway to improve Step 5 (assessing cumulative effects).	Advances in Geographic Information Systems (GIS) are enabling advanced raster algorithms that permit integration of multiple metrics to assess change, which can be associated with Bayesian Belief Networks that can quantify uncertainties (Stelzenmüller et al., 2015). Tools, indicators and statistical methods to detect or predict change in ecosystems are advancing rapidly, which are reviewed and highlighted in Foley et al. (2015). Studies are also advancing that narrow down the range of potential indicators that need to be measured to evaluate the status of, for example, marine food webs (Tam et al., 2018). Investigation is required to determine how these indicators and existing datasets (from long-term monitoring under the Water Framework Directive, for example; Muxika et al., 2007; Teichert et al., 2016; Van Hoey et al., 2010) could be adapted to support improved CEA, particularly strategic CEA.

Table 25. Areas for future research related to the wider CEA context and the supporting rationale

Research need	Rationale
Establish and formalise commonalities across CEAs completed in shared management areas	Enabling consistency between CEAs where common approaches should be identifiable (e.g. across different maritime industries) is critical to aid regional coherence. Commonalities of language and approaches to, for example, risk assessment need to be formalised. This could be achieved through a forum tasked with agreeing and overseeing implementation of standard CEA terminology in shared management areas (e.g. EU-level), dissemination of uncertainty typologies, development of best-practice guidelines on boundary-setting, risk assessment approaches. The forum could also act as a hub for knowledge dissemination and advocate for CEA to be demonstrably integrated into planning and management.
Enable access to historical data and reinforce data standards, explore historical data as a resource to support CEA baselines. Pooling data and survey/monitoring resources across maritime industries	In the European Union, databases of biological monitoring surveys and indicator monitoring have been created as research has supported Member States to implement the Water Framework Directive (2000/60/EC) and Marine Strategy Framework Directive (2008/56/EC). The databases have supported advances in measuring existing condition and change relative to management objectives (e.g. Borja et al., 2016; Muxika et al., 2007), to test the efficacy of indicators (e.g. Queirós et al., 2016) and to investigate interactive and cumulative stressors (e.g. Teichert et al., 2016). Implementation of the MSFD learnt from and adapted experiences from

Research need	Rationale
	implementation of the WFD (Van Hoey et al., 2010), a process that could also advance CEA. Pooling data and survey/monitoring resources across developments and activities is financially expedient, as collaborative efforts will reduce uncertainties. An example in the UK is the data collection and sharing model implemented by the UK aggregate extraction sector.
Identify cross-sector indicators that are appropriate to investigate activity-effect-receptor footprints and interactions	A challenge for development or activity proponents is the range of potential receptors and interactions that could be included in an assessment. Identification of indicator receptors that can be applied to research, monitor and validate specific effect footprints would aid consistency of practice across sectors (e.g. underwater noise and vibration arising from all human activities present in a management area), and ease the scoping process for development proponents. Indicator receptors may also support more efficient monitoring and validation, and support identification of periods of high/low risk relative to the assimilative capacity (see Elliott et al., 2018) of the receptor as the effect budget changes over time.
Increased validation studies to provide feedback on predicted or modelled effects and consequences of cumulative effects.	Survey and monitoring data often does not resolve uncertainties about effect uncertainties, including for MREDs (Cefas, 2009a, 2009b). Baseline survey costs and monitoring costs thus remain high for each development, including within a single management area. Currently there is a lack of validation of predicted or modelled cumulative effects: for example, a review of 40 marine CEAs identified that 20%

Research need	Rationale
	validated results (Korpinen and Andersen, 2016), and no predicted collision risk models used to predict the cumulative effects of offshore wind on seabird populations have been validated (Green et al., 2016). Validation of predicted effects and recovery rates in affected receptors is critical if later efficiencies are to be realised and to improve CEA.
Enabling strategic baselines and reference conditions to support project- and plan-level CEA	In the UK, the assessment and monitoring is led by developers, in contrast to the German and Belgian approach where data collection and accessibility has been centrally coordinated (Degraer et al., 2013; Federal Maritime and Hydrographic Agency (BSH) and Federal Ministry for the Environment, 2014). The practical benefits of integrated monitoring programmes at supporting regional and local management information needs are compelling (Kupschus et al., 2016). Conversely, the data-rich, information-poor situation currently characterising much marine data collection adds to development costs while resolving little (Fox et al., 2017; Wilding et al., 2017). Integrated monitoring and knowledge accumulation is more difficult in the UK, and in terms of CEA, the broader, strategic perspective is urgently needed to improve project-level CEA.
Integration of social components of social-ecological systems into CEAs	An observation made at the 2018 ICES Annual Science Conference, where a session was dedicated to CEA, was that many scientists are focussed on integrating data and improving the resolution of models to quantify environmental change. The social component of social-ecological systems was much less represented,

Research need	Rationale
	which is problematic when we are embedded in social-ecological systems and when management will always need to engage in discussion with stakeholders.
Integrate CEA into decision-making	CEA should be an influential source of information in decision-making, but is not (Judd et al., 2015). Other fields such as health care may have lessons relevant to CEA, where difficulties translating research findings into practical outcomes led to the emergence of implementation theory that aids modelling of intervention outcomes and the identification of determinants of success when seeking to overcome inertia in established processes (Nilsen, 2015; Rapport et al., 2018). As CEA researchers seek to test and refine CEA to become a practical management tool, implementation theory offers methodologies that have been developed to promote the systematic uptake of research into routine practice (Nilsen, 2015).

8.2 Recommendations

- Conceptualise EIA and SEA as nested under CEA;
- Recognise that meeting legal obligations to assess and manage cumulative effects requires multiple, consistent assessments at different scales and that include different receptors;
- Recognise that coherent regional assessment and management of cumulative effects requires an overarching strategic process to provide context to the multiple, consistent assessments;
- Clarify the conception of CEA that is to be applied within a management area;
- Agree common language for CEAs to be applied within a management area;
- Produce and implement guidelines to improve the consistency and quality of project-level CEA at management area level to include:
    - A definition of project-level CEA that accounts for the characteristics of effects accumulating in social-ecological systems;
    - Principles for risk assessment approaches and treatment of uncertainty;
    - A standard for the collection and recording of data, and for identifying robust evidence;
    - Principles and a pathway for applying evidence in a structured way to produce the CEA;
    - Best practice for scoping, defining activity-effect-receptor footprints, defining receptor condition, and specifying boundaries and interactions;
    - Guidance on how to derive significance determinations when data is deficient
- Stipulate open access to data from baseline, monitoring and validation studies
- Support practitioners with access to information about receptors and reference conditions

9 Conclusions

- Progress in CEA is essential to meet legal obligations to assess cumulative effects and to support a transition to sustainable development. Systems thinking and a cumulative effects mindset are important concepts to guide research to balance the need for reductionism and holism in CEA practice.
- The evolving understanding of cumulative effects in social-ecological systems demands that questions be asked about the purpose and practice of project-level and plan-level environmental assessments, whether current approaches are fit for purpose relative to contemporary management and the imperative to transition to sustainable development.
- Assessments of cumulative effects are the most meaningful output of project- and plan-level assessments. This thesis advocates a change in emphasis whereby CEA is the sole output of such assessments for use in decision-making.
- For project- and plan-level CEAs to be effective requires consistent practice at comparable levels (e.g. across sectors) and a coherent regional CEA process to provide the broader perspective required to give context to CEA practice. The dual CEA practice/CEA process approach is argued to be necessary to reduce uncertainties about MRED effects as developments increase in scale.
- The imperative to address climate change highlights the urgency of the task and the need for debate about trade-offs, particularly in social-ecological systems with limited or no capacity to absorb the consequences of increased cumulative effects loads.
- The principles and CEA pathway proposed are a practical contribution to the body of research seeking to improve CEA to benefit marine management and planning. Initial tests of the CEA pathway point to the availability of evidence and approaches to improve project-level CEA relative to contemporary marine management and planning information needs.

- Challenges to implementing the CEA pathway were largely related to ambiguities about which methodologies would be appropriate. The tests completed concluded that the underlying logic was sound and the outputs enabled improved assessments of the risk that additional human activities will disrupt the structure and functioning of social-ecological systems. Further testing in broader scenarios was recommended to draw more conclusive statements about the practicality of the CEA pathway.
- The test of the CEA pathway using the approaches applied resulted in outputs that would support engagement with stakeholders to communicate why meaningful CEA is vital, to debate the consequences and trade-offs of development/no development, and to foster support to challenge the status quo in project- and plan-level environmental assessments.

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APPENDICES

Appendix A Chapter 5 supplementary material

A.1 Evaluation results

Table A-1, Table A-2 and Table A-3 provide the detail of the evaluation. The tables have been separated from the original Excel spreadsheet to support readability. The phase number and step numbers are consistent across the four tables. The title of each phase and step is provided in Table A-1 only. Thereafter, only the numerals are listed in the left-most column of Table A-2, Table A-3 and Table A-4.

Table A-1 provides the descriptive summary of the evidence (data and information) found to support the herring case study. Table A-2 provides the supporting information and results of the ‘appropriate for task’ evaluation. Table A-3 provides the supporting information and results of the ‘application uncertainties’ evaluation. Table A-4 lists improvements and enabling mechanisms identified that support reduction of uncertainties identified for each step during the evaluation.

Table A-1. Descriptive summaries of the evidence collated for the case study and which form the basis for the evaluation scores recorded in Table A-2 and Table A-3.

	Phase		Step	Description of data/information available to herring case study
1	Preparatory steps	1.a	Apply common language	Precise terminology that is appropriate to CEAs in context of EIAs and regional obligations under the MSFD is available from peer-reviewed literature (see sources). In terms of progressing towards coherence of diverse diagnostic analyses of SES dynamics and relationships, system variables included in the assessment can be classified in keeping with the formalisation of Ostrom's framework (Hinkel et al., 2014).
		1.b	Apply formalised typology of uncertainty	A structured, defendable approach to analyse uncertainties is available based on existing peer-reviewed literature. The treatment of data and uncertainty can be specified to enable reviewers to understand and replicate the process applied. Skinner et al. (2014) provide a comprehensive typology to reduce interpretation of meaning, to aid identification of uncertainties, and to guide analyses of risk implications and prioritisation. Hence for the case study a robust structured approach to uncertainty would be straightforward to define based on existing literature.
		1.c	Apply formalised risk assessment principles	Environmental risk assessment principles are well established, the key issue is the adoption of a common approach to characterising and assessing risk. The ICES marine and coastal ecosystem-based risk management handbook bridges ISO 31000 standard for risk assessment and management with the ecosystem-based approach that European Union Member States seek to implement under the MSFD. Sufficient information from a reputable source exists to implement a scientifically defensible approach to risk assessment for the assessment.
		1.d	Expend effort in proportion to the risk of adverse change	(NSAH) The effect of percussive piling on herring is a known source of uncertainty for regulators and has caused delays during the consenting process. Consenting conditions (such as targeted surveys and temporal restrictions on piling) have been placed on developments to reduce uncertainties though the robustness of the surveys and monitoring has been questioned (Marine Management Organisation, 2014). Herring is an important commercial fish species for local, inshore vessels during the winter months. Herring is also a critical component of the North Sea ecosystem (Fauchald et al., 2011; Mackinson et al., 2007).
				(TEH) As NSAH, above, with additional precaution warranted due to low population status. With regard to the TEH population, there is an issue of perspective, as in regional economic terms, the fishery is of low value, with catches measured in tens of tonnes. This raises a question about the value of the population, including intrinsic value. The financial wellbeing of a small number of inshore fishing vessels is linked to the success of the winter herring fishery that targets this stock. Further, there is the subjective point that efforts should be made to prevent the extinction of a stock that is managed exclusively by the UK government and contributes to the biodiversity of the study area. A discrete spring spawning herring population has become extinct in the Skagerrak and Kattegat (ICES HAWG 2007) indicating an extinction risk for the Thames estuary herring population.
2	CEA specification	2.a	Specify activity and assessment objective	Activity: Offshore wind development in the greater Thames estuary and adjoining waters; Assessment objective: assess the risk that offshore wind farm installation in the study area has a detrimental effect on the herring populations in the study area.

	Phase		Step	Description of data/information available to herring case study
		2.b	Develop temporal and spatial effects footprint of activity	Environmental Statements accompanying license applications contain detailed information on the expected lifecycle processes, including construction (principle phase associated with underwater noise and vibration at levels likely to stimulate strong responses in herring). The information about processes is not precise; technology can evolve between the time of writing and the start of the construction period, and the scale and scope of a development may alter in light of geological information or financial uncertainty. Hence Environmental Statements include what is termed the 'realistic worst case scenario', which attempts to identify the most likely maximum duration and extent of the processes associated with the lifecycle of the development. Trawling through Environmental Statements yields more detail about the potential footprint of offshore wind developments than is typically found in generalised assessments found in scientific literature. Validation of predicted effects is limited by issues with monitoring data associated with Round 1 & 2 OWF (Marine Management Organisation, 2014).
		2.c	Use current evidence base to identify cause-effect interactions	An a priori Pathway of Effects (PoE) model is straightforward to construct based on existing and available data/information. Identifying generic pathways between effects and organisms likely to be present is supported by the wealth of scientific literature and data on the North Sea ecosystem and components thereof. A broad range of data is publically available from reputable sources, including substrate maps, benthic biotopes, foodweb models, and time-series of data on the abundance and distribution of epibenthic and pelagic fisheries species. A wealth of grey literature (e.g. Environmental Statements) provides summaries of baseline surveys completed for individual developments and activities. Landings data from commercial fisheries, which can be obtained on request from the MMO, can indicate the presence and weight landed of targeted species at ICES statistical rectangle scale, by month and year. At a broad level, a rapid assessment of what is likely to be present can be conducted quickly that is transparent and grounded in science. Uncertainty arises about the distribution, abundance and temporal variability of less studied, rare or cryptic organisms. Here is where appropriate baseline surveying is valuable. Uncertainty is also related to unknown cause-effect relationships. A PoE model can be constructed a priori with cause-effect relationships posited based on known mechanisms by which stressors interact with receptors known or likely to be present. A question arises about the depth of knowledge required about non-lethal effects, consequences of exposure for different life stages and about the profile of the effect generated by the activity.

	Phase		Step	Description of data/information available to herring case study
		2.d	Specify focal receptors	A qualitative process to identify receptors to take into subsequent stages (valued receptors that become the focus of assessment) relies on the preceding PoE. A structured approach is required to select receptors that are i) potentially impacted by the assessment activity and associated effects by virtue of sensitivity and likelihood of exposure; ii) are of value, as defined by legislative obligations, socio-economic importance, scientiific interest (role in ecosystem integrity and functioning, for example). The focal receptor here is herring, which comprises one metapopulation, North Sea autumn spawning herring (NSAH), and a discrete spring spawning population, Thames estuary herring (TEH). NSAH is a complex metapopulation comprising three component populations, including the Orkney/Shetland, Buchan and Downs stock components. The Downs stock component contributes the main proportion of the NSAH in the study area, which migrate annually to spawning grounds approximately east and south of the study area, and spawn later in the year than the other two stock components. There remains debate about whether the Downs stock component should be included or not in the NSAH metapopulation (ICES HAWG 2018). Monitoring and maintaining the diversity of local populations is considered by ICES HAWG to be critical to successful management of the overall herring stock.
3	Receptor pivot	3.a	Use current evidence base to characterise receptor/s	(NSAH) A substantial knowledge base grounded in current and historical science is available to support characterisation of the North Sea herring population. Sufficient peer-reviewed literature is accessible, notably from the ICES Herring Assessment Working Group (HAWG) that supports a robust characterisation of the biological, ecological and economic aspects of herring lifecycles, demographics and productivity. The quality of ICES HAWG outputs has been favourably evaluated (Simmonds, 2009) indicating sufficient certainty about the quality and application of data and information used to characterise and monitor the autumn spawning herring metapopulation and subpopulations. Additional useful information, though rough in terms of spatial resolution, is available via Fishbase (for fishes), where species envelopes are available for herring based on minimum, preferred minimum, preferred maximum and maximum envelopes, comprising depth, temperature, salinity, primary production and distance to shore. Spring spawning herring spawn significantly closer to shore than the listed preferred minimum distance to shore (6 km), highlighting the approximate nature of the generalised envelopes. Recent literature emphasises that uncertainties exist in all areas (Geffen, 2009; Hufnagl et al., 2015; Petitgas et al., 2013). Uncertainties emerge in relation to the relative importance of environmental drivers regulating lifecycle processes (Hufnagl et al., 2015), in relation to ecosystem interactions (Heikinheimo, 2011; Rockmann et al., 2011), and at population and individual behaviour levels where evidence of the plasticity and adaptability of herring populations is emerging (Geffen, 2009). However, for the purposes of the assessment, sufficient, high-quality information is available to document and characterise the herring lifecycle including reproductive strategy and potential bottlenecks relative to resilience and resistance.
				(TEH) As above, with the caveat that knowledge about the Thames herring life cycle is based on historical studies. TEH is excluded from the ICES HAWG assessments and the most recent dedicated peer-reviewed study specific to this population is from 2004 (Roel et al., 2004).

	Phase		Step	Description of data/information available to herring case study
		3.b	Specify temporal and spatial lifecycle and key ecosystem interactions	(NSAH) Sufficient historical and current data and information is available to characterise the temporal and spatial variability of North Sea herring. Information is available about spawning grounds (Dickey-Collas et al., 2010; Rockmann et al., 2011) (including of larval distribution via ICES IHLS dataset). Spatial resolution of ICES data is good for areas surveyed, however these do not include the areas closest to shore in the study area, which are associated with the spring spawning population (not NSAH). Catch statistics provide good spatial cover relative to the study area for mature herring (ICES statistical rectangle) and can be used to glean insights into temporal (monthly and annual) and spatial distribution. Caveats about fishery dependent data apply (Pecoraro et al., 2017). For the over-10 metre fleet, consistency over time is likely to be higher, as the current data collection system has been established for longer, although specific to herring, misreporting and issues with fishery dependent data have been noted in the past (ICES HAWG 2007) but are currently considered to be a minor issues in the North Sea herring fishery (ICES HAWG 2018). Changes in the catch reporting system for 10-metre and under vessels in 2006 result in low confidence prior to 2006 (MMO *pers. comm*). A priori relationships between herring and the environment are known based on the literature available for and specific to herring, notably ICES HAWG 2015. Key processes influencing herring populations includes access to spawning habitats (potential for noise barriers), hence ICES HAWG advising no aggregate extraction at likely spawning sites (ICES HAWG 2007, though see Marine Space report) The data/information available about herring is sufficient for the purposes of improving CEA. Environmental forcing and density-dependent effects play key roles in herring productivity and population dynamics, though underlying mechanisms are not well understood (ICES HAWG 2018). A caveat regarding confidence in existing knowledge is the consequence of new research, which has previously required accepted thinking to be revised (Geffen, 2009). In terms of ecosystem relationships, Fauchald et al. (2011) point to herring in the North Sea occupying an intermediate trophic level where diversity is lower than higher and lower levels, pointing to a wasp-waist system with herring a critical component influencing the abundance of seabird populations and zooplankton. Small pelagics, including herring, thus have an important role in controlling ecosystem relationships (Fauchald et al., 2011). This presents an alternative view to that often presented, that the North Sea ecosystem is a bottom-up regulated system. Research also points to the “prey to predator” feedback loop (Bakun and Weeks, 2006) being applicable, whereby decreased predator abundance (such as cod due to overfishing) reduces predation pressure on herring, that in turn predate on cod larvae (Heikinheimo, 2011).

	Phase		Step	Description of data/information available to herring case study
				(TEH) Past information is available for the sub-population of the Thames estuary, but is not up to date, with populations surveys stopped in 2007/8 (data can be obtained via Cefas via a request for information). Some research is available relating to specific periods (such as localised plankton surveys 1993-1997; Fox, 2001). Important temporal periods relate to the observed spatial distribution of adult herring returning to the coastal waters in the study area prior to spawning, from November onwards, finally moving into spawning aggregation prior to spawning from February through to April/May (Wood, 1981) depending on water temperature, with temperatures above 5 degrees celcius thought to be a spawning cue (Power et al., 2000). Related to key relationships, Power et al (2000) discuss some of the concomitant importance of herring (and sprat) abundance in the Thames estuary, as important components of the community structure. The Thames herring larvae hatch within 2-4 weeks after spawning (March to mid-May), depending on water temperature and appear to remain close to the coast (Wood 1981). Metamorphosis occurs in July-August (Wood 1981). Juveniles are found in the Thames estuary in large numbers in August with peaks in November to March, and then declining, perhaps following a cue to migrate offshore once water temperatures exceed 10 degrees Celsius (Power et al., 2000). This is a notably different pattern than the herring populations spawning further offshore (Banks and Downs populations) where the water flow takes larvae and juveniles around to the eastern reaches of the Southern North Sea (ICES HAWG 2014). Greater reliance on historical information hence limited knowledge of changes in fecundity, spawning site usage, potential for allee effect. The sub-population in the Thames estuary is subject to greater uncertainty, as directed surveying ceased in 2008 and abundance information (SSB) is reliant on CPUE calculations with fishing effort also influenced by the market for herring at the time. Fishery-dependent data is also subject to other potential biases (Geehand and Pierre 2015, in Pecoraro et al., 2017).
		3.c	Identify key human activities contributing to cumulative effect load	(NSAH) Knowledge about the lifecycle of herring is sufficient to determine direct sensitivities (fishing mortality, spawning habitat disturbance, noise) and hence human activities directly contributing to the cumulative effects load. The role of indirect, exogenous factors (pollution, eutrophication, water quality, sedimentation, climate change) are less clear, and knowledge about how activities interact to cumulatively influence herring populations is minimal. Pollution has been a major issue in the North Sea for decades (Ducrotoy et al., 2000). However, in context of this assessment (which seeks to be proportional for practitioners associated with assessments of the cumulative effects of individual developments) an argument can be made that the current 'good' status of North Sea herring (ICES 2014; ICES 2018) indicates herring have not been significantly impacted by historical pollution. For this assessment, The Crown Estate provides open access spatial data that indicates where maritime industries required a lease to occupy the seabed. This information can be entered into a GIS to identify which are present in the study area and which to include in the assessment based on potential interactions with herring (e.g. overlap with potential spawning habitat). Information available points to key endogenic activities (relative to the study area) contributing to the status of the herring population including offshore wind farms (noise and vibration), ports and shipping (noise and vibration), aggregate extraction (spawning habitat disturbance), wind export cable routes (spawning habitat disturbance) and commercial fishing (mortality). Good spatial data is available from reliable sources (OSPAR, TCE, MMO , Cefas) to apply GIS to identify the proximity of fixed infrastructure or license areas to sensitive herring habitat

	Phase		Step	Description of data/information available to herring case study
				(TEH) human activities as above, with additional mortality experienced due to power station water intakes in the Thames estuary (Power et al., 2000) and a small-scale whitebait fishery operated by a handful of vessels in winter months (pair-trawling from Southend) that can take juvenile herring (Roel et al., 2004; Wood, 1981). Good spatial data is also available (as per NSAH) to apply GIS to identify the proximity of fixed infrastructure or license areas to sensitive herring habitat.
		3.d	Set assessment temporal and spatial boundaries and system variables	(NSAH) Taking the known lifecycle patterns into account and the locations of the other contributing human activities, boundaries can be established for the assessment. The rationale for the boundaries needs explaining, as described in the application entry below. Sufficient spatial data is available for the study area and the receptor characterisation and the focal activity footprint support identification of rational temporal boundaries, taking into account lags between effects and the effects of disturbance emerging in the herring population.
				As NSAH, above
4	Baseline	4.a	Use existing data or expert judgement to assess receptor trend/pattern	(NSAH) Robust data sets are available that cover a long temporal period, are spatially defined, and are specific to the receptor. A long time-series is thus available based on SSB for NSAH that is sufficient to assess trends and patterns in the population. Simmonds (2009) reviewed the quality of ICES herring assessments and concluded that the combination and application of data sources (acoustic surveys, bottom trawl surveys, post-larval surveys and larval surveys, and catch-at-age data) result in high quality assessments and hence high confidence in the SSB data. Quite how robust SSB is as a proxy for reproductive potential remains a discussion point. Kell et al (2016) point to the variability of stock reproductive potential over time, due to changing fecundity for example, and that SSB as a proxy can underestimate uncertainty, an issue when assessing risk. How suitable SSB is, as a proxy to determine population trends in context of human activities, is also an open question. Herring is subject to aleatory uncertainty (Skinner et al., 2014) arising due to stochastic traits of herring populations and predictions of future productivity from year-to-year are of limited use as changes in environmental variables and linked ecosystem components can have a profound effect of recruitment, but we are not able to fully understanding the interactions and implications of change.
				(TEH) A time-series of SSB is available for Thames estuary herring that was previously calculated using data from targeted monitoring surveys that ran between 1981 and 2007. Since the cessation of these surveys, SSB has been calculated from CPUE derived monitoring effort and landings by a network of sentinel fisheries dotted around the study area (Readdy, *pers. com*). Fishery-dependent data caveats apply (Pecoraro et al., 2017) and effort by the herring drift-net fishery is influenced by market demand (Wood, 1981). Reliance on fishery-dependent data gives rise to a concern that the SSB calculated may miss changes in what is a depleted population (compared with historical levels) that are significant in determining how resilient the TEH is to cumulative effects (Figures 6 and 7, discussed below).

	Phase		Step	Description of data/information available to herring case study
		4.b	Specify measures of resilience and resistance	(NSAH) For the herring populations, time-series of recruitment and SSB (SSB for TEH) in theory reflect the cumulative effects of both pulse and press disturbances that have and continue to act on surveyed herring populations (or previously surveyed in the case of TEH) and the range of biotic and abiotic environmental forcing. There is high uncertainty about how anthropogenic disturbances (other than fishing mortality) contribute to the complex interplay of factors that influence herring population dynamics and demographics. The time-series of SSB for both populations provide insight into the resistance (sensu Standish et al., 2014) of herring to previous disturbances and pressures. Monthly catch data are useful to investigate potential pulse disturbances assuming consistency of fishing effort from year to year. The long time-series of SSB provides insight into the resilience of herring over time to previous disturbances and of the status of the current population relative to historical levels. This assumes that SSB is accepted as a proxy from which the capacity of the herring population to maintain interactions with connected system components can be considered. The availability of robust SSB time-series data supports measurement of changes in the abundance of herring and hence changes to the resilience of the social-ecological system arising from changes in a key component of a wasp-waist ecosystem.
				(TEH) As NSAH, above.
		4.c	Specify thresholds if available, or specify risk tolerances	(NSAH) For North Sea herring, ICES assessments provide a series of management reference points that can be used to inform thresholds. SSB reflects population change over time although the current method for calculating SSB assumes a linear relationship between stock size and recruitment, which is known not to be true, hence discussion about adoption of total egg production as a future measure of productivity (Kell et al., 2016). Nevertheless, the stock is currently considered to be at full reproductive capacity and to be sustainably fished (ICES HAWG 2018). In terms of thresholds, a management plan exists between the EU and Norway, since 1997 and amended in 2004 (ICES HAWG 2007), that seeks to maintain an agreed minimum level of spawning stock biomass (SSB) and which establishes reference points. Below precautionary reference points, management action is warranted. Relative to the study area, the ICES assessment focuses on the autumn spawning stock (that itself comprises three sub-stocks), which is the key population supporting industrial fishing effort. For NSAH, the HAWG takes into account data from fishery dependent and independent surveys. While the assessment is conducted from a fishery perspective and results in management advice relative to commercial fishing, the SSB calculated reflects recruitment, which should reflect changes in the population caused by cumulative effects. For the assessment, the current ICES HAWG assessment provides a robust source of information to identify a threshold for the population and where the population is relative to the threshold. One point worth raising is the effect on persistence of life history, habitat alteration, species assemblage change, genetic responses to exploitation and depensation (Hutchings & Reynolds 2004), although depensation does not appear to be an issue with NSAH (Nash et al., 2009).

	Phase		Step	Description of data/information available to herring case study
				(TEH) The key issue with respect to this assessment is the lack of current fishery independent data on the spring spawning population spawning in the study area, which is excluded from the ICES HAWG assessments. No specific threshold is available for TEH, though compromise precautionary spawning biomass reference points are discussed in Wood (1981) and Roel et al (2004), whereby recruitment may be impaired if the SSB is less than 300 (Roel et al., 2004) to 220 (Wood 1981) tonnes. Wood (1981) recommended a management objective of maintaining SSB around 350 tonnes to provide a buffer to offset poor recruitment years. There is, therefore, evidence from which to establish a threshold for the TEH population for a CEA. The relevance of factors other than fishing mortality in persistence and recovery of marine fish populations (Hutchings & Reynolds 2004) are perhaps more pertinent for TEH than for NSAH, as the population is depleted.

		4.d	Specify trends in other key variables	**Human Activities:** **Offshore wind farms (OWF)** OWF in context of herring contribute pulse disturbance. The OSPAR (2009) maritime activity trend analysis points to an increase in construction of structures and of offshore wind farms specifically in marine waters in the North Sea in general (very low spatial resolution). Round 1 and 2 wind farms have been constructed in the study area commencing in 2004 and round 3 wind farms are in the process of construction or will be constructed in the near future. How relevant these are to the focal receptor requires knowledge about the spatial and temporal extent of the disturbance generated by percussive piling and knowledge of whether percussive piling is likely for future developments. Round 4 development is mooted by the Crown Estate and the UK government has clarified its support for offshore wind in recent policy announcements (2018 ref). Information available points to an increase in the spatial and temporal extents of offshore wind in the North Sea. Within the study area, the possibility for expansion seems limited to already demarcated license application areas, as per Crown Estate maps. For the case study, there is a rationale for specifying an increasing trend in the study area in the near future (Round 3 developments being constructed). **Commercial fishing** No information on trends is included in the OSPAR (2009) maritime activity trend analysis. Working on the assumption that landings data has been collected in a uniform manner over the period of the time-series developed (2000-2015), sufficient data is available to identify increases/decreases in fishing pressure based on landed weight. CPUE, which would be more accurate, cannot be calculated with any certainty, as information provided by the MMO aggregates statistics related to 5 or less vessels. **Aggregate extraction** No trend is ascribed to sand and gravel extraction in the OSPAR (2009) maritime activity trend analysis. The MAREA herring cumulative impact assessment suggests increased aggregate extraction is desired by aggregate companies. The license application areas are demarcated by the Crown Estate and information is available about the likely spatial extent. Thus a worst case scenario can be estimated for an assessment and an activity trend derived. Spatial data from MMO points to future exploration areas for aggregate extraction. **Ports and shipping** The OSPAR (2009) maritime activity trend analysis points to an increase in dredging related to harbour deepening (capital and maintenance dredging) in the North Sea in general (very low spatial resolution). A correlated activity and trend is the expected increase in dumping of dredged material at sea. The trend in shipping, contributing to the underwater noise levels, is expected to increase in the North Sea in general (very low spatial resolution), which is supported by the likely increase in shipping expected to travel to and from the expanding port infrastructure in the study area. Data on shipping density is available for 5 years from MMO, providing some basis for investigating trends, however events such as the 2008 financial crash limit certainty in estimating trends based on short time-series. Evidence from the Northeast Pacific indicate an increase in underwater noise caused by increased shipping volume that correlates with global economic growth (Frisk, 2012, cited in Merchant et al., 2014). **Exogenic and endogenic processes:**

	Phase		Step	Description of data/information available to herring case study
				(Ex.P & En.P) Variability in flow patterns and advection to spawning grounds (e.g. Fair Isle Current and North Atlantic Oscillation - see Petitgas et al., 2010 pg 18). Long thought to be critical, but there is no unequivocal support for the hypothesis (Dickey-Collas et al., 2010). Even if key environmental forcing factors, arguably not relevant in context of timescale and projects, hence highlighted yellow. Relevant to determining potential contribution to trend in receptor and to future scenarios to consider if there are factors likely to influence future resilience, but again determination of time scale and avoiding incremental declines. Understanding environmental drivers is complex, as different spawning grounds are subject to different environmental variability and parental factors key, thus validity of searching for individual drivers is questionable (Dickey-Collas et al., 2010). (En.P) Bottom temperature near spawning ground (Nash & Dickey-Collas 2005; Payne et al., 2009). Arguably not relevant in context of timescale and projects, hence highlighted yellow, though potential for influence at 'SCEA' scale should be considered. (Ex.P & En.P) Trophic interactions (summarised in Petitgas et al., 2010) - Zooplankton abundance important, evidence suggests this influences spatial distribution of herring feeding grounds and shoal density from year to year. Also a range of other trophic interactions and evidence pointing to herring production and distribution being related to changes in the abundance of horse mackerel, mackerel, sandeel and zooplankton species. There are also complex relationships between sprat and herring, and increased herring abundance in combination with decreased zooplankton abundance increases the impact of herring on plaice and cod egg survival rates. Predation (on herring) rates also vary with time (Dickey-Collas et al., 2010). Suggest that these relationships are beyond the scope of a CEA, but should be included as considerations in the ongoing SCEA.
5	Cumulative effects assessment	5.a	Assess magnitude and duration of change to cumulative effect load due to focal activity effects	There are numerous areas of uncertainty and in terms of determining what the cumulative effect of a development or several developments will be, there is scope for flexibility of approach. The key finding here is that with the establishment of a more robust baseline and transparency of approach, better CEA is possible using existing information even if only at a qualitative level. The principles of the CEA approach can support improved CEA by drawing attention to the system structure and adopting the receptor's perspective of the effects of the focal activity cumulating with those effects already carried. Mapping the relationships between the receptor and variables contributing to the resilience (in this case productivity) of the receptor assists this step. With the relationships mapped out, temporal and spatial elements of the relationships can be considered in relation to the magnitude and duration of change created by the disturbance. The key shortcoming is knowledge about how effects cumulate and to what extent individual activities and localised events contribute to the cumulative effects load, however an argument can be made that the steps of the approach combine to provide a better position from which to consider how the cumulative effects load may alter, if it is accepted that the baseline (in this instance observing changes in SSB) provides an indication of the cumulative effects of the key variables acting on herring.
				(TEH) - as NSAH, above

	Phase		Step	Description of data/information available to herring case study
		5.b	Assess effect of change on persistence of interactions between receptor and related variables	(NSAH) This step brings together the receptor life-history, the systems view of interactions governing the receptors productivity and consideration of the effects of the focal activity on key interactions based on the SES specified. In context of the case study, the key concern is for OWF construction noise to interfere with spawning aggregations and spawning behaviour, and potentially the abundance of juvenile herring, based on Perrow et al. (2011). The structure of the habitat is critical to the persistence of species found in those habitats (Chambers et al., 2017). In terms of herring, there is a clear reason to consider how the focal effects may interact with the bottleneck created by spawning grounds, and the role that the extent, quality and connectivity of spawning grounds has on the resilience of herring, and on resilience (persistence) of associated interactions with the system. There is a good evidence base from which to consider how disturbances to aggregating herring and to spawning grounds could impact the resilience of the population. Incremental reductions in spawning grounds, temporary due to noise disturbance or permanent due to removal of aggregate, may exacerbate egg mortality by concentrating spawning at limited grounds. Where successive spawning waves occur at one ground, eggs laid in early spawning waves can be suffocated by uppermost layers (Wood 1981). There is evidence that when the population is in decline, the population retreats to key spawning grounds, and when expanding, previously used spawning grounds may be recolonised - restoring and maintaining spatial diversity may provide greater resilience to local changes in exploitation, environment and fish behaviour (McPherson et al., 2001, cited in Dickey-Collas et al., 2010). Identifying which are the key spawning grounds is important and also which create localised abundances that are consequential to predators. The consequences of resistance being overwhelmed at local scales require research, recognising the relationships between herring and other ecosystem components, and the consequences for coastal fisheries. The causal loop diagram provides a structure to guide such considerations and warrants further exploration as a means of supporting cumulative effects assessment. However, there is scant information available to assess with any confidence the effect of change on the persistence of interactions, notably as scale increases beyond localised temporary impacts to interactions.
				(TEH) As NSAH, above. Additionally, a concern arises due to the depleted state of the population. The length of time a fish population remains at low abundance influences the capacity to recover and increases the likelihood that a shift to different state variables will occur. A longer temporal period of depleted abundance increases the time over which environmental variables may alter in ways that are unfavourable to recovery (Hutchings 2014).

	Phase		Step	Description of data/information available to herring case study
		5.c	Use current evidence base to appraise potential for non-linear response to increased effect load	(NSAH) Hewitt et al., 2014 - Experiments indicate that non-linear effects are commonplace, particularly when an organism or system is stressed. Experiments by Neumann-Lee (2016) show stress responses can be highly context dependent, with similar species reacting differently to the same stressors and populations responding differently across geographical scales, pointing to the site and species specific nature of cumulative effect responses. Obtaining clarity about effect interactions and the nature of non-linear responses will require research. A question arises whether the condition/resilience of the receptor now provides insight into the likelihood that effects will be linear/non-linear. If the receptor is in poor condition, are non-linear effects more likely? Development and human activities continue apace and climate variability is increasing. Relative to the need to improve CEA in context of marine planning and licensing, how important is clarity about non-linear effects? If an organism or system is stressed, can it be assumed that greater precaution should be applied as the likelihood of non-linear effects increases? One important question is what is meant by non-linear effects; non-linear as in effect propagating through a system (receptor productivity system, or the broader social ecological system), or non-linear as in multi-stressor response? The former is supported by the systems approach CEA. The latter is much more dependent on experimental studies, where a further question arises of applicability of experimental results into a more complex, adaptive scenario. For herring, very little experimental data is available, based on a Scopus search.
				(TEH) Taking the above into account, the TEH can be argued to be a stressed population and thus applying the preceding logic, is at greater risk of non-linear responses to cumulative effects and as climate change effects come into play.
		5.d	Appraise cost/benefit of mitigation measures	This step is value-laden and requires participation by affected parties to identify whether the costs associated with the effects of development on focal receptors are acceptable or not. For herring the presence of thresholds and a robust time-series provides a perspective from which to gauge how management objectives relative to herring could be affected. The systems perspective provides a means of communicating how the productivity of herring may be affected and support participatory discussions to consider the consequences of temporary reductions in abundance on associated species and commercial fishing. Impulsive piling noise would affect other species as well as herring, thus a more encompassing CEA would provide a more robust position from which to discuss the costs and benefits of mitigation. The principal option for mitigation relative to impulsive noise is to avoid piling at times when herring are aggregating to spawn, during spawning and potentially when the eggs are hatching. This restricts when development can occur, which has implications for the developer. In the case of TEH, there is a clear rationale to prevent additions to the cumulative effects load carried by this population, which is depleted.
6	Future scenarios	6.a	Consider duration of activity/license conditions	License information identifies the licensed duration of the activity. Given the infrastructure expenditure in establishing OWF, is it likely that the seabed lease will be extended?

		6.b	Develop future scenarios based on predicted change in variables/policy direction	**Population predictions** - projecting the productivity of herring is notoriously difficult given the stochastic nature of the populations and the complexity involved in determining stock size, which applies advanced, highly complex stock assessment modelling. Recruitment add the most uncertainty to future yield estimates (Dickey-Collas et al., 2010). In terms of human activities, fishing clearly has the greatest influence on recruitment: total catches of NSAH in 2017 amounted to 484,717 tonnes relative to an estimated SSB of 1.9 million tonnes in 2017. For NSAH, acoustic surveys point to a reduction in the abundance of mature fish and of immature fish in the stock in recent years, and the most recent herring larval survey recorded total numbers of larvae in the same order of magnitude as preceding years (ICES HAWG 2018). While SSB remains above the management reference point, SSB in 2017 has decreased by 20% from 2016 SSB and the abundance of new recruits into the fishery is 43% down on the long-term geometric mean (ICES HAWG 2018). ICES HAWG predicts NSAH 3 years forward in its assessments and predicts SSB to decline below a management reference point in 2019 due to weak year classes in 2014 and 2016. Stock productivity is historically low, with repeated below average year classes (Payne et al., 2009). Year class strength is determined during the larval phase and there is a current pattern of poor larval survival relative to historical averages (Payne et al., 2009). The conclusion is that NSAH is in a low-productivity regime (ICES HAWG 2018). Relative to the assessment, this highlights the need to consider carefully how resilient herring is to future disturbances that may impact risk bottlenecks, such as disturbances to spawning aggregations and spawning grounds. **Climate & oceanographic variables** - Climate in the North Sea is strongly influenced the inflow of water from the Atlantic and prevailing winds and by the North Atlantic Oscillation (Ducrotoy et al., 2000). No trends in salinity were observed over 120 years of observation, which remains relatively stable in the open sea at 35 ppt (Ducrotoy et al., 2000). Sea level rise is expected in the North Sea of 50cm by 2100, although the tilting European landmass creates local land elevations (Ducrotoy et al., 2000). UKCP09 provides a robust evidence base from which to derive projection of future changes in environmental variables. The North Sea has already seen a period of rapid environmental change since the 1960s and 1970s (Sundby et al., 2017). Primary production is a further key variable and recent research points to changes in the relative and absolute abundances of warm/cold water Calanus species, with implications for herring. The feeding plasticity of herring is an area of current research, particularly in light of climate change effects on prey availability (Denis et al., 2016). Trends in human activities are subject to substantial uncertainties, particularly as economic changes can result in substantial changes in activity levels, such as shipping following the 2008 financial crisis. A broad-brush approach to determining likely trends is possible based on the identified blue growth objectives in European Union waters and the general adherence to the maxim of development via growth economics by nation states. The potential of this step is to determine whether pressures are likely to reduce, remain stable, or increase into the future, i.e. whether the future resilience is likely to change and thus to estimate whether disturbance to the herring population now or in the near future is more/less acceptable as the recovery potential is influenced by scenarios. Recognising the low confidence in predictions (arguably other than climate change projections that are subject to intensive robust research), information is sufficient to support broad-brush scenarios that may be used to appraise the implications of likely scenarios on management objectives.

	Phase		Step	Description of data/information available to herring case study
		6.c	Appraise implications of scenarios relative to management objectives	See previous step.

Table A-2. Supporting information behind the 'appropriate for task' scores presented in Figure 23. Scores are categorised as described in Table A-1.

Step	Summary	Appropriate for task score	Sufficiency of data/ information available relative to step	Temporal resolution	Spatial resolution	Quality score	Access-ibility	Sources
1.a	See descriptive summary	2.0	2	2	2	2	2	Judd et al., 2015; Oesterwind et al., 2016; Hinkel et al., 2014
1.b	See descriptive summary	2.0	2	2	2	2	2	Cardenas & Halman 2016; Skinner et al., 2014a; Skinner et al., 2014b; Skinner et al., 2016
1.c	See descriptive summary	2.0	2	2	2	2	2	Cormier et al., 2013; ISO 31000; Greenleaves, Cefas & others - check Bergmann 2004, Francis and Shotton 1997; Lane and Stephenson 1997 (ICES HAWG 2007 pg 504)
1.d	(NSAH) Sufficient information is available to determine that there is a risk to existing management objectives, warranting expenditure of effort.	2.0	2	2	2	2	2	ICES HAWG 2015; ICES HAWG 2018; Fauchald et al., 2011; Mackinson et al., 2007.
	(TEH) As NSAH, above.	2.0	2	2	2	2	2	Roel et al., 2004; Wood 1981, ICES HAWG 2007

Step	Summary	Appropriate for task score	Sufficiency of data/ information available relative to step	Temporal resolution	Spatial resolution	Quality score	Access-ibility	Sources
2.a	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.b	Information is available from Environmental Statements that is of sufficient detail to enable a spatio-temporal footprint of effects to be developed that can be applied to inform the next steps of this phase of the CEA approach. The temporal and spatial resolution of the available information is of partial sufficiency, as it relates to stressors rather than effects, requiring interpretation. Quality is partial as the reliance is on Environmental Statements.	1.4	2	1	1	1	2	Numerous references reviewed in Willsteed et al., 2017; Also Environmental Statements, though see limitations, evaluated in Willsteed et al., 2018. Principle source of information for development is reliance on Environmental Statements, which are reviewed by regulators, but require interpretation to convert to effects, and validation information is lacking.

Step	Summary	Appropriate for task score	Sufficiency of data/ information available relative to step	Temporal resolution	Spatial resolution	Quality score	Access-ibility	Sources
2.c	A Pathway of Effects model can be constructed a priori with cause-effect relationships posited based on known mechanisms by which stressors interact with receptors known or likely to be present. Identifying generic pathways between effects and organisms likely to be present is supported by the wealth of scientific literature and data on the North Sea ecosystem and components thereof. A broad range of data is publically available from reputable sources, including substrate maps, benthic biotopes, foodweb models, and time-series of data on the abundance and distribution of epibenthic and pelagic fisheries species. A wealth of grey literature (e.g. Environmental Statements) provides summaries of baseline surveys completed for individual developments and activities. Landings data from commercial fisheries, which can be obtained on request from the MMO, can indicate the presence and weight landed of targeted species at ICES statistical rectangle scale, by month and year. At a broad level, a rapid assessment of what is likely to be present can be conducted quickly that is transparent and grounded in science. Uncertainty arises about the distribution, abundance and temporal variability of less studied, rare or cryptic organisms. Here is where appropriate baseline surveying is valuable. Uncertainty is also related to unknown cause-effect relationships. A question arises about the depth of knowledge required about non-lethal effects, consequences of exposure for different lifestages and about the profile of the effect generated by the activity.	2.0	2	N/A	N/A	2	2	Judd et al., 2015; CSAS ERAF
2.d	A qualitative process to identify receptors to take into subsequent stages (valued receptors that become the focus of assessment) relies on the preceding PoE. A structured approach is required to select receptors that are i) potentially impacted by the assessment activity and associated effects by	2.0	2	2	2	2	2	See entries in column C, E and chapter 5 manuscript.

Step	Summary	Appropriate for task score	Sufficiency of data/ information available relative to step	Temporal resolution	Spatial resolution	Quality score	Access-ibility	Sources
	virtue of sensitivity and likelihood of exposure; ii) are of value, as defined by legislative obligations, socio-economic importance, scientiific interest (role in ecosystem integrity and functioning, for example). Suffcient information of good quality is available to support identification of valued receptors (focal receptors).							
3.a	(NSAH) A substantial knowledge base grounded in current and historical science is available to support characterisation of the focal receptor. The quality and spatial and temporal resolution of the information is good and publically available. A robust characterisation of the biological, ecological and economic characteristics of the focal receptor is straightforward to produce.	2.0	2	2	2	2	2	See entries in column C, E and chapter 5 manuscript.
	(TEH) As above, with the difference that recent data is fishery-dependent and there is a greater reliance on historical research.	1.6	2	1	1	2	2	See entries in column C, E and chapter 5 manuscript.
3.b	(NSAH) Sufficient historical and current data and information is available to characterise the temporal and spatial variability of the focal receptor, and to identify the key processes thought to influence the productivity of the receptor. Surveys for ICES do not include the nearshore waters of the study area. Commercial fishery catch statistics provide detail about the abundance of mature herring at ICES statistical rectangle level by month. Catch data can be obtained via Environmental Information Request submitted to the Marine Management Organisation (accessibility score 1). In terms of ecosystem relationships, research is ongoing into identifying how influential abiotic and biotic relationships are on the productivity of herring. For the purposes of this step, a good scientific foundation is available to justify which ecosystem interactions should be considered in an assessment.	1.8	2	2	1	2	2	See entries in column C, E and chapter 5 manuscript.

Step	Summary	Appropriate for task score	Sufficiency of data/ information available relative to step	Temporal resolution	Spatial resolution	Quality score	Access-ibility	Sources
	(TEH) Fishery independent survey data collection ceased in 2007/8, with subsequent years relying on catch data. Catch data can be obtained via Environmental Information Request submitted to the Marine Management Organisation (accessibility score 1). Information on ecosystem interactions is informed by historical studies and is partly dependent on intraspecies extrapolation from the metapopulation. Information is sufficient to complete the specification required at this step, however the uncertainty is increased by the lack of current, directed research into this population.	1.2	1	1	1	2	1	See entries in column C, E and chapter 5 manuscript.
3.c	(NSAH) Direct sensitivities to human activities are known based on scientific literature and those contributing to the cumulative effects load can be identified. Good spatial data is available from reliable sources (OSPAR, TCE, MMO, Cefas) to apply GIS to identify the proximity of fixed infrastructure or license areas to sensitive herring habitat.	2.0	2	2	2	2	2	See entries in column C, E and chapter 5 manuscript.
	(TEH) as NSAH, above. Additional knowledge about specific local situation avaiable from historical studies. Good spatial data is also available (as per NSAH) to apply GIS to identify the proximity of fixed infrastructure or license areas to sensitive herring habitat.	1.8	2	1	2	2	2	See entries in column C, E and chapter 5 manuscript.

Step	Summary	Appropriate for task score	Sufficiency of data/ information available relative to step	Temporal resolution	Spatial resolution	Quality score	Access-ibility	Sources
3.d	(NSAH) Taking the known lifecycle patterns into account and the locations of the other contributing human activities, boundaries can be established for the assessment. The rationale for the boundaries needs justification and is subjective. Based on the activity footprint, the receptor lifecycle and the patterns of activities contributing to the cumulative effect load, a rationale can be provided to complete the step, taking into account time lags between effects and consequences.	1.7	2	N/A	N/A	1	2	Quality score of 1 reflects lack of specific guidance. Much CEA literature (in a development context) discusses or provides examples of boundaries stemming from river and watershed research. Most frameworks/guidelines (e.g. RUK/NERC 2013; Natural England 2014; CSAS) provide generic advice that is not straightforward to apply in practice.
	(TEH) as NSAH. above.	1.7	2	N/A	N/A	1	2	As NSAH, above
4.a	(NSAH) Robust data sets are available that cover a long temporal period (more than the case-study period), are spatially defined, and are specific to the receptor. A long time-series is available based on robust, scientifically defendable data and data collection methodologies that permits observation of trends and patterns in the population. The metric is robust as a proxy to measure changes in the health of the receptor population.	2.0	2	2	2	2	2	See chapter 5 manuscript.
	(TEH) as NSAH, above. The reliance on fishery-dependent data for recent years (since 2007) introduces uncertainty.	1.2	1	1	2	1	1	See chapter 5 manuscript.
4.b	(NSAH) The population metric used to identify trends is appropriate to observe past changes caused by the cumulative effects load and catch data can be used to look for higher resolution spatio-temporal changes due to localised disturbance. Hence existing evidence supports crude examination of both resilience and resistance. The lower score	1.0	1	N/A	N/A	0	2	See chapter 5 manuscript and Chapter 4.

Step	Summary	Appropriate for task score	Sufficiency of data/ information available relative to step	Temporal resolution	Spatial resolution	Quality score	Access-ibility	Sources
	reflects the lack of confidence in using SSB as a measure of resilience without further testing. Integration with information about current use of spawning grounds (connectivity - Standish et al., 2014) and the scale of the offshore wind farm disturbance relative to the bottleneck risk (access to and quality of spawning grounds) would improve confidence in using existing data to derive estimates of resilience.							
	(TEH) As NSAH, above.	1.0	1	N/A	N/A	0	2	See chapter 5 manuscript and Chapter 4.
4.c	(NSAH) Receptor-specific management reference points are available based on robust ongoing monitoring of the receptor population, that are spatially and temporally appropriate, of high quality and which are publically available.	2.0	2	2	2	2	2	ICES HAWG 2018
	(TEH) Thresholds are discussed in historical scientific literature that provides an evidence based from which to define a threshold relative to the assessment. The spatial resolution is appropriate, the temporal resolution is partial due to the reliance on historical information. The literature is available and is peer-reviewed and/or from a reputable source.	1.6	2	1	2	1	2	Wood, 1981; Roel et al., 2004
4.d	Limited data is available to support the identification of trends. Time series where available are short (e.g. shipping density 5-years). Good spatial information is available, temporal information much less so. Defendable trends can be specified based on information available from various sources (medium and high quality). There is a rationale for assuming a static or increasing trend based on stated policy, including economic policy (e.g. blue growth objectives). Trends in abiotic and biotic variables (ecosystem processes) are of variable resolution relative to the case study area. The quality of data/information sources for ecosystem processes is high. The time-scales involved relative to project-activity level CEA suggest human	1.0	1	1	1	1	1	OSPAR 2009

Step	Summary	Appropriate for task score	Sufficiency of data/ information available relative to step	Temporal resolution	Spatial resolution	Quality score	Access-ibility	Sources
	activities only should be included in the assessment until the future scenarios phase.							
5.a	(NSAH) Sufficient information is available to identify how the principal effect linking the focal activity and focal receptor will disturb the receptor. Assumptions about the magnitude and duration of effect can be derived from sources of medium quality (e.g. Environmental Statements) and high quality (e.g. government survey reports (Belgium and Germany)). Good evidence is available to specify when and where the effect poses a hazard to the receptor, which is captured in the receptor pivot phase, although variability from year-to-year presents uncertainties. Bottleneck risks can be established and spatio-temporal exposure maps can be produced to predict/analyse risk relative to the receptor. Evidence is available from analogous situations to inform resistance estimates and recovery. The baseline that can be established based on existing information enables progress in assessing how the novel disturbance will add to the cumulative effect load, however the relative contribution of activities/processes to the cumulative effect load is unknown, an issue for management and consenting of individual activities. A further substantial information uncertainty is the baseline related to the effects, noticably noise (Farcas et al., 2016) and changes to activities levels impinging on spawning grounds. Qualitative progress can be made through causal inference, which in combination with causal link/loop diagrams can provide a fuller appreciation of how changes in the overall cumulative effect load may influence the receptor.	1.2	1	1	2	1	1	Farcas et al., 2016; Hawkins and Popper 2016
	(TEH) - as NSAH, above	1.2	1	1	2	1	1	Wood, 1981; Roel et al., 2004
5.b	Information is insufficicent to complete this step with any confidence. The application of causal link diagrams or causal	0.0	0	0	0	0	0	

Step	Summary	Appropriate for task score	Sufficiency of data/ information available relative to step	Temporal resolution	Spatial resolution	Quality score	Access-ibility	Sources
	loop diagrams can support assessment of how disturbances may propagate through the system governing the productivity and resilience of the receptor. However, this is untested at this stage. The key advantage gained at this point in time from the approach is the more complete picture of how disturbances contribute to the cumulative effects load, which can assist improved risk assessment.							
	As NSAH, above.	0.0	0	0	0	0	0	
5.c	Information is insufficicent to complete this step with any confidence. Evidence for non-linear effects typically stems from experimental research and, for ecosystems, from statistical analysis of suitable survey data to identify stressor interactions. Such information was not identified for herring following rapid searches on Scopus. An assumption of additive responses would be advisable in the absence of information to the contrary. Causal loop diagrams may assist a qualitative process of appraising non-linear effects in a structural systems sense (rather than organismic multistressor sense), which is supported by spatial and temporal information about the receptor, the disturbance and recovery rates, hence score 1.	0.6	1	1	1	0	0	
	As NSAH, above.	0.6	1	1	1	0	0	
5.d	Sufficient information is available to identify the extent and duration of noise energy entering the environment and hence to assess how the receptor would be affected. Uncertainties arise from the scale and consequences of the disturbance to the receptor, but using justified assumptions based on best available information, consequences to the receptor and linked system components can be predicted. Qualitative estimates of ecological and socio-economic consequences can be derived to inform an appraisal of the value of mitigating predicted effects. Management objectives relative to the receptor and the	1.0	1	1	1	1	1	

Step	Summary	Appropriate for task score	Sufficiency of data/ information available relative to step	Temporal resolution	Spatial resolution	Quality score	Access-ibility	Sources
	broader system can be specified, which provides support to assessing the risk of not mitigating effects. The key issue is the uncertainty in temporal and spatial information about the effect on the receptor and linked system components, reducing confidence in any determinations of cost/benefit.							
6.a	Sufficient information is available via the national planning portal to identify the length of seabed lease. The MMO license register provides further information, including spatial but not temporal, about licenses and permits for activities. For the purposes of developing the information base for future scenario development, sufficient information is available.	1.8	2	1	2	2	2	
6.b	The information available supports short-term (3-year) predictions of receptor abundance that are useful for considering the cumulative risk of additional developments/activities impinging on the receptor during the recovery period from the focal activity disturbance. Good evidence is readily available to support inclusion of trends in key abiotic processes (temperature, pH, etc) influencing receptor productivity, which include robust models with upper and lower bounds. Assumptions can be made about human activities based on economic forecasts, current trends and evidence of historical persistence of activities. For all variables included, justifiable high/medium/low type scenarios can be developed. The resolution of such information is clearly limited and the nature of complex adaptive systems works against predictions of anything but high granularity. However, the information available is arguably sufficient to determine how broadbrush future conditions could impact the resilience of the receptor and the broader social-ecological system. With this information, the final step of appraising the implications of scenarios relative to management objectives can be completed.	1.4	1	1	1	2	2	(Dickey-Collas et al., 2010; Ducrotoy et al., 2000; ICES HAWG, 2018; Payne et al., 2009; Sundby et al., 2017; UKCPO9, 2009)
6.c	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table A-3. Supporting information behind the 'application uncertainties' scores presented in Figure 24. The scores is categorised as described in Table A-1.

Step	Application uncertainties/variability	Uncertainty classification (Skinner et al., 2014)	Uncertainty score
1.a	Sufficient information exists to apply precise terminology to the assessment. Application uncertainty arises due to the lack of standardisation or acceptance of one set of definitions at regulator/practitioner level. While this uncertainty exists, different assessments may apply variations of definitions.	Epistemic - language - ambiguity	1
1.b	Sufficient information exists to support a defensible approach to dealing with uncertainty and specifying how data is dealt with. To support coherence between assessments to support regional information needs, how data is treated (how CPUE is derived, for example) and how uncertainty is categorised and accounted for should be consistent across assessments. At present, variance between terms applied in existing uncertainty typologies risks inconsistent implementation in a risk assessment. Application uncertainty arises due to the lack of standardisation or acceptance of one typology at regulator/practitioner level.	Epistemic - language - ambiguity	1
1.c	Sufficient information exists to apply a defined, accepted risk assessment approach. The uncertainty arises due to the potential for different assessments to apply different risk assessment approaches in the absence of cross-sectoral adoption of one standard or approach.	Epistemic - language - ambiguity	1
1.d	Leading on from the risk principles uncertainty, there is uncertainty about translating broad-scale management objectives (such as those defined in the UK Marine Policy Statement) to the specific objectives of the CEA. This introduces the potential for differing interpretations of risk and hence effort justified to address uncertainties associated with the risk.	Epistemic - language - ambiguity	1
	As above.	Epistemic - language - ambiguity	1
2.a	N/A	N/A	N/A

Step	Application uncertainties/variability	Uncertainty classification (Skinner et al., 2014)	Uncertainty score
2.b	Translating processes into effects relies on the context of the receiving environment and receptors. Organisms highly sensitive to noise, such as herring, will experience ensonification over greater ranges than organisms less sensitive to increased noise. There remain substantial uncertainties about the sensitivities of many ecological receptors to the effects of offshore wind farms (MMO, 2013), including of herring to sound pressure (Hawkins et al., 2013). Knowledge about the baseline environment is also relevant, for example the Southern North Sea is turbid, which can influence the propagation of noise through the water column and sediment types influence the transmission of noise and vibration (Hawkins et al., 2013). In this instance the baseline environment is sufficiently well documented, as is the sensitivity of herring to noise energy (noting the lack of precision; Hawkins et al., 2013).	Epistemic - data - precision; Epistemic - system - effect	1
2.c	Issue arising with resolution of spatial and temporal information at scales relevant to a development. Confidence in conclusions about spatial and temporal heterogeneity will improve with information from robust baseline surveying or validation of predicted distributions. The principles behind PoE models are well described in literature and are unambiguous, hence score 2.	Epistemic - data - availability; Epistemic - system - cause; Epistemic - system - effect	2
2.d	Uncertainty arises from the lack of an agreed formal approach to define value, which is an ambiguous and can be defined along relational and intrinsic lines (Piccolo, 2017). In keeping with the intellectual shift towards social-ecological systems thinking espoused in Chapter 4, the complexity of such systems makes it difficult to justify a focus on protected species alone. Biodiversity is a key factor influencing ecological stability (Donohue et al., 2016) pointing to the need to carefully consider how valued and hence focal receptors are defined mindful of objectives allied to the ecosystem approach. Uncertainty also arises from the potential unknowns associated with a system and hence the potential to miss adverse impacts on the system as a result of ignorance about stressor-effect-receptor interactions.	Epistemic - language - ambiguity (potentially Aleatory - variability - human); Epistemic - system - effect; Epistemic - system - process. Depending on the level of knowledge about the social-ecological system, aleatory - extrapolation uncertainties may be introduced, for example where laboratory studies are used to represent real-world situations.	1

Step	Application uncertainties/variability	Uncertainty classification (Skinner et al., 2014)	Uncertainty score
3.a	The principal uncertainty arises from deciding what level of detail/certainty is necessary to derive a satisfactory output relative to the intent of the CEA approach. For the purposes of the CEA approach, the intention is to have a sufficient understanding of the focal receptor to aid subsequent steps that seek to develop a picture of the important system interactions and boundaries. The available information can be applied to achieve this intent unambiguously.	Epistemic - language - underspecificity	2
	As NSAH, above.	Epistemic - language - underspecificity	2
3.b	Plasticity of herring populations (such as fecundity and site fidelity) introduces variability, which may be important during later steps. As with step 9, the principle uncertainty arises from deciding what level of detail/certainty is necessary to derive a satisfactory output relative to the intent of the CEA approach. For the purposes of the CEA approach, the intention is to have a sufficient understanding of the spatial and temporal boundaries relative to the focal receptor, and to identify key ecosystem interactions. The available information can be applied to achieve this intent unambiguously.	Epistemic - language - underspecificity	1
	As NSAH, above.	Epistemic - language - underspecificity; Aleatory - extrapolation - intraspecies	1
3.c	The available information can be applied to achieve this intent unambiguously.	Epistemic - language - underspecificity	2
	The available information can be applied to achieve this intent unambiguously.	Epistemic - language - underspecificity	2

Step	Application uncertainties/variability	Uncertainty classification (Skinner et al., 2014)	Uncertainty score
3.d	Proportionality, which is subjective, creates significant uncertainty when defining where boundaries should be drawn and, to a lesser extent, which variables should be included. Interpretation and system boundary judgements are inevitable (Helfgott, 2018). Information is available about the spatial extent of offshore wind farms, aggregate extraction license areas, and shipping channels within the case study region (which itself is arbitrary). A decision needs to be made about what proportional boundaries are relative to a given development and herring. For this case study, the TEH population during spawning season is discrete and associated with a defined area and period (though it is obviously a migratory species). The study area encompasses known spawning grounds for this sub-population, thus spatial boundary setting is straightforward. In context of NSAH herring, the spatial boundary could in theory cover the North Sea, which is not practical for individual assessments. Cumulative effects theory specifies a broader perspective than those typically included in EIAs, and the case study brings into perspective the potential for cumulative noise effects on herring populations due to overlapping construction periods of offshore wind farms. The temporal extent highlights the need for discourse to determine 'reasonable'. Herring typically mature after 36 months, so the scale of a disturbance to recruitment may not become apparent for three years, within which time other activities, including potentially additional wind farms in the study area, may add to the cumulative effect load experienced by the local herring population. Despite these challenges, the application score is 1, reflecting the existing knowledge from cumulative effects theory to expand perspectives and the availability of information identified for preceding steps that would support a broader perspective. In other words, progress from the narrow EIA perspective is possible.	Epistemic - language - underspecificity; Epistemic - System - Process; Combined - model - output; Combined - decision - decision	1
	As NSAH, above	Epistemic - language - underspecificity; Epistemic - System - Process; Combined - model - output; Combined - decision - decision	1
4.a	The key uncertainty is how to apply the available data (what analysis is useful) and what period of time is appropriate.	Epistemic - language - ambiguity; Aleatory - variability - natural; Combined - model - output	1
	As NSAH, above	Epistemic - language - ambiguity; Aleatory - variability - natural; Combined - model - output	1

Step	Application uncertainties/variability	Uncertainty classification (Skinner et al., 2014)	Uncertainty score
4.b	Uncertainty is high (see Chapter 6 for a discussion of challenges implementing resilience/resistance).	Epistemic - data - availability; Epistemic - language - ambiguity; Epistemic - language - underspecificity; Epistemic - system - process; Combined - model - output	0
	(TEH) As NSAH, above.	Epistemic - data - availability; Epistemic - language - ambiguity; Epistemic - language - underspecificity; Epistemic - system - process; Combined - model - output	0
4.c	The identification and application of thresholds are not without debate (Groffman et al., 2006; Hiers et al., 2016). However, in context of the case study, clear reference points are available based on robust science (Simmonds, 2009), which are straightforward to apply – CEAs can determine the current population status relative to reference points and assess the significance of change caused by focal activities relative to the reference points.	Aleatory - variability - natural	2
	As NSAH, above, with the caveat that the threshold was last investigated in 2004.	Aleatory - variability - natural; Aleatory - extrapolation - temporal	1
4.d	Determining which variables should be included is open to interpretation. Slow variables, which are key influences, are arguably beyond the scope of a project/activity CEA unless the temporal period of focal effects is of sufficient duration to overlap with meaningful change in slowly changing variables.	Epistemic - data - availability; Epistemic - data - precision; Aleatory - extrapolation - spatial [human activities, global to local]	1
5.a	Uncertainties are numerous and relate to different scales of inquiry. There is a lack of scientific agreement about how to measure/analyse effect cumulation. Uncertainties persist about the magnitude and duration of noise effects, which can be measured in different ways and which are also species specific. Recent noise assessment best practice guidelines are available to reduce variability of measurement (Farcas et al., 2016; Hawkins and Popper, 2016). Specific uncertainties exist about effect cumulation relative to herring. Assumptions are necessary and can be based on best available knowledge obtained through literature review. Qualitative progress is possible, based on broad-brush, low confidence approaches. However, the range of uncertainties and the associated scales of inquiry result in score 0.	Epistemic - data - availability; Epistemic - data - precision; Epistemic - system - cause; Epistemic - system - effect; Epistemic - system - process; Aleatory - variability - natural; Aleatory - extrapolation - intraspecies; Combined - model - output; Combined - model - decision	0

Step	Application uncertainties/variability	Uncertainty classification (Skinner et al., 2014)	Uncertainty score
	(TEH) As NSAH, above.	Epistemic - data - availability; Epistemic - data - precision; Epistemic - system - cause; Epistemic - system - effect; Epistemic - system - process; Aleatory - variability - natural; Aleatory - extrapolation - intraspecies; Combined - model - output; Combined - model - decision	0
5.b	Uncertainties are numerous and relate to different scales of inquiry. There is a lack of scientific agreement about how to measure/analyse persistence of relationships. There is a lack of empirical research into the significance of changes to interactions linked to the resilience/productivity of the receptor, or to interactions between the receptor and linked system components. Qualitative progress is possible, based on broad-brush, low confidence approaches. However, the range of uncertainties and the associated scales of inquiry result in score 0.	Epistemic - data - availability; Epistemic - data - precision; Epistemic - language - ambiguity; Epistemic - system - cause; Epistemic - system - effect; Epistemic - system - process; Aleatory - variability - natural; Aleatory - extrapolation - intraspecies; Combined - model - output; Combined - model - decision	0
	(TEH) As NSAH, above.	Epistemic - data - availability; Epistemic - data - precision; Epistemic - language - ambiguity; Epistemic - system - cause; Epistemic - system - effect; Epistemic - system - process; Aleatory - variability - natural; Aleatory - extrapolation - intraspecies; Combined - model - output; Combined - model - decision	0
5.c	Non-linearity needs to be defined, as it can relate to organism and ecosystem scales. Non-linear effects at organism-level require experimental studies, of which there are few and none identified relating to noise plus other variables.	Epistemic - data - availability; Epistemic - data - precision; Epistemic - language - ambiguity; Epistemic - system - cause; Epistemic - system - effect; Epistemic - system - process; Aleatory - variability - natural; Aleatory - extrapolation - intraspecies; Combined - model - output; Combined - model - decision	0
	(TEH) As NSAH, above.	Epistemic - data - availability; Epistemic - data - precision; Epistemic - language - ambiguity; Epistemic - system - cause; Epistemic - system - effect; Epistemic - system - process; Aleatory - variability - natural; Aleatory - extrapolation - intraspecies; Combined - model - output; Combined - model - decision	0

Step	Application uncertainties/variability	Uncertainty classification (Skinner et al., 2014)	Uncertainty score
5.d	An uncertainty related to appraising the efficacy of temporal restrictions in creating effects is the plasticity shown by the receptor, where the timing of the bottleneck risk may adapt to expected environmental conditions (Winters and Wheeler, 1996). At a more general level, specifications or guidance is lacking to assist definition of costs relative to the receptor. Uncertainty arises from the lack of an agreed formal approach to define value, which is an ambiguous and can be defined along relational and intrinsic lines (Piccolo, 2017). The CEA assists in this regard by providing a boundary object *(sensu* Thornton and Hebert, 2015) to support completion of the step involving multiple stakeholders' participation. Reductions in uncertainties associated with preceding steps will support improved resolution of the uncertainties for this step.	Epistemic - language - ambiguity; Combined - model - decision	1
6.a	The available information can be applied to achieve this intent unambiguously.	Epistemic - data - availability; Epistemic - language - underspecificity	2
6.b	Sufficient information exists to support a defensible approach to developing scenarios. There are a range of approaches to scenario development, thus the lack of standardisation or acceptance of one approach at regulator/practitioner level introduces potential incompatibility between assessments/scenarios generated.	Epistemic - language - ambiguity	1
6.c	N/A	N/A	N/A

Table A-4. List of improvements and enabling mechanisms identified that support reduction of uncertainties identified for each step during the evaluation.

Step	Improvements/enabling mechanisms	Comment
1.a	Harmonised and implemented common language standard applied to human activities within a defined region.	
1.b	Harmonised and implemented common typology and approach to characterising/analysing uncertainties within assessments	
1.c	Harmonised and implemented common risk assessment approach applied to human activities within a defined region.	
1.d	Regional guidance; defined management objectives against which potential risk can be appraised	

Step	Improvements/enabling mechanisms	Comment
	Regional guidance; defined management objectives against which potential risk can be appraised	Information about TEH is from 2004 or earlier. ICES HAWG reports exclude TEH. Hence scores of 1 for temporal and spatial resolution for TEH, as information is not current.
2.a	N/A	N/A
2.b	In principle, scoping could be supported by a common framework for activities in a logically coherent area. A peer-reviewed a priori ecosystem model, with species, habitats and communities categorised and linked to appropriate sampling/survey measures would support the generation of peer-reviewed PoE models for each human activity (such as offshore wind farms). Baseline surveying could validate and improve the resolution of the generic ecosystem structure and feed into improved identification of cause-effect-receptor pathways to take into detailed analysis. Validation is key to improving the accuracy of footprint models.	The temporal duration and spatial extent of effects generated by the processes are defined by the receiving environment, information which is not always well specified in Environmental Statements, hence score of 1.
2.c	Given how comprehensive PoE model approaches can vary, guidance to practioners would be advantageous to reduce variability between assessments.	
2.d	Guidance to practitioners clarifying requirements and depth of information required.	
3.a	Guidance to practitioners clarifying requirements and depth of information required.	
	Guidance to practitioners clarifying requirements and depth of information required.	
3.b	Guidance to practitioners clarifying requirements and depth of information required.	
	Guidance to practitioners clarifying requirements and depth of information required.	
3.c	Guidance to practitioners clarifying requirements and depth of information required.	
	Guidance to practitioners clarifying requirements and depth of information required.	
3.d	Guidance to practitioners clarifying requirements and depth of information required.Further research into the effects of spatio-temporal scale and the relationship between overlapping effects and receptor lifecycles to reduce uncertainty about 'reasonable boundaries' and 'proportionality'.	
	Guidance to practitioners clarifying requirements and depth of information required.Further research into the effects of spatio-temporal scale and the relationship between overlapping effects and receptor lifecycles to reduce uncertainty about 'reasonable boundaries' and 'proportionality'.	
4.a	Exploration of time-series and approaches in the absence of time-series data/reference points (e.g. Froese et al., 2018; estimating stock status from length-frequency data). Guidance specifying 'appropriate' periods to define the baseline.	
	Exploration of time-series and approaches in the absence of time-series data/reference points (e.g. Froese et al., 2018; estimating stock status from length-frequency data). Guidance specifying 'appropriate' periods to define the baseline.	
4.b	Targeted research into the role of herring in the social-ecological system and the effects if persistence is overwhelmed. Clarity about the application of resilience thinking relative to CEAs. Guidance to aid regulators and practitioners integrate and interpret resilience/resistance/persistence in CEAs.	

Step	Improvements/enabling mechanisms	Comment
	Targeted research into the role of herring in the social-ecological system and the effects if persistence is overwhelmed. Clarity about the application of resilience thinking relative to CEAs. Guidance to aid regulators and practitioners integrate and interpret resilience/resistance/persistence in CEAs.	
4.c	Considered sufficient for task	
	Targeted research to increase confidence in current population status and suitability of thresholds defined in the past. Information about spawning (spatial and temporal) is out of date.	
4.d	Baseline data on spatial and temporal changes in human activity variables and periodic assimilation of monitoring data.	
5.a	Baseline noise monitoring. Research into the consequences of localised noise impacts on system components connected to the receptor. Research into the cumulative effect of underwater noise on top of the cumulative effects load carried by the receptor. With greater clarity about acceptable methodologies to support regulatory information needs, develop guidance to practitioners clarifying requirements and depth of information required.	
	Research into the consequences of localised noise impacts on system components connected to the receptor. Research into the cumulative effect of underwater noise on top of the cumulative effects load carried by the receptor. With greater clarity about acceptable methodologies to support regulatory information needs, develop guidance to practitioners clarifying requirements and depth of information required.	
5.b	Research into the resistance/resilience of interactions within the focal system and the consequences of persistence being overcome. Clarification of meaning in context of development and CEAs.	
	Research into the resistance/resilience of interactions within the focal system and the consequences of persistence being overcome. Clarification of meaning in context of development and CEAs.	
5.c	Experimental research into multi-stressor effect interactions. Research into non-linear systems responses (species and broader system).	
	Experimental research into multi-stressor effect interactions. Research into non-linear systems responses (species and broader system).	
5.d	Targeted research to renew/refine the spawning envelope for the spring spawning population.	
6.a	Baseline data on spatial and temporal changes in human activity variables and periodic assimilation of monitoring data. Activity forecasts based on policy/trend analysis.	
6.b	Harmonised and implemented common approach to scenario development	
6.c	Harmonised and implemented common risk assessment approach applied to human activities within a defined region. Defined management objectives against which potential risk can be appraised	

A.2 Information used to generate the spatio-temporal effects footprint

Offshore works and processes associated with offshore wind farms in UK waters have been identified using three Environmental Statements[12] for Round 3 offshore wind farms (OWF), which were collated to support the CEA evaluation presented in Chapter 3. Round 3 developments are substantially larger that preceding development rounds, including the scale of turbines, however the processes involved in construction, operation and maintenance, and decommissioning are assumed to be analogous. This supporting information specifies the assumptions that underlie the spatio-temporal effects footprint and sets out the logical path from the processes identified to the spatio-temporal effects footprint presented in Chapter 6, section 6.3.1. Offshore works during the construction phase comprise works associated with site investigations, installation of wind turbines, meteorological mast, offshore collector stations, converter stations, and associated foundations, and offshore export cables and inter-array cables. The latter part of the construction phase may overlap with the commencement of the operational phase, i.e. electricity may be generated before all turbines are operational.

Offshore works/processes during the operations and maintenance phase primarily comprise processes required to maintain functioning of the electricity generation and transmission infrastructure.

Offshore works during the decommissioning phase assume that the license conditions will require all infrastructure that protrudes from or is close to the seabed to be removed. This is predicted to require the removal of wind turbine foundations above the seabed, removal of meteorological masts, offshore collector and converter stations and foundations, and removal of export and inter-array cables. Site investigation surveys are presumed necessary to confirm the seabed is free of fasteners that could pose a risk to fishing vessels with demersal gear.

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[12] East Anglia 1; Rampion; Navitus Bay

Variables/assumptions:

i) Standard wind turbine foundation types include monopiles, gravity bases, steel jacket with pin piles, and suction caisson. It is assumed here that monopiles are installed at all OWF in the study area, with large diameter piles >6.5m, i.e. suitable for >5MW turbine, driven to 55m depth. 81% offshore wind turbine foundations installed in European waters are monopiles (Wind Europe, 2016). Detail of the gravity base, suction caisson, and steel jacket with pin piles foundations follows, which provides an indication of how effects might alter if another foundation types were installed (e.g. changes to the scale of introduced hard substrate):
   a. gravity base with a diameter of up to 50m at seabed level and a base height of up to 10m, 7.5m diameter at sea-level. Scour protection up to 60m from foundation base, 1m depth. Not suitable in areas of large, mobile sand waves. Installation involves dredging to level seabed (22,500m3 per foundation) and in areas of sand installation of gravel layer for stability. Installation process 24hours including preparation. Dredged material disposed of within water column at site.
   b. suction caisson with a diameter of up to 25m at seabed level and a base height of up to 5m. Scour protection up to 60m from foundation base, 1m depth. In areas of mobile sand waves, seabed preparation required comprising digging a trench (11,500m3 per foundation). Installation process 24hours including preparation. Dredged material disposed of within water column at site.
   c. steel jackets with pin piles with a spread of up to 35m at seabed level, up to 4 pin piles each of up to 2.5m diameter. Penetration depth of piles 50m. Assumed footprint 30m x 30m (8.0MW turbine in 35m water depth) including scour protection 1m depth. Piling duration of 7 hours per pin pile, assumed installation by percussive piling (note alternative is drilling, with greater suspended sediment implications).

ii) Scour protection typically uses layers of natural, crushed rock which is resistant to degradation for the duration of the lifetime of the turbines. Volume and type of scour protection material around OWF infrastructure depends on the particle size of the seabed sediment, diameter and type of foundation installed, water depth and hydrographic regime the foundation is installed in. The hydrographic regime in the study area is similar (permanently mixed) and OWF in the study area are broadly installed in similar sediment types. Hence it is assumed that similar rock scour protection is installed around each turbine foundation. In reality the design and volume of scour protection placed (if at all) is subject to detailed investigation, as rock placement is costly (about 6% of the total turbine installation cost).

For the purposes of this assessment, calculations for the area and volume of rock placement for 6m diameter piles placed in 20m water depth in the North Sea are applied, requiring a radius of 12m of scour protection around each monopile. This equates to a volume of 837m^3 of rock placed around each monopile.

iii) Given the presence of fishing activity in and around OWF in the study area, it is assumed that export cables and inter-array cables are buried in the absence of hard ground.

iv) Offshore collector station foundation description in the Environmental Statements refer to the possibility of a gravity base or steel jacket with pin piles. The dimensions for the foundation are greater than for wind turbines due to greater dimension (up to 40m by 30m) and topside weight of the collector station (2,000 to 3,500 tonnes). Piled foundations are assumed here.

v) Offshore converter station foundation description in the Environmental Statements refer to the possibility of a gravity base or steel jacket with pin piles. The dimensions for the foundation are greater than for wind turbines due to greater dimension (up to 120m by 75m) and topside weight of collector station (18,000 tonnes). Piled foundations are assumed here.

vi) The number of vessel movements in the location of the OWF and to and from utilised ports during construction is predicted to be around 5700 during the construction phase (rounded up from 5695 quoted in East Anglia 1 Environmental Statement Volume 1, Chapter 4 – description of development), comprising 45 vessels.

vii) Continuous or phased construction processes are possible with concurrent piling if two jack-up rigs are available. Here, it is assumed that one piling vessel is available, therefore no concurrent piling would occur at each site. The time taken to pile varies depending on subsurface sediment/strata type. Here it is assumed that a >6.5m steel monopile requires 8 hours to be driven to the required depth of 55m, i.e. 1 pile per day.

These processes are collated into tables, one for each stage of the OWF lifecycle: construction (Table A-5); operations and maintenance (Table A-6); and decommissioning (Table A-7). The spatio-temporal characteristics of stressors or outcomes associated with the processes are described to enable the effect profiles to be developed at a subsequent stage of the assessment. Where a single process describes a number of events, a decision needs to be made about the characterisation of the resultant stressor or outcome. A temporal example is the installation of scour protection, which will occur at each turbine, with the process assumed to last one day per turbine location but extending over the duration of the turbine foundation installation period.

Table A-5. Components and processes associated with the construction phase of a generic offshore wind farm based on information contained in Environmental Statements of Round 3 Offshore Wind Farms in UK waters.

Construction component	Process	Duration and frequency	Stressor or outcome driving change and spatio-temporal characteristics	Link to effect categories Table 12 (Chapter 6)
Site investigation surveys	Geophysical investigations of the seabed, environmental baseline surveys	1 year, intermittent	(1) Increased suspended sediment concentrations from localised seabed contact – discrete point source, duration measured in days; (2) Structural disturbance to habitat from localised seabed contact - discrete point source, duration measured in days; (3) Underwater noise & vibration – seismic surveys – discrete point source, strong impulsive noise signal, duration measured in hours (4) Underwater noise & vibration – vessel movements – discrete point source, localised noise and vibration, duration measured in days	(1) – (1.a) (2) – (2.a) (3) – (3.a) (4) – (3.b)
Installation of met mast infrastructure	Single large diameter hollow steel pile driven into substrate to provide lateral resistance to loading. Jack up vessel anchors, pile positioned and piled using percussive piling involving hydraulic hammer.	1 day	(1) Increased suspended sediment concentrations from localised seabed contact – discrete point source, duration measured in days; (2) Structural disturbance to habitat from localised seabed contact - discrete point source, duration measured in days; (5) Underwater noise & vibration - discrete point source, strong, repetitive impulsive noise signal, duration measured in hours (6) Hydrological change – discrete point source, duration spans operational life of OWF; (7) Presence of novel substrate - discrete spatial point, duration spans operational life of OWF	(5) – (3.c) (6) – (4.a) (7) – (5.a)

Construction component	Process	Duration and frequency	Stressor or outcome driving change and spatio-temporal characteristics	Link to effect categories Table 12 (Chapter 6)
Installation of wind turbine foundations	Jack up vessel anchors, pile positioned and piled using percussive hammer.	1 day per turbine	(8) Increased suspended sediment concentrations – multiple discrete point sources spread over the extent of OWF, duration of each point measured in days; (9) Structural disturbance to habitat – multiple discrete point source spread over the extent of OWF, duration of each point measured in days; (10) Underwater noise & vibration – multiple discrete point sources spread over the extent of OWF, strong impulsive noise signal, duration spread over the extent of foundation installation period; (11) Underwater noise & vibration – vessel movements – multiple discrete point sources spread over the extent of OWF, duration of each point measured in days; (12) Hydrological change – multiple discrete point sources spread over the extent of OWF, duration spans operational life of OWF; (13) Presence of novel substrate – multiple discrete spatial points, duration spans operational life of OWF	(8) – (1.b) (9) – (2.b) (10) – (3.d) (11) – (3.e) (12) – (4.b) (13) – (5.b)
Installation of scour protection material	Barge with rock scour protection moors and places scour protection around each foundation	1 day per turbine	(8) Increased suspended sediment concentrations – multiple discrete point sources spread over the extent of OWF, duration of each point measured in days; (9) Structural disturbance to habitat – multiple discrete point source spread over the extent of OWF, duration of each point measured in days; (11) Underwater noise & vibration – vessel movements – multiple discrete point sources spread over the extent of OWF, duration of each point measured in days;	(14) – (3.f)

Construction component	Process	Duration and frequency	Stressor or outcome driving change and spatio-temporal characteristics	Link to effect categories Table 12 (Chapter 6)
			(14) Underwater noise & vibration – multiple discrete point sources spread over the extent of OWF, localised noise and vibration, duration spread over the extent of foundation installation period; (12) Hydrological change – multiple discrete point sources spread over the extent of OWF, duration spans operational life of OWF; (13) Presence of novel substrate – multiple discrete spatial points, duration spans operational life of OWF	
Installation of wind turbines	Appropriate vessels berths alongside foundation; mast, nacelle and blades attached to foundation, mast and nacelle respectively	1 day per turbine	(4) Underwater noise & vibration – vessel movements – discrete point source, localised noise and vibration, duration measured in days (15) Presence of novel aerial structure – multiple discrete spatial points, duration spans operational life of OWF	(15) – (5.c)
Installation of offshore collector station infrastructure	Jack up vessel anchors, pile positioned and piled using percussive hammer.	1 week	(1) Increased suspended sediment concentrations from localised seabed contact – discrete point source, duration measured in days; (2) Structural disturbance to habitat from localised seabed contact - discrete point source, duration measured in days; (5) Underwater noise & vibration - discrete point source, strong, repetitive impulsive noise signal, duration measured in hours (6) Hydrological change – discrete point source, duration spans operational life of OWF;	

Construction component	Process	Duration and frequency	Stressor or outcome driving change and spatio-temporal characteristics	Link to effect categories Table 12 (Chapter 6)
			(7) Presence of novel substrate - discrete spatial point, duration spans operational life of OWF	
Installation of offshore converter station infrastructure	Jack up vessel anchors, pile positioned and piled using percussive hammer.	1 week	(1) Increased suspended sediment concentrations from localised seabed contact – discrete point source, duration measured in days; (2) Structural disturbance to habitat from localised seabed contact - discrete point source, duration measured in days; (5) Underwater noise & vibration - discrete point source, strong, repetitive impulsive noise signal, duration measured in hours (6) Hydrological change – discrete point source, duration spans operational life of OWF; (7) Presence of novel substrate - discrete spatial point, duration spans operational life of OWF	
Installation of inter-array cabling	Pre-lay grapnel run along route; ploughing & cable lay; post-installation trenching or jetting. Crossing points with existing cables & pipelines protected with concrete mattressing	100m per hour	(16) Increased suspended sediment concentrations – discrete source over an extended spatial line, duration measured in weeks; (17) Structural disturbance to habitat - discrete source over an extended spatial line, duration measured in weeks; (18) Underwater noise & vibration - discrete point source, localised noise and vibration, duration measured in weeks	(16) – (1.c) (17) – (2.c) (18) – (3.g)
Installation of export cabling	Pre-lay grapnel run along route; ploughing & cable lay; post-	100m per hour	(16) Increased suspended sediment concentrations – discrete source over an extended spatial line, duration measured in weeks;	

Construction component	Process	Duration and frequency	Stressor or outcome driving change and spatio-temporal characteristics	Link to effect categories Table 12 (Chapter 6)
	installation trenching or jetting. Crossing points with existing cables & pipelines protected with concrete mattressing		(17) Structural disturbance to habitat - discrete source over an extended spatial line, duration measured in weeks; (18) Underwater noise & vibration - discrete point source, localised noise and vibration, duration measured in months	

Table A-6. Operation & maintenance (O&M) works and processes for a generic offshore wind farm. Note a frequency column is included to identify whether a process is intermittent or continuous during the operational phase. The lease for English OWF is assumed to be 50 years and the design life of current technology assumed to be 20-25 years.

O&M component	Process	Duration and frequency	Stressor or outcome driving change, spatio-temporal characteristics	Link to effect categories Table 12 (Chapter 6)
Turbine operation	Turbines in place for duration of lifecycle; Aerodynamic noise and mechanical noise transmit through structure into the water column during operation causing	25 years, continuous	(19) Underwater noise & vibration – multiple discrete point sources spread over the extent of OWF, localised noise and vibration, duration spans operational life of OWF; (20) Presence of novel aerial structures – moving turbine blades – multiple discrete spatial points, duration spans operational life of OWF	(19) – (3.h) (20) – (5.d)

O&M component	Process	Duration and frequency	Stressor or outcome driving change, spatio-temporal characteristics	Link to effect categories Table 12 (Chapter 6)
	underwater noise and vibration			
Stations operation	Stations in place for duration of lifecycle	25 years, continuous	(19) Underwater noise & vibration – multiple discrete point sources spread over the extent of OWF, localised noise and vibration, duration spans operational life of OWF; (7) Presence of novel substrate - discrete spatial point, duration spans operational life of OWF	
Cable operation	Cables in place for duration of lifecycle; EMF generated by current transported along cable	25 years, continuous	(21) Presence of electro-magnetic fields - discrete sources over multiple extended spatial lines, duration spans operational life of OWF	(21) – (5.e)
Turbine inspections	Vessel transports personnel to turbines	25 years, intermittent (monthly)	(4) Underwater noise & vibration – vessel movements – discrete point source, localised noise and vibration, duration measured in days	
Offshore converter stations & collector stations inspections	Vessel transports personnel to stations	25 years, intermittent (weekly)	(4) Underwater noise & vibration – vessel movements – discrete point source, localised noise and vibration, duration measured in days	
Turbine replacement	Periodic replacement of damaged/fatigued turbine/turbine components	25 years, intermittent	(4) Underwater noise & vibration – vessel movements – discrete point source, localised noise and vibration, duration measured in days	

O&M component	Process	Duration and frequency	Stressor or outcome driving change, spatio-temporal characteristics	Link to effect categories Table 12 (Chapter 6)
Cable inspections	Surveys along length of cable	25 years, intermittent (monthly)	(4) Underwater noise & vibration – vessel movements – discrete point source, localised noise and vibration, duration measured in days	
Cable repair	Periodic replacement of damaged/fatigued cable/connectors	25 years, intermittent	(1) Increased suspended sediment concentrations from localised seabed contact – discrete point source, duration measured in days; (2) Structural disturbance to habitat from localised seabed contact - discrete point source, duration measured in days; (18) Underwater noise & vibration - discrete point source, localised noise and vibration, duration measured in weeks	

Table A-7. Assumed decommissioning works for a generic offshore wind farm.

Decommissioning component	Process	Duration of process	Stressor or outcome driving change, spatio-temporal characteristics	Link to effect categories Table 12 (Chapter 6)
Removal of met mast infrastructure	Offshore works vessel stationed at each foundation location. Pile cut below the surface and	1 day	(1) Increased suspended sediment concentrations from localised seabed contact – discrete point source, duration measured in days; (2) Structural disturbance to habitat from localised seabed contact - discrete point source, duration measured in days;	(22) – (4.c) (23) – (5.f)

Decommissioning component	Process	Duration of process	Stressor or outcome driving change, spatio-temporal characteristics	Link to effect categories Table 12 (Chapter 6)
	removed. Any scour protection removed.		(4) Underwater noise & vibration – vessel movements – discrete point source, localised noise and vibration, duration measured in days (22) Hydrological change – discrete point source, duration spans foreseeable future; (23) Removal of established substrate – discrete point source, duration spans foreseeable future	
Removal of wind turbines	Appropriate vessels berths alongside foundation; mast, nacelle and blades removed from foundation	1 day per turbine	(4) Underwater noise & vibration – vessel movements – discrete point source, localised noise and vibration, duration measured in days	
Removal of wind turbine foundations and scour protection	Offshore works vessel stationed at each foundation location. Pile cut below the surface and removed. Barge with crane moors and removes scour protection from around each foundation	1 day per turbine	(8) Increased suspended sediment concentrations – multiple discrete point sources spread over the extent of OWF, duration of each point measured in days; (9) Structural disturbance to habitat – multiple discrete point source spread over the extent of OWF, duration of each point measured in days; (11) Underwater noise & vibration – vessel movements – multiple discrete point sources spread over the extent of OWF, duration of each point measured in days; (24) Hydrological change – multiple discrete point sources, duration spans foreseeable future; (25) Removal of established substrate – multiple discrete point sources, duration spans foreseeable future	(24) – (4.d) (25) – (5.g)

Decommissioning component	Process	Duration of process	Stressor or outcome driving change, spatio-temporal characteristics	Link to effect categories Table 12 (Chapter 6)
Removal of inter-array cabling	Vessel retrieves cable along length of cable route, concrete mattressing, crossing points or scour material removed	100m per hour	(16) Increased suspended sediment concentrations – discrete source over an extended spatial line, duration measured in weeks; (17) Structural disturbance to habitat - discrete source over an extended spatial line, duration measured in weeks; (18) Underwater noise & vibration - discrete point source, localised noise and vibration, duration measured in months	
Removal of offshore collector station infrastructure	Offshore works vessel stationed at each foundation location. Pile cut below the surface and removed. Any scour protection removed.	1 week	(1) Increased suspended sediment concentrations from localised seabed contact – discrete point source, duration measured in days; (2) Structural disturbance to habitat from localised seabed contact - discrete point source, duration measured in days; (4) Underwater noise & vibration – vessel movements – discrete point source, localised noise and vibration, duration measured in days (22) Hydrological change – discrete point source, duration spans foreseeable future; (23) Removal of established substrate – discrete point source, duration spans foreseeable future	
Removal of offshore converter station infrastructure	Offshore works vessel stationed at each foundation location. Pile cut below the surface and	1 week	(1) Increased suspended sediment concentrations from localised seabed contact – discrete point source, duration measured in days; (2) Structural disturbance to habitat from localised seabed contact - discrete point source, duration measured in days;	

Decommissioning component	Process	Duration of process	Stressor or outcome driving change, spatio-temporal characteristics	Link to effect categories Table 12 (Chapter 6)
	removed. Any scour protection removed.		(4) Underwater noise & vibration – vessel movements – discrete point source, localised noise and vibration, duration measured in days (22) Hydrological change – discrete point source, duration spans foreseeable future; (23) Removal of established substrate – discrete point source, duration spans foreseeable future	
Removal of export cabling	Vessel retrieves cable along length of cable route, concrete mattressing, crossing points or scour material removed	100m per hour	(16) Increased suspended sediment concentrations – discrete source over an extended spatial line, duration measured in weeks; (17) Structural disturbance to habitat - discrete source over an extended spatial line, duration measured in weeks; (18) Underwater noise & vibration - discrete point source, localised noise and vibration, duration measured in months	
Site inspection surveys	Geotechnical investigations of the seabed, grapnel runs and environmental surveys to confirm adequate decommissioning	1 year	(1) Increased suspended sediment concentrations from localised seabed contact – discrete point source, duration measured in days; (2) Structural disturbance to habitat from localised seabed contact - discrete point source, duration measured in days; (3) Underwater noise & vibration – seismic surveys – discrete point source, strong impulsive noise signal, duration measured in hours (4) Underwater noise & vibration – vessel movements – discrete point source, localised noise and vibration, duration measured in days	

Table A-8. Results of classifying the spatial and temporal extents of stressors/outcomes associated with offshore wind farms using the classification scale presented in Table 11, Chapter 6. The sensitivity*likelihood of exposure is then estimated using expert judgement to score the likelihood that a stressor/outcome will add to the cumulative effects load acting on receptors. Numerals 1.a to 5.g correlate with the effect classification as shown in Table 11, Chapter 6.

Receptor	Variable	1.a	1.b	1.c	2.a	2.b	2.c	3.a	3.b	3.c	3.d	3.e	3.f	3.g	3.h	4.a	4.b	4.c	4.d	5.a	5.b	5.c	5.d	5.e	5.f	5.g
N/A	Spatial extent	1.5	1	2	1.5	1.5	2	3	1.5	3	4	1.5	1.5	1.5	1	1	1.5	1	1.5	1	2	2	2	1.5	1	2
N/A	Temporal extent	1	1	2	1	1	2	1	1	1	3	1.5	3	2	4	4	4	4	4	4	4	4	4	4	4	4
Herring (assume spatial and temporal overlap)	Likelihood of adding to cumulative effect load (sensitivity*likelihood of exposure)	2	2	2	1	1	1	8	6	8	16	6	6	6	6	1	1	1	1	1	1	1	1	1	1	1
Commercial fishing operations (assume spatial and temporal overlap)	Likelihood of adding to cumulative effect load (sensitivity*likelihood of exposure)	1	1	1	6	12	12	8	4	8	16	9	4	9	4	1	1	1	1	16	16	1	1	12	12	16
Seabirds (assume spatial and temporal overlap)	Likelihood of adding to cumulative effect load (sensitivity*likelihood of exposure)	2	2	2	4	4	4	4	8	4	6	8	4	8	4	4	4	4	4	4	4	16	16	1	1	1

Receptor	Variable	1. a	1. b	1. c	2. a	2. b	2. c	3. a	3. b	3. c	3. d	3. e	3. f	3. g	3. h	4. a	4. b	4. c	4. d	5. a	5. b	5. c	5. d	5. e	5. f	5. g
Benthic productivity	Likelihood of adding to cumulative effect load (sensitivity*likelihood of exposure)	12	12	12	16	16	16	4	1	2	8	1	2	4	1	12	12	12	12	16	16	1	1	4	16	16

A.3 Supporting information behind the Causal Loop Diagram

Table A-9. Assumed effect of the interactions on the persistence of the focal receptor and the importance for the case study CEA. Interaction numbers match Table A-10 above and refer to interactions included in the Causal Loop Diagram (Figure 30 Error! Reference source not found.**).**

No.	Interaction (cause to effect)	Assumed effect on persistence	Importance for CEA (2000-2015)	Rationale	Bottleneck risk
1	Herring population productivity - Egg production	Strong	Low	Egg production fundamental to persistence of species. Part of positive reinforcing loop. Assume constant over period of CEA.	No
2	Herring population productivity - Prey availability	Weak	Low	Ecological interaction that has persisted over long period of time; Part of a balancing loop, assume self-organising. Assume constant over period of CEA.	No
3	Herring population productivity - Density dependent regulation of growth	Weak	Low	Ecological interaction that has persisted over long period of time; Part of a balancing loop, assume self-organising. Assume constant over period of CEA.	No
4	Density dependent regulation of growth - Growth of surviving fish	Weak	Low	Ecological interaction that has persisted over long period of time; Part of a balancing loop, assume self-organising. Assume constant over period of CEA.	No

No.	Interaction (cause to effect)	Assumed effect on persistence	Importance for CEA (2000-2015)	Rationale	Bottleneck risk
5	Growth of surviving fish - Herring population productivity	Strong	Medium	Growth of surviving fish fundamental to persistence of species. Forms component of a balancing loop, but is influenced by other variables/interactions. No direct relationships with managed human activities, however, changes to growth could be influential, hence medium importance.	No
6	Herring population productivity - Pelagic fishing	Strong	Low	Productivity determines fishing quotas, which in turn are a key factor influencing recruitment and hence persistence of the species; Low importance to CEA due to high level of management, with quotas reflecting assessed productivity. Assume managed balancing loop.	Yes
7	Herring population productivity - Predation	Weak	Low	Ecological interaction that has persisted over long period of time; Part of a balancing loop, assume self-organising. Assume constant over period of CEA.	No
8	Pelagic fishing - Fishing mortality	Strong	Low	Pelagic fishing efforts determines fishing mortality, which is a key factor influencing recruitment and hence persistence of the species	Yes
9	Fishing mortality - Recruitment of new fish	Strong	Low	Fishing mortality is a key factor influencing recruitment and hence persistence of the species. Low importance to CEA due to high level of management, with quotas reflecting assessed productivity. Assume managed balancing loop.	Yes/No
10	Predation - Recruitment of new fish	Strong	Low	Ecological interaction that has persisted over long period of time; Part of a balancing loop, assume self-organising. Assume constant over period of CEA.	No

No.	Interaction (cause to effect)	Assumed effect on persistence	Importance for CEA (2000-2015)	Rationale	Bottleneck risk
11	Natural mortality - Recruitment of new fish	Medium	Low	Ecological interaction that has persisted over long period of time. Assume self-organising. Assume constant over period of CEA.	No
12	Recruitment of new fish - Herring population productivity	Strong	High	Recruitment fundamental to persistence of species. Influenced by other variables/interactions, including direct relationships with managed human activities. Changes to recruitment could be influential, hence high importance.	No
13	Egg production - Recruitment of new fish	Strong	Low	Egg production fundamental to persistence of species. Part of positive reinforcing loop. Assume constant over period of CEA.	No
14	Prey availability - Favourable over-wintering phase for larvae	Strong	Low	Overwintering phase is key for larval survival, potential for a strong link with prey availability. Exogenic environmental influences. Assume constant over period of CEA.	No
15	Prey availability - Growth of surviving fish	Strong	Low	Prey availability a key factor influencing growth rates. Subject to environmental influences at exogenic scales and temporal periods outside CEA boundaries. Assume constant over period of CEA	No
16	Favourable over-wintering phase for larvae - Recruitment of new fish	Strong	Low	Overwintering phase is key for larval survival, potential for a strong link with prey availability. Exogenic environmental influences. Assume constant over period of CEA.	No
17	Climate change - Growth of surviving fish	Weak	Low	Climate change a slow variable. Herring has a wide temperature tolerance. Assume constant over period of CEA.	No

No.	Interaction (cause to effect)	Assumed effect on persistence	Importance for CEA (2000-2015)	Rationale	Bottleneck risk
18	Climate change - Regime shifts	Strong	Low	Evidence that shift from cold water to warm water *Calanus* spp. has occurred due to climate change in North Sea, with deleterious effects on herring. As climate change a slow variable, assume constant over period of CEA.	No
19	Climate change - Predation	Unknown	Low	Unknown effect of increased presence of species that predate on herring larvae. As climate change a slow variable, assume constant over period of CEA.	No
20	Climate change - Quality and availability of spawning grounds	Unknown	Low	Unknown effect of changing climate on quality of spawning grounds for herring. As climate change a slow variable, assume constant over period of CEA.	Yes
21	Regime shifts - Prey availability	Strong	Low	Evidence that shift from cold water to warm water *Calanus* spp. has occurred due to climate change in North Sea, with deleterious effects on herring. As climate change a slow variable, assume constant over period of CEA.	No
22	Quality and availability of spawning grounds - Recruitment of new fish	Strong	High	Persistence of species fundamentally linked to access to spawning grounds of suitable quality at specific periods of time.	Yes
23	Structural disturbance to benthic habitat - Quality and availability of spawning grounds	Strong	High	Persistence of species fundamentally linked to access to spawning grounds of suitable quality at specific periods of time.	Yes
24	Noise and vibration - Quality and availability of spawning grounds	Strong	High	Persistence of species fundamentally linked to access to spawning grounds of suitable quality at specific periods of time.	Yes

No.	Interaction (cause to effect)	Assumed effect on persistence	Importance for CEA (2000-2015)	Rationale	Bottleneck risk
25	Offshore wind farm construction - Noise and vibration	Strong	High	Strong evidence that strong underwater noise can interrupt interaction between herring and spawning grounds.	Yes
26	Ports and shipping - Noise and vibration	Medium	Medium	Strong evidence that strong underwater noise can interrupt interaction between herring and spawning grounds. Shipping has existed for a long period of time in the CEA area and herring has persisted. Shipping noise forecast to increase contributing to chronic noise levels, hence medium importance.	Yes
27	Aggregate extraction - Noise and vibration	Medium	Medium	Strong evidence that strong underwater noise can interrupt interaction between herring and spawning grounds. Aggregate extraction has existed for a long period of time in the CEA area and herring has persisted. Plans to expand aggregate dredging, contributing to chronic noise levels, hence medium importance.	Yes
28	Aggregate extraction - Structural disturbance to benthic habitat	Strong	High	Strong evidence that aggregate extraction overlapping with spawning habitat has a long-term damaging effect. Aggregate extraction has existed for a long period of time in the CEA area and herring has persisted. Plans to expand aggregate dredging, potential to incrementally reduce available spawning habitat, hence high importance.	Yes

No.	Interaction (cause to effect)	Assumed effect on persistence	Importance for CEA (2000-2015)	Rationale	Bottleneck risk
29	Demersal trawling - Structural disturbance to benthic habitat	Strong	High	Strong evidence that demersal fishing with heavy gear has a medium-term damaging effect. Beam-trawling and Otter trawling have existed for a long period of time in the CEA area and herring has persisted. Potential to incrementally impact available spawning habitat, hence high importance.	Yes
30	Offshore cables - Structural disturbance to benthic habitat	Medium	Medium	Cable laying/trenching overlapping with spawning habitat will have a long-term damaging effect. Plans to increase the number of power cables. Potential to incrementally reduce or disturb available spawning habitat, hence high importance.	Yes

A.4 Supporting information for human activity trends

Table A-10. Summary of trends in maritime industries in the case study area and associated ecological effects relative to the focal receptor. Trends and future contributions are indicated by arrows: → static; ↑ increasing; ↓ decreasing. Supporting evidence behind the trends specified is provided in Table A-11, below.

Activity	Associated ecological effect	Trend (contribution to case study cumulative effect load)	Importance relative to CLD (High/ Medium/ Low)	Rationale (relative to herring)	Disturbance type (Nimmo et al., 2015)	Assumed recovery period	Future contribution to cumulative effects load
Fishing	Selective extraction of living resources caused by capture in fishing gear	→	High	System has been subject to stressor for long time; assessed fish stocks fished at or below FMSY; system assumed here to be resilient to 'normal' fishing pressure. High importance due to major source of mortality for focal receptor	Press	No release	→
	Benthic habitat disturbance caused by gear contact with sea bed	↓	Medium	Assume gradual reduction in swept area reducing load, important where activity overlaps with spawning grounds, hence medium.	Press	Dependent on substrate type	↓
	Underwater noise caused by vessels and gear contact with sea bed	↓	Medium	Assume reducing pressure, but contributor to overall noise budget hence medium.	Press	No release	→

Activity	Associated ecological effect	Trend (contribution to case study cumulative effect load)	Importance relative to CLD (High/ Medium/ Low)	Rationale (relative to herring)	Disturbance type (Nimmo et al., 2015)	Assumed recovery period	Future contribution to cumulative effects load
Shipping	Underwater noise and vibration	→	Medium	Based on time-series of shipping volume in case study area (2000-2015) static contribution over case study, but contributor to overall noise budget hence medium.	Pulse; Press	No release	↑
	Increased competition with novel species caused by ballast water discharge and hull fouling	→	Low	Assume implementation of ballast water measures effective in case study area. No evidence found that known invasive species of high significance to herring populations to date.	Press	N/A	↑
Ports	Benthic habitat disturbance caused by navigational dredging	→	Low	Assume navigational dredging limited to existing shipping channels, i.e. no incremental novel loss of essential habitat	Pulse; Press	3-7 years depending on substrate type	→
	Underwater noise from navigational dredging	→	Low	Assume navigational dredging limited to existing shipping channels, i.e. no incremental noise overlap with essential habitat	Pulse; Press	Release at end of dredging	→

Activity	Associated ecological effect	Trend (contribution to case study cumulative effect load)	Importance relative to CLD (High/ Medium/ Low)	Rationale (relative to herring)	Disturbance type (Nimmo et al., 2015)	Assumed recovery period	Future contribution to cumulative effects load
Offshore wind	Benthic habitat disturbance caused by construction works and installation of cables	↑	High	Assume high where there is spatial overlap with herring essential habitat	Pulse; Press	3-7 years depending on substrate type	↑
	Substrate gain caused by installation of turbine foundations and scour material	↑	Low	Discrete points in habitat, assume inconsequential interaction with herring spawning behaviour and essential habitat	Press	Permanent	↑
	Underwater noise caused by turbine and other piled seafloor infrastructure installation	↑	High	Assume high where there is spatial overlap with herring essential habitat	Pulse	Release at end of piling	↑
	Increased competition with novel species caused by habitat provision	↑	Low	Assume no significant interaction between herring and organisms attracted to novel substrate	Press	Permanent	↑

Activity	Associated ecological effect	Trend (contribution to case study cumulative effect load)	Importance relative to CLD (High/ Medium/ Low)	Rationale (relative to herring)	Disturbance type (Nimmo et al., 2015)	Assumed recovery period	Future contribution to cumulative effects load
Aggregate extraction	Habitat disturbance caused by removal of sediments	→	High	Assume high where there is spatial overlap with herring essential habitat	Press	3-7 years depending on substrate type	↑
	Underwater noise caused by draghead during dredging	→	High	Assume high where there is spatial overlap with herring essential habitat	Pulse	Release at end of extraction period	↑
Cable and pipeline installation	Habitat disturbance caused by installation	↑	High	Assume high where there is spatial overlap with herring essential habitat	Pulse; Press	3-7 years depending on substrate type	↑
	Substrate gain caused by unburied cables, mattresses	↑	Low	Assume no significant interaction between herring and organisms attracted to novel substrate	Press	Permanent	↑
	Underwater noise caused by installation	↑	Medium	Assume trenching characteristics (1km per day) result in minimal exposure to noise where spatio-temporal overlap, but contributor to overall noise budget hence medium.	Pulse	Release at end of trenching period	↑

Table A-11. Summary of supporting evidence collated to inform activity and ecological effect trends specified in Table A-10, above.

Activity	Associated ecological effect	Summary of evidence	Confidence in summary	Sources
Fishing	Selective extraction of living resources caused by capture in fishing gear	Assume contribution to stressor trend is static. The majority of assessed commercial fish stocks in the North Sea are fished at or below F_{MSY} (ICES 2016). North Sea herring fished at or below FMSY (ICES HAWG 2018). Less clarity regarding TEH. MMO landings data would support analysis of spatio-temporal trends (ICES statistical rectangle scale and monthly or annual periods).	High	MMO, FAO, ICES
	Benthic habitat disturbance caused by gear contact with sea bed	STECF data – Fishing effort roughly halved between 2004-2012 in the North Sea in general; Spatial extent of abrasion visible via DATRAS data for CPUE per length per hour and swept area, one year only (2015); VMS data shows decrease in proportion of swept seafloor by about 7.5% between 2009 and 2013 (ICES 2016); General trend towards gears with lighter footprint (fuel savings as well as ecological benefits over 'heavy' gear).	Medium	DATRAS, ICES, STECF
	Underwater noise caused by vessels and gear contact with sea bed	As above.	Low	DATRAS, ICES, STECF

Activity	Associated ecological effect	Summary of evidence	Confidence in summary	Sources
Shipping	Underwater noise and vibration	A time-series of annual shipping freight traffic (thousand tonnes) can be developed covering the temporal and spatial extents of the case study. The UK Department for Transport Maritime and Shipping statistics can be queried to extract data for port groups 'Thames and Kent', 'Haven' and 'Wash and Northern East Anglia' broadly coinciding with the case study area between 2000-2015. The resultant trend is broadly static. Looking forward the long-term trend can be expected to increase based on scenarios and forecasts by the Port of London Authority (78% increase in maritime trend is predicted between 2014 and 2035). Lloyds Register also predicts a long-term increase in maritime traffic, including an increase in the size and number of vessels in all categories. Hatch et al. (2008) identified larger vessels as emitting a disproportionally large relative proportion of overall shipping noise. Evidence is available showing an increase in the overall underwater noise levels in UK waters (Merchant et al., 2016; Merchant et al., 2017). AIS data could be used to better inform noise contributions, as achieved in the South marine plan area.	Medium	UK Government maritime and shipping statistics; MMO; Port of London Authority; Lloyds Register; McKenna et al., 2012; Bassett et al., 2012; Roberts and Elliott 2017; Merchant et al., 2017; Slabberkoorn et al., 2010; Merchant et al., 2016; Andersson et al., 2011; Hatch et al., 2008; Bassett et al., 2012

Activity	Associated ecological effect	Summary of evidence	Confidence in summary	Sources
	Increased competition with novel species caused by ballast water discharge and hull fouling	Biopollution an increasing concern in North Sea waters (Elliott et al., 2017). Current evidence points to invasive species being a greater issue for benthic/hard substrate habitats (Ducrotoy and Elliott 2008). No evidence found that known invasive species of high significance to herring populations to date. However, caution warranted, as invasive copepods species found in North Sea in 2011 (ICES 2016) and evidence that cumulative effects including climate change may lead to jellyfish blooms that can significantly alter the structure of pelagic ecosystems (Richardson et al., 2009).	Low	Elliott et al., 2017; ICES 2016; Ducrotoy and Elliott 2008; Richardson et al., 2009
Ports	Benthic habitat disturbance caused by navigational dredging	London Gateway Port capital dredging between about 2010 and 2014; periodic maintenance dredging thereafter. MMO data shows spatial extent of dredging licenses. MMO data also provides temporal informaiton with project start and end dates, would support analysis of trend over case study period. For future trends, assume existing navigation channels will remain open or be deepened to accommodate larger ships (e.g. "triple E" container vessels), but no new channels, hence static trend.	Medium	MMO
	Underwater noise from navigational dredging	As above.	Low	MMO
Offshore wind	Benthic habitat disturbance caused by construction works and installation of cables	Summarised in Willsteed et al., 2017. Future trend for OWF in Southern North Sea and North Sea in general is increasing.	High	MMO, OSPAR; Willsteed et al., 2017

Activity	Associated ecological effect	Summary of evidence	Confidence in summary	Sources
	Substrate gain caused by installation of turbine foundations and scour material	Summarised in Willsteed et al., 2017. Future trend for OWF in Southern North Sea and North Sea in general is increasing.	High	MMO, OSPAR; Willsteed et al., 2017
	Underwater noise caused by turbine and other piled seafloor infrastructure installation	Summarised in Willsteed et al., 2017. Future trend for OWF in Southern North Sea and North Sea in general is increasing.	High	MMO, OSPAR; Willsteed et al., 2017
	Increased competition with novel species caused by habitat provision	Summarised in Willsteed et al., 2017. Future trend for OWF in Southern North Sea and North Sea in general is increasing.	High	MMO, OSPAR; Willsteed et al., 2017
Aggregate extraction	Habitat disturbance caused by removal of sediments	MMO data shows spatial extent of aggregate dredging licenses. MMO data also provides temporal informaiton with project start and end dates, would support analysis of trend over case study period.	Medium	MAREA
	Underwater noise caused by draghead during dredging	MMO data shows spatial extent of dredging licenses. MMO data also provides temporal informaiton with project start and end dates, would support analysis of trend over case study period.	Medium	MAREA
Cable and pipeline installation	Habitat disturbance caused by installation	MMO data shows spatial extent of cable application licenses. MMO data also provides temporal informaiton with project start and end dates, would support analysis of trend over case study period. Discussions with IFCA suggest likelihood of future cables in case study area (W. Wright, pers. com)	Low	MMO; IFCA

Activity	Associated ecological effect	Summary of evidence	Confidence in summary	Sources
	Substrate gain caused by unburied cables, mattresses	MMO data shows spatial extent of cable application licenses. MMO data also provides temporal informaiton with project start and end dates, would support analysis of trend over case study period. Discussions with IFCA suggest likelihood of future cables in case study area (W. Wright, pers. com)	Medium	MMO; IFCA
	Underwater noise caused by installation	MMO data shows spatial extent of cable application licenses. MMO data also provides temporal informaiton with project start and end dates, would support analysis of trend over case study period. Discussions with IFCA suggest likelihood of future cables in case study area (W. Wright, pers. com)	Medium	MMO; IFCA

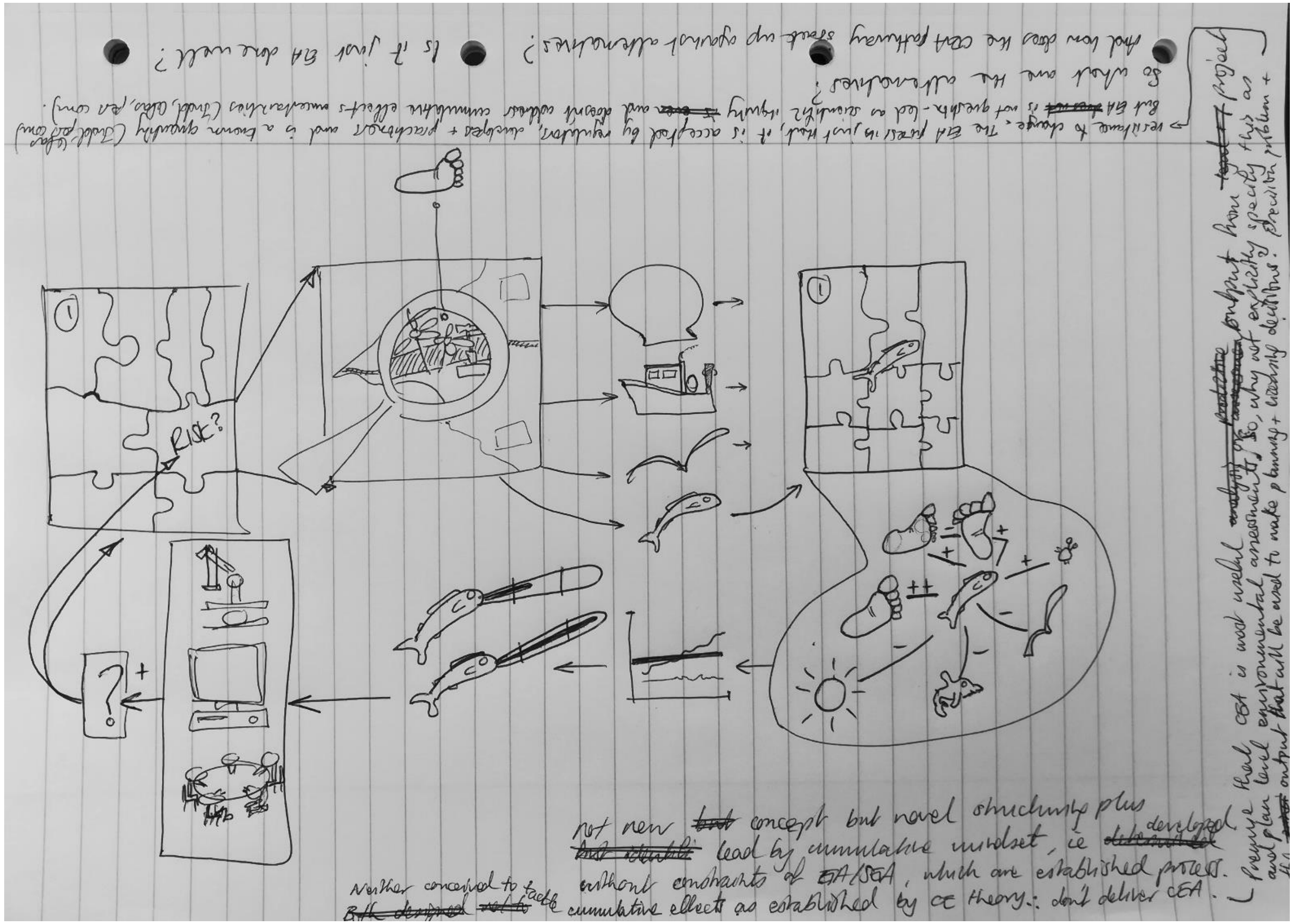

Figure 39. Sketch of the CEA pathway showing the circular route from identifying the risk that requires assessment through to the output that contributes to local and regional understanding of cumulative effects within the system.