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Review

An effective set of principles for practical implementation of marine cumulative effects assessment

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ABSTRACT

The term "cumulative effects assessment" is frequently used yet the underlying principles and definitions are poorly specified. Consequently, there is no consistency or standardisation in approaches leaving marine managers and developers perplexed on how best to discharge their legal obligations to undertake cumulative effects assessment. This paper explores some of the origins of the terminology and re-interprets how these may best be applied to standardise the vocabulary and approaches to cumulative effects assessment.

We define cumulative effects assessment as a systematic procedure for identifying and evaluating the significance of effects from multiple sources/activities and for providing an estimate on the overall expected impact to inform management measures. The analysis of the causes (source of pressures and effects), pathways and consequences of these effects on receptors is an essential and integral part of the process.

Environmental risk assessment concepts, in particular sound problem formulation, have been used to provide a clear structure for cumulative effects assessment. We recommend that risk screening, prioritisation and evaluation should be a critical component of cumulative effects assessment to facilitate a filtering of the complex issues for consideration of the likelihood of exposure of receptors to pressures and the likelihood of a receptor responding to those pressures. This paper is intended to provide practical assistance to marine environmental impact assessment practitioners, marine environmental regulators and policy makers.

1. Introduction

The terms "cumulative", "in combination" and "collective" are in wide usage by regulators, managers, practitioners and academics engaged in undertaking and evaluating assessments of environmental "effects", "impacts" and/or "pressures", however, there is a lack of clarity on how these terms should be defined and applied in environmental evaluation and management operations.

The scale and regulatory drivers for any cumulative effects assessment are critical both in terms of defining the scope of the assessment (to determine which suite of activities, environmental pressures and ecosystem components should be included) and the methodologies which are best suited to making that assessment. However, at present the attempts to develop cumulative effects assessment methodologies have two main paths depending on whether they are initiated from a legal or a scientific perspective.

The common interpretation of the various legal drivers for cumulative effects assessment is a consideration of which human activities, plans or projects need to be included in the study and then to determine the associated environmental effects and sensitive ecosystem components. Whereas, the common interpretation for scientific evaluations of cumulative effects is how environmental pressures interact to effect ecosystem components and then track these back to the causal human activities. Whilst this may seem a subtle distinction it means that there is a split in research efforts and an incompatibility in the emerging methodologies.

The Marine Strategy Framework Directive stipulates that the management of human activities applies an ecosystem-based context. In this paper we consider whether the application of an ecosystem approach to cumulative effects assessment is also appropriate to other legislative drivers. We believe that the adoption of some common principles will facilitate the consolidation of research efforts towards resolving the conundrum of cumulative effects assessment.

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2. The problem

The following list of examples from different European legislative drivers illustrates how different terminologies are used for describing different aims when assessing cumulative, combined and collective effects, which adds considerable confusion:

- Article 6(3) of EC Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora indicates the need to appropriately assess 'in-combination' effects that a plan or project may have with other plans or projects.
- Article 4(3) of the European Environmental Impact Assessment (EIA) Directive (85/337/EEC) (as amended), referring to the screening stage, states 'the characteristics of the project must be considered having regard, in particular, to . . . the cumulation with other projects'. In relation to the content of an Environmental Statement, Article 5(1) of the EIA Directive requires 'assessment of the direct effects and any indirect, secondary, cumulative, short, medium and long-term, permanent or temporary, positive and negative effects of the project.
- The Marine Strategy Framework Directive (2008/56/EC) stipulates that "Marine strategies shall apply an ecosystem-based approach to the management of human activities, ensuring that the collective pressure of such activities is kept within levels compatible with the achievement of good environmental status . . ." and ". . . an analysis of the predominant pressures and impacts including human activity, on the environmental status of those waters which [. . .] covers the main cumulative and synergistic effects; . . .".

Such legislation places legal obligations on member states to introduce assessment and management measures, thus placing environmental, social and economic burdens on governments and industries. Such obligations include, for example, the collection and evaluation of data in Environmental Impact Assessments, licensing systems for marine activities, protection of species and habitats, the development and implementation of measures to achieve environmental benefits and the sustainable use of marine resources. To ensure that such burdens are proportionate (i.e. allow regulatory decisions to be taken which are both affordable and acceptable to society) it is critical that ambiguity and uncertainty in the terminology is reduced.

This paper has been written on the basis that the identification of commonalities in terminology, objectives and approaches for cumulative effects assessment may allow for more consistent and coherent assessments of cumulative effects (rather than having different approaches for each legislative driver). However, we recognise that the endpoint of assessments to address these legislative drivers may be different. Therefore we need to determine the point of departure—i.e. at what point do the assessment requirements of cumulative effects to comply with these legislative drivers start to differ significantly necessitating the use of different methods/tools, e.g.

- there is a potential commonality/rationalisation of the data requirements (and some methods) across these legislative drivers (e.g. ultimately MSFD data used in project-level environmental impact assessment (EIA); EIA data used in MSFD assessments or Maritime Spatial Planning)
- there is potential for determining 'best-fit' between cumulative effects assessments undertaken at different spatial and temporal scales to apply the principles of ecosystem based assessment and management (e.g. cumulative effects assessments done for project EIAs may inform Maritime Spatial Planning or MSFD scale assessments and vice versa).

Whilst it is implicit that the three legal instruments described above require cumulative effects to be assessed they do not explicitly define the term. Table 1 provides examples of various definitions of CEA from the USA, Canada and Europe.

Whilst the definitions in Table 1 pre-date the Marine Strategy Framework Directive there have been few attempts to update or redefine these terms, hence the lack of clarity in research to develop assessment methodologies. As a step towards determining what is/is not possible this paper explores some of the terminology to identify commonalities that can be applied across the various legislative drivers.

It is irrefutable that the prime objectives of the instruments listed in Table 1 (all of which use the terms "cumulative", "in combination" or "collective" effects) are the protection and management of the environment. As such, we establish and apply the convention that any definition of terminology should focus on "effects", "impacts" and/or "pressures" (stressors) to assess if and how they may individually, collectively, cumulatively or in combination interact. It is therefore the combination and interaction of pressures that should be the crux of environmental assessment and management measures. As such our proposed approach deals with the environmental response to single or multiple pressures (from single or multiple activities) rather than the traditional perspective of environmental impact assessments to determine which plans, projects or human activities should be included in the assessment of "cumulative", "in combination" or "collective" effects. This ensures that all cumulative effects assessments are based on an ecosystem based approach which provides a common structure, whether the impetus is the EU Environmental Impact Assessment, Habitats, Marine Strategy Framework Directives or any other legal or scientific driver.

Applying this perspective provides us with a second convention, which is that the terms "cumulative", "in combination" and "collective" are effectively intended to achieve the same objective, i.e. to predict and assess the overall impact on environmental features from multiple pressures. These two conventions provide

Table 1
Definitions of CEA.

Cumulative impacts: Impacts that result from incremental changes caused by other past, present or reasonably foreseeable actions together with the project *Impact interactions:* The interactions between impacts whether between the impacts of just one project or between the impacts of other projects in the areas *Indirect impacts:* Impacts on the environment, which are not a direct result of the project, often produced away from or as a result of a complex pathway. Sometimes referred to as second or third level impacts, or secondary impacts	EU (Walker and Johnston, 1999)
"impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (federal or non-federal) or person undertake such other actions. Cumulative impacts can result from individually minor, but collectively significant, actions taking place over a period of time"	USA (Council on Environmental Quality, 1997)
"cumulative effects are changes to the environment that are caused by an action in combination with other past, present, and future human actions."	Canada (The Cumulative Effects Assessment Working Group, 1999)

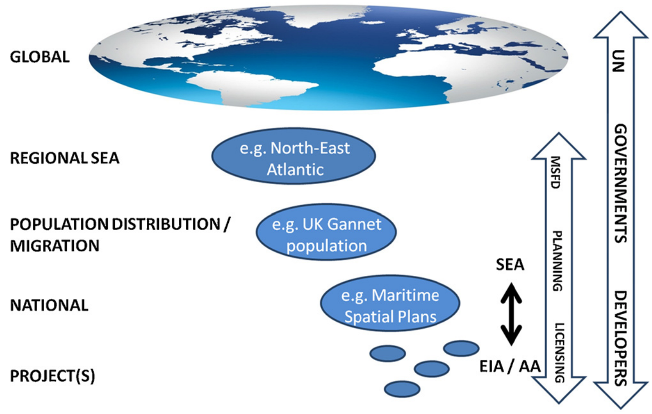

Fig. 1. Relative spatial scales of CEA.

the basis for a rationalisation and simplification of regulatory measures at project, national and regional scales (e.g. clarity between measures to enforce environmental legislation through the development and implementation of complementary, rather than independent, assessments at a variety of spatial scales (Fig. 1). Fig. 1 also demonstrates the need for cumulative effects assessment to go beyond national boundaries, due to the scale of the effect or the distribution of the receptor. Defining the spatial scale in clear and unambiguous terms is therefore a critical component of effective CEA.

The temporal scale is equally critical to CEA as the frequency and duration of the pressure(s) will determine the nature and scale of response by the receptors. And, finally, the recovery potential of an ecosystem after exposure to a certain combination of pressures might be of paramount importance for selecting appropriate management measures.

Taking the premise that the terms "cumulative", "in combination" and "collective" are intended to achieve a common goal of assessing the total effects of multiple pressures provides a new perspective to existing definitions of the terminology listed in Table 1, indicating that common principles may be equally applied without compromising compliance with the regulatory drivers. As such substituting "cumulative" with either "collective" or "in combination" in the definitions would result in the same outcome.

The objective of this paper is to provide a common vocabulary for use across all legal instruments as a basis for developing a harmonised set of principles for the evaluation of 'cumulative' effects. We describe a common process for marine policy-makers, regulators, advisors and industries for practical implementation of regulations. This paper presents a framework for defining and applying a consistent terminology based on the principles of ecosystem based management and environmental risk assessment. It balances the legislative and scientific expectations in order to set out a simple framework, based on the principles of environmental risk assessment, for designing joint cumulative, collective and in combination effects assessments for use by marine policy-makers, regulators, advisors and industries.

3. Environmental risk assessment

Cumulative effects assessments involve establishing and evaluating linkages between multiple activities with multiple effects on multiple ecosystem components. Including the complex interactions of direct and indirect effects in assessments very quickly generates a complicated and unwieldy network of multiple linkages. How to manage this complexity is a challenge to all forms of cumulative effects assessment. The assessment of all potential combinations of activities, pressures and ecosystem components is clearly impractical and as such a mechanism needs to be employed to filter the parameters included in the assessment. We believe that the most appropriate filter is a consideration of the pathways between activities, pressures and ecosystem components, in particular the likelihood (risk) of exposure (Knights et al., 2013, 2015). Application of risk assessment principles allows for a scientifically defendable rationalisation of the parameters within the assessment towards a meaningful and achievable assessment.

We therefore recommend that CEA should be based around the principles of environmental risk assessment. Risk-based decision-making is a process of choice, based on identifying the likely consequences of different options and selecting the best course of action related to minimising and managing environmental risks (Defra, 2011). A simple four component cyclical framework for environmental risk assessment is described in Defra (2011):

(1) formulating the problem;
(2) carrying out an assessment of the risk;
(3) identifying and appraising the management options available; and
(4) addressing the risk with the chosen risk management strategy.

We recommend that this four step framework is equally applicable to cumulative effects assessment, whereby:

(1) the purpose of the cumulative effects assessment is clearly defined (formulating the problem)
(2) the likely combinations of activities, pressures and ecosystem components are identified, the associated risks identified and the nature and scale of any cumulative effects assessed
(3) the options to manage the outputs of the cumulative effects assessment are evaluated to determine if/how management actions may alter the level of risk
(4) the implementation of the management action is monitored (and further remedial actions identified and implemented).

Whilst there have been several articles in the peer-reviewed literature which present methods for considering the combined or cumulative effect of multiple pressures (e.g. Karman and Jongbloed, 2008; Ban et al., 2010; Eastwood et al., 2007; Stelzenmüller et al., 2008, 2010; de Vries et al., 2012; Halpern et al., 2008, 2009, 2012; Korpinen et al., 2012; Coll et al., 2012; Andersen and Stock, 2013; Micheli et al., 2013; Batista et al., 2014; Andersen et al., 2015) there are no internationally agreed and routinely applied methodologies to do so. In part this relates to:

1. Inconsistencies in the language used to define and describe cumulative effects (MMO, 2013); and
2. Most of the current approaches appear to assume that (i) environmental pressures and effects do not interact, and (ii) that the individual pressure–effect relationships are linear. This most certainly under- or over-estimates impacts, depending on whether synergistic/antagonistic interactions are present and depending on the actual shape of the pressure–effect relationships of the involved pressures. Consequently, this may impinge on the application and effectiveness of management measures (Crain et al., 2009; Halpern and Fujita, 2013).

Given the current inconsistencies in terminology and interpretation, it is unsurprising that policy-makers, regulators, industries and other marine users are struggling to agree on methodologies for identifying, predicting and assessing cumulative effects. These observations are not made to challenge the validity of the approaches currently described in the literature but we suggest that greater practical use can be made of such approaches across a range of marine management scales and purposes (e.g. EIA, MSFD, Maritime Spatial Planning) if the terminologies and parameters that they use can be considered within a common set of principles.

In general, environmental legislation is designed to safeguard or even improve the state of the environment. If we take a closer look at the European Environmental Impact Assessment Directive (2011/92/EU), the Directive on the conservation of natural habitats and of wild fauna and flora (92/43/EEC) and the Marine Strategy Framework Directive (2008/56/EC), it is clear that they all have the underlying purpose of requiring assessments to be undertaken to address issues of environmental protection and management. With this purpose in mind it is logical for any effect assessment to be based on if and how the environment responds to the pressures being exerted on it. It is safe to assume that the environment has the potential to respond to cumulative, in-combination or collective effects irrespective of whether they are exerted from a single sector (or activity) or from multiple sectors (or activities).

This assumption is embodied in ecosystem based management approaches (Christensen et al., 1996; McLeod et al., 2005) which aims to maintain the whole ecosystem, including humans, in a healthy, productive and resilient condition so that it can provide the services humans want and need. However usage of the term "cumulative effects (impacts)" in practical applications (e.g. Environmental Impact Assessments) is frequently ambiguous, e.g. it is rarely stated whether the cumulative effect assessment is related to:

- multiple occurrences of a single pressure (from single and/or different sources) on a single receptor type (e.g. underwater noise effects on harbour porpoise from a combination of pile-driving vessel movements and seismic surveys); or
- multiple occurrences of multiple pressures (from single and/or different sources) on multiple receptors (e.g. underwater noise; contaminants; smothering jointly effects on biogenic reef; herring spawning grounds; marine mammal feeding grounds); or
- multiple occurrences of multiple pressures on single receptors (e.g. underwater noise; contaminants; smothering effects on herring spawning grounds).

We recommend that the use and definition of such terms is essential if the current attempts to develop cumulative effect assessment methodologies are to attain wider acceptance and application in marine management activities by regulators. To this end we recommend that the use of the term "cumulative effect" should always be accompanied by a detailed problem formulation description, e.g.

- Assessment of the cumulative effect of underwater noise from multiple pile-driving activities on marine mammals;
- Assessment of the cumulative effect of water temperature changes from power station outfalls, climate change and groundwater run-off on migratory fish.

In these examples there is a clear statement of:

- which pressures are considered in scope for the assessment,
- from which source(s) they originate, and
- which receptor(s) are investigated.

The purpose of the cumulative effects assessment also needs to be clearly stated, as particularly in Environmental Impact Assessments, a CEA can have rather different aims and scopes. It can be prospective, i.e. assessing in the planning phase of a project whether a certain activity is deemed acceptable—or it can be retrospective, i.e. assessing whether an ongoing activity is deemed acceptable. The main difference between both perspectives is the fact that in a prospective scenario no direct empirical evidence on the environmental impact is at hand and management options need to be developed from modeling exercises or from an argumentation by analogies, based on experiences from similar projects. In both scenarios a CEA can be employed to estimate the cumulative effect in an area, identify the vulnerable receptor types, or rank the different pressures.

A CEA can be targeted towards the assessment of similar or dissimilar pressure types, acting on one or different receptor types, e.g.

- CEA of underwater noise from multiple sources (e.g. pile-driving, seismic surveys, explosions, military sonar) on single receptor types such as marine mammals; or
- CEA of dissimilar pressure types (e.g. underwater noise, contaminants, hunting/fishing, by-catch, prey abundance) on multiple receptor types (e.g. fish, marine mammals, seabirds)

An unspecified use of the term CEA often implies that the latter is being assessed. However, current approaches are mostly considering only the first, much simpler, situation. This embodies the second step in the risk assessment framework in which the likelihood of pressure co-occurrence and interactions along the exposure pathways are determined. We hence recommend that the purpose and scope of a CEA should be clearly defined.

Existing approaches to CEA (e.g. Karman and Jongbloed, 2008; Ban et al., 2010; Eastwood et al., 2007; Stelzenmüller et al., 2008, 2010; de Vries et al., 2012; Halpern et al., 2008, 2009, 2012), to varying degrees, produce outputs related to the state of the environment (consequent to the multiple pressures acting upon it) in the form of two-dimensional maps of cumulative pressures (Halpern and Fujita, 2013). Approaches to mapping cumulative pressures (e.g. Halpern et al., 2008) are a potentially valuable resource for marine managers. However, where this value needs to be assessed is their application in a marine management context, demonstrating their use to inform management decisions. However, what is often missing is a direct account of how the outputs of the cumulative pressure mapping exercise may be applied in practical management measures to maintain or improve that state (steps 3 and 4 of the risk assessment framework). Some studies are making progress in this regard (e.g. Andersen et al., 2015; Knights et al., 2014; Piet et al., 2015), but the evaluation of management options in light of CEA outcomes is a key focus for future research.

Cumulative pressure mapping exercises assist in problem formulation and the conceptualisation of the risk(s) to be evaluated however they are not in themselves a comprehensive cumulative effects assessment. The output of the cumulative effects assessment should be the identification and appraisal of management options detailing how the cumulative risks are to be addressed.

Consideration of "cumulative", "in-combination" or "collective" pressures and effects requires assessors to identify the effects of marine sectors which drive impacts so they can identify more appropriate and effective management measures. A key component of this is developing an understanding of the relationships (risks) between the source of a pressure, the pathways by which exposure might occur, and the environmental receptors that could be harmed (Table 2). Within the source–pressure–pathway–receptor linkages:

- **Source:** is the causal factor for pressure(s) and effects. In simple terms the source (e.g. pile driving, dredging) is derived from an activity (e.g. installation of an offshore wind farm, port operation). Unambiguous identification of the source(s) of the pressures included in the CEA is essential if effects are to be appropriately managed.

Table 2
Examples of identifying and representing the Source – Pressure – Pathway – Receptor linkages (modified from Defra, 2011).

Activity	Source	Pressure	Pathway	Receptor
Construction of an offshore wind farm	Pile-driving	Underwater noise	Underwater acoustics	Sedentary marine species Mobile marine species
Port operation	Navigation dredging	Suspension of sea bed sediments in the water column	Hydrodynamics	Migratory fish Filter feeders
Mineral extraction	Dredging	Removal of seabed habitat	Mechanical disturbance	Sedentary marine species

- **Pressure:** is an event or agent (biological, chemical or physical) exerted by the source to elicit an effect (that may lead to harm or cause adverse impacts).
- **Effects:** human activities exert pressures which have effects which *may* lead to impacts on receptors (i.e. activity/source → pressure/effect → pathway → receptor → impact). So pressure and effect are always coupled so that every pressure has an effect, but not every pressure necessarily leads to an impact, e.g. dredging of seafloor sediments has the effect of temporarily mobilizing sediment into suspension in the water column but this may not have a discernible impact on water quality or biota.
- **Pathway:** is the mechanism by which a receptor is exposed to the pressure and effect (e.g., hydrodynamic regime, ingestion of contaminated water, ingestion of contaminated soil or food, direct contact with contaminated water or soil).
- **Receptors**: are physical (beaches, sandbanks, mudflats) or ecological (e.g. fish, birds, mammals, plants) or economic (tourism, business) or social/cultural (public enjoyment of open space) entities which are sensitive to the hazards under investigation. In other words, entities which would be affected if exposed to the combined pressures**.**
- **Impact:** is a measurable, detrimental, change to a species or habitat attributable to a human activity. "Effects" can be managed to reduce or prevent "impacts". This embodies the consideration of environmental risk in that whilst human activities exert pressures they do not always impact the environment. For example, various human activities exert pressures on the marine environment through increased nutrient loading resulting in effects of oxygen depletion/hypoxic zones, such effects can be magnified into impacts (e.g. reproductive problems in fish).

Most environmental risks are spatially and temporally limited, so a critical early need is to delineate the assessment, i.e. to establish which pressures might be caused by a human activity, to whom (or which part of the environment), where (location), when (in time) and for how long (recovery) (see Defra, 2011). Formulating a given problem in clear and unambiguous terms is critical for selecting an appropriate assessment methodology and thus improving risk management decisions. The proposed source–pressure–pathway–receptor linkages help to specify the complex hypothesised relationships between the source of a pressure, the pathways by which exposure occurs in the scenario of interest, and of the receptors in a visual or written form. The linkages conceptualise which receptors could be at risk by an exposure to the pressure(s) under consideration and provides the focus for which the strength of the link between pressure source and receptor exposure to be evaluated (the pathway), i.e. all unlikely linkages can be filtered out. This is particularly important as a means of reducing the complexity when considering cumulative effects where a multitude of sectors and activities contribute to a complex array of different sources for different pressures that act via multiple pathways on the various receptors.

An initial screening can be used to rank the different sources and pressures, in order to guide a more detailed cumulative effect assessment, while a risk prioritisation typically provides a list of main concerns for further action. We recommend that risk screening, prioritisation and evaluation should be a critical component of cumulative effects assessment to facilitate a filtering of the complex issues for consideration of the likelihood of exposure of receptors to pressures and the likelihood of a receptor responding to those pressures.

For example, abrasion is a pressure which is frequently associated with boats due to damage caused by the deployment of anchors or from propeller wash. However exposure to such abrasion will not be manifested over the entirety of the spatial footprint of shipping activity. As such it is important that in this example abrasive pressures from shipping activities are only applied at anchoring points and water depths of less than 25 m (the zone in which propeller wash has been demonstrated to affect the seabed (Soomere and Kask, 2003)). This process, whereby the problem is formulated and scoped, may need to be revisited as the assessment proceeds.

Taking the thought process described above into consideration, our recommended definition for "cumulative effects assessment" is modified from that provided by Cooper (2003) to embody environmental risk assessment principles:

"Cumulative effects assessment (CEA) is a systematic procedure for identifying and evaluating the significance of effects from multiple pressures and/or activities on single or multiple receptors. CEA provides management options, by quantifying the overall expected effect caused by multiple pressures and by identifying critical pressures or pressure combinations and vulnerable receptors. The analysis of the causes (source of pressures), pathways, interactions and consequences of these effects on receptors is an essential and integral part of the process."

4. Challenges

Our working assumptions are that pressures can only contribute to cumulative effects:

(a) if susceptible receptors (e.g. vulnerable species or habitats) are present;
(b) if a given receptor is affected by the different pressures present;
(c) if pressures overlap in time and space, **or**, collectively contribute to a net change in state (i.e. cumulation of temporally and spatially discrete pressures).

The spatial and temporal parameters and assessment of pressure extent and magnitude is therefore a critical part of the overall assessment process.

Whilst this appears to be a logical and straightforward premise, the practical application of this concept presents a number of challenges. Halpern and Fujita (2013) describe a series of assumptions and challenges which shape how any assessment of environmental effects (including cumulative effects assessment) are currently designed. Here we elaborate on these challenges:

(a) **Scale**—needs to be defined upfront to ensure that the appropriate resolution and necessary data can be defined and made available. For example, it needs to be decided whether the problem at hand should be assessed (and ultimately managed) at a global, regional, national, population distribution/migration or project scale (Fig. 1). For a cumulative effects assessments it is important to understand if and how effects overlap in space and/or whether a series of discrete effects may ultimately have an aggregated cumulative effect.

(b) **Limitations in spatial data**—it is unrealistic to expect that 100% coverage of data (maps) describing the spatial extent of human activities, associated environmental pressures, ecosystem components (receptors) and pathways can be generated. A combination of actual data and modeled values might help to improve spatial coverage of relevant data. It follows that cumulative effects assessments will be limited by the weakest data set for the most important pressures and receptors.

(c) **Location of pressure sources in all three dimensions**—the evaluation of cumulative effects requires an understanding of the 3D-location of activities and pressures, i.e. whether they are in the pelagic or benthic zones, above or below water or across the entire ecosystem. Traditionally, two-dimensional GIS layers have been used as a proxy for mapping pressures. For some pressure types (e.g. abrasion), there is a correlation between the footprint of the activity and footprint of the pressure, however, this could provide an overestimation of the spatial extent of the pressure as there is often no measure of frequency or intensity. For other pressure types (e.g. underwater sound and suspended sediments) the pressure will be exerted over an area larger than the spatial footprint of the activity and in these instances using the footprint of the activity as a proxy for the pressure will underestimate the spatial extent of the pressure. Also, pressures such as underwater sound and suspended sediments have a three-dimensional aspect which is unaccounted for in a two-dimensional map.

(d) **Temporal pattern**—activities may be undertaken in the same spatial area but at different times of the day or different times of year. Some pressures may also persist (see below). The sensitivity of receptors to the pressures associated with these activities may also have seasonal variations (e.g. most fish species have defined spawning seasons). It is therefore essential for the cumulative effects assessment methodology to incorporate these temporal parameters.

(e) **Pressure–effect interactions**—a limitation of current approaches for cumulative effects assessments is that they assume that environmental pressures or effects do not interact and that they combine in a linear relationship. However, the reality is that pressures or effects might interact to generate a variety of outcomes, including synergistic or antagonistic joint effects. As the scientific methodologies to fully evaluate these interactions are evolving continuously, it is important that knowledge gaps are acknowledged and identified as contributing to the level of uncertainty in the CEA. Previous work on the joint effects of toxic chemicals might provide a suitable starting point for further exploring this issue (Backhaus and Faust, 2012).

(f) **Pressure persistence**—whilst some pressures are concurrent with their causal activities (e.g. underwater noise and pile-driving) others have the potential to persist after the activity has ceased (e.g. abrasion of seafloor habitats from bottom trawling; sediment plumes from aggregate extraction). Such distinctions will need to be incorporated into the rationale for cumulative effects assessment to ensure that pressures are appropriately combined.

(g) **Resilience**—some receptors are more resilient to pressure (change) than others. As such it is important that the sensitivity and vulnerability of receptors to the suite of pressures are appropriately described in the cumulative effects assessment.

(h) **Recovery potential**—some receptors have the potential to recover quickly from a catastrophic event whereas for other receptors recovery from the effects can take a long time (if at all). Such distinctions need to be included in the cumulative effects assessment to ensure that the magnitude of the overall effect (and management measures) are appropriately defined and targeted.

(i) **Uncertainty**—is defined in Defra (2011) as the degree to which knowledge (e.g. about the sensitivity of a receptor to a pressure or the factors which influence exposure) is limited. Uncertainty originates from randomness and incomplete knowledge. Given the broad range of parameters that warrant consideration in a cumulative effect assessment, it is essential to incorporate uncertainty assessment principles, e.g. the means to discriminate between three dimensional interactions of location, level and nature of uncertainty (Walker et al., 2003; Knights et al., 2014).

These challenges are likely to persist unless efforts are coordinated around some common guiding principles for CEA as proposed in this paper. It also follows that it is essential that any

Table 3
Recommended conventions and terminologies for developing CEA methodologies.

1	Definitions should focus on environmental pressures and effects to assess if and how they may interact and may cause a joint effect exceeding the individual effects
2	The terms "cumulative", "in combination" and "collective" are effectively intended to achieve the same objective (i.e. describe the overall impact on single or multiple receptors from single or multiple pressures)
3	CEA methodologies should be based on the environmental response to pressures and complementary approaches can be developed to assess "cumulative", "in combination" and/or "collective" effects (allowing coherence in assessments across the various legislative drivers)
4	In all uses of the term cumulative effects there is a clear statement of: all the pressure(s) that are considered in the CEA; The source(s) for each pressure; and The receptor(s) that are potentially affected by each pressure
5	The purpose and scope of the cumulative effects assessment needs to be clearly defined. That is, it should be clearly stated whether the aim is to provide options during the planning of an activity, to assess and predict to total effect caused by multiple pressures, to identify critical pressures and/or the most vulnerable receptors
6	The spatial and temporal scale of the cumulative effects assessment and any resultant management action needs to be clearly defined. This should include persistence, resilience and recovery potential
7	Cumulative effects assessment should be based around the principles of environmental risk assessment, involving the following four principal steps formulating the problem; carrying out an assessment of the risk; identifying and appraising the management options available; and addressing the risk of the chosen risk management strategy
8	Source–Pressure–Pathway–Receptor conceptual models should be used to define and refine the cumulative effects assessment
9	The assumptions and uncertainty within the cumulative effects assessment must be clearly stated
10	The assessment should start under the assumption that the different pressures and effects act in an additive fashion, but should include at least a qualitative appraisal of the likelihood and potential consequences of specific interactions (e.g. synergisms/antagonisms)
11	Where necessary the output of the cumulative effects assessment should include the identification and appraisal of management options detailing how the cumulative risks are to be addressed

approach is designed around available data and has sufficient flexibility to adapt and evolve to incorporate additional or alternative data sets and advances in scientific understanding.

5. Framework for cumulative effects assessment

For the assessment of the cumulative effects of multiple pressures it is critical that a complete inventory of pressures potentially present in a scenario is drawn prior to the assessment (e.g. Knights et al., 2013). Table 3 summarises our recommended conventions for developing CEA methodologies. These conventions have been formulated into a simple risk-based framework for bringing together the different components of a cumulative effects assessment (Fig. 2). In determining policy and management options, it is helpful to distinguish between pressures that are directly amenable to management (e.g. oil and gas exploration) and pressures that cannot be directly influenced (e.g. climate change, storm events, etc.).

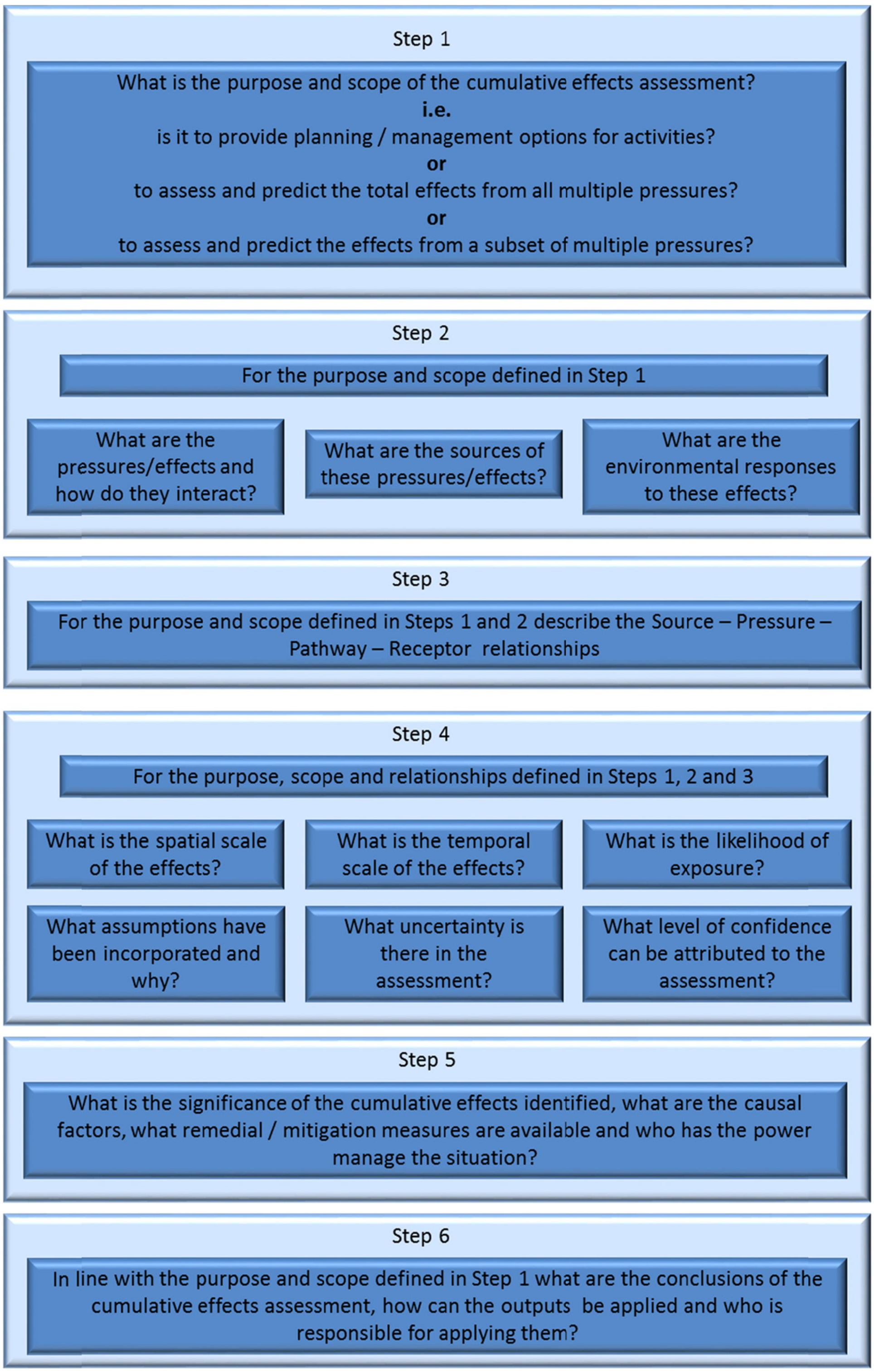

Fig. 2. A simple risk-based framework for defining and undertaking cumulative effects assessments.

The fundamental questions of interest for analyzing the cumulative effects of pressures and effects are:

- Is the expected joint effect of a cumulative pressure and effect higher (or lower) than the intensity of each pressure and effect acting singly? In this context it is critical to assess whether the various pressures and effects overlap sufficiently in time and space to result in a potential cumulative effect on the receptor(s) of interest.
- Is the cumulative effect of joint pressures and effects simply quantitatively different from the response to each individual pressure and effect—or do fundamentally new response types emerge and/or are different receptors put at risk (e.g. synergistic or antagonistic interaction), i.e. deviation from the expected outcome that is used for predicting the joint effects??
- What is the expected size (i.e. magnitude, extent, intensity) of the effect caused by a given combination of pressures? This requires a decision on which interactions are to be considered, gathering the necessary input data, running the model and describing the final uncertainty in the model.

It becomes clear that whether and to what extent interactions are considered when predicting the joint effects of multiple pressures and effects is critical. It is advisable to start with a simple "null hypothesis" on how several pressures and effects act in concert, which usually revolves around the decision on whether they act independently or similarly. This explicit evaluation of a "no interaction" hypothesis between pressures and effects provides for an informed evaluation using terms such as "additivity", "synergism", "antagonism" and "interaction" in a meaningful way.

In a perfect world the relationship between pressure intensity and impact as well as their underlying mechanics are known for each pressure and effect, which would support assumptions of pressures and effects acting either similarly or independently. In real life, however, knowledge on the behaviour and impact of individual pressures and effects is fragmented. This affects the selection between the two assumptions and subsequent application of 'additive', 'synergistic' and 'antagonistic' mechanisms in CEA. The current assumption in the environmental assessment of the effect of multiple chemicals, for example, is that chemicals act similarly, i.e. affect the receptor of interest by similar mechanisms. Relevant models predict a slightly higher joint toxicity than models based on the competing assumption that individual chemicals act independently on the receptor of interest (Kortenkamp et al., 2009).

The currently available empirical knowledge on the joint cumulative action of multiple pressures and effects is rather limited. More empirical evidence is needed, in particular in order to assess whether and to what extent the approaches from mixture toxicity assessment can be applied in the broader field of multiple pressure and effect assessment or whether specific interactions might interfere with such "broad brush" approaches.

6. Conclusions

The explicit application of environmental risk assessment principles provides the basis for simplifying the underlying problems of undertaking meaningful CEAs in a transparent and scientifically defendable manner. This entails reaching agreement on the terminology which is employed in the assessment of cumulative, collective or in combination effects. Table 3 presents a set of working conventions and Fig. 2 a simple risk-based framework to facilitate this. Formulating and subsequently assessing a logical and sequential set of problems allows for a structured assessment of cumulative effects to be undertaken. A fundamental part of this process is using risk assessment criteria to filter and prioritise the complex interaction of sources, pressures, pathways and receptors. The next logical step is to develop the presented approach into a structured guidance for regulators and industry for use in local (environmental impact assessment) and regional (Marine Strategy Framework Directive) scale evaluations of cumulative effects. We advocate that uncertainty assessment principles should be an integral part of future CEAs to ensure that assessments are based on optimised (realistic and available) datasets and knowledge and that methodologies do not become prohibitively aspirational or expensive. Finally, cumulative effects assessment exercises should by tailored from the very beginning to provide tangible outcomes that facilitate appropriate marine management.

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