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Critical Review

Toward a Harmonized Approach for Environmental Assessment of Human Activities in the Marine Environment

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ABSTRACT

With a foreseen increase in maritime activities, and driven by new policies and conventions aiming at sustainable management of the marine ecosystem, spatial management at sea is of growing importance. Spatial management should ensure that the collective pressures caused by anthropogenic activities on the marine ecosystem are kept within acceptable levels. A multitude of approaches to environmental assessment are available to provide insight for sustainable management, and there is a need for a harmonized and integrated environmental assessment approach that can be used for different purposes and variable levels of detail. This article first provides an overview of the main types of environmental assessments: "environmental impact assessment" (EIA), "strategic environmental assessment" (SEA), "cumulative effect assessment" (CEA), and "environmental (or ecological) risk assessment" (ERA). Addressing the need for a conceptual "umbrella" for the fragmented approaches, a generic framework for environmental assessment is proposed: cumulative effects of offshore activities (CUMULEO). CUMULEO builds on the principle that activities cause pressures that may lead to adverse effects on the ecosystem. Basic elements and variables are defined that can be used consistently throughout sequential decision-making levels and diverse methodological implementations. This enables environmental assessment to start at a high strategic level (i.e., plan and/or program level), resulting in early environmental awareness and subsequently more informed, efficient, and focused project-level assessments, which has clear benefits for both industry and government. Its main strengths are simplicity, transparency, flexibility (allowing the use of both qualitative and quantitative data), and visualization, making it a powerful framework to support discussions with experts, stakeholders, and policymakers. *Integr Environ Assess Manag* 2016;12:632–642. © 2015 SETAC

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INTRODUCTION

Globally, many marine ecosystems are under high pressure as a consequence of maritime activities such as fishing, shipping, oil and gas activities, and offshore dumping (Halpern et al. 2008). This high pressure results in loss of habitats and species and the services they provide (Millennium Ecosystem Assessment 2005). Foreseen increases in activities of existing maritime sectors such as shipping and development of new sectors such as offshore renewable energy (Lloyd's Register 2013) will increase pressure on marine ecosystems and thus call for policies to regulate pressures to ensure sustainable use of resources. For policy development and sustainable management by both government and industry, insight is needed in the causal maritime activity-pressure-effect relations on ecosystems or their components (i.e., species or species groups, ecosystem functions, and habitats), the overlap in time and space of activities and ecosystems, and the (cumulative) pressures these activities exert on ecosystems or its components. A multitude of approaches to environmental assessment (EA) is available to provide insight required for sustainable management. Recent studies suggest, however, that further improvement of EA approaches is needed to increase its contribution to sustainable development (Zhang et al. 2010; Gunn and Noble 2011; João et al. 2011; Knights et al. 2014; Gibbs and Browman 2015). Identified limitations include a lack of broadly accepted and applied definitions and conceptualizations; limited tiered relationship between strategic- and project-level assessments (Gunn and Noble 2011); a lack of integrated methods that include economic, social, and ecological parts (Zhang et al. 2010); and a need for coherent, repeatable, and transparent approaches for assessing the level of pressure from (overlapping) human impacts and the risks to the ecosystem at a regional sea scale (Knights et al. 2014) and global scale (Halpern and Fujita 2013). In addition, a considerable scope for risk-based approaches to be applied to the management of marine activities has been acknowledged (Gibbs and Browman 2015).

The aim of this article is to address such limitations in EA. The application of EAs provides the foundation for setting boundaries and offers windows of opportunities for maritime developments on various strategic, spatial and temporal scales. It is therefore important to know

- Which EA approaches are available, and what their purpose is

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- What their current limitations and needs are
- How the best "fit for purpose" and consistency in EAs can be achieved

To answer these questions, this article first provides an overview of existing types of EAs, and their purposes. Second, it introduces a generic framework for EA applicable for a wide range of purposes and describes the needs and benefits of consistency and harmonization in EA throughout sequential decision-making levels. The framework is intended as a conceptual "umbrella" for the fragmented approaches, enabling the selection of the best fit for purpose and consistency among EAs.

APPROACHES TO ENVIRONMENTAL ASSESSMENT

In general, EA is a process to predict the environmental effects of proposed initiatives before they are carried out (Canadian Environmental Assessment Agency 2011). In general, the main purpose of environmental assessment is to incorporate environmental factors into decision making to minimize or avoid adverse environmental effects. Usually the following steps are required for an EA: determining if the assessment is (legally) required (i.e., screening), determining the nature and detail of the information to be included (i.e., scoping), describing the proposed activities and alternatives, describing the environment, determining the likely impacts of the proposed activities and their alternatives on the environment (i.e., analyses), proposing mitigation measures, and reporting. Four widely used approaches to EA are described here. Three are essentially the same in addressing the expected type and magnitude of effects of proposed project activities (environmental impact assessment [EIA]) or proposed plans and programs (strategic environmental assessment [SEA]), either individually or as a combination (cumulative effect assessment [CEA]). A fourth approach is to consider—besides the magnitude of the effect—the likelihood of occurrence, as addressed in risk assessment (RA).

Environmental impact assessment can be defined as the process of identifying, predicting, evaluating, and mitigating the biophysical, social, and other relevant effects of development proposals before major decisions being taken and commitments made (IAIA 1999). The purpose of an EIA is thus to inform and/or influence planning decisions for individual projects, such as the installation of an offshore windfarm, often as part of a permit application. However, there are questions regarding the purpose and effectiveness of EIA in the context of specific development sectors (Smart et al. 2014). Issues raised by Smart et al. (2014) for windfarm development include misalignment between theoretical and practical framings of EIA, public perceptions of bias, a lack of consistency in guidance across authority boundaries, and a need for online centers for archiving EIA information.

Strategic environmental assessment can be considered as a process by which environmental considerations are required to be fully integrated into the preparation of new or amended laws, plans, programs and other strategic actions before their final adoption. There is a wide variety of definitions of SEA, with more than 100 definitions published between 1992 and 2011, showing that SEA is an evolving concept (Da Silva et al. 2014). The SEA and EIA procedures are very similar, but some main differences are: SEA is conducted at the plan or program (instead of project) level; environmental effects should be monitored (mandatory for European Union [EU] Member States); stakeholder consultations should be carried out; and environmental considerations should be integrated into the plan or program. Environmental impact assessment and SEA are required by law in many countries, and their results are publicly acknowledged and available (Abaza et al. 2004). For decades, EIAs have been one of the primary policy instruments for environmental management and have become a globally consistent approach in managing impacts of human activities in all kind of environments, including the coastal and marine environment (Gibbs and Browman 2015). However, the project EIA is known for its limited scope (Gunn and Noble 2011) whereas SEA occurs when alternative futures and options for development and conservation are still open. In principle, the benefits of early environmental awareness should result in more informed, efficient, and focused project-level assessments and decisions (Noble et al. 2013). This requires starting the environmental assessment on a high strategic level and following it across sequential decision-making levels (Partidário 2000) (Figure 1).

Cumulative effect assessment is defined as the process of systematically analyzing and assessing cumulative environmental change (Spaling 1994). Thus, where SEA and EIA consider effects of proposed plans, programs or projects individually, CEA considers effects of the combined activities. A CEA is often applied as part of a project-based EA. In Canada, for example, a CEA is mandatory for all EIAs under the Canadian Environmental Assessment Act since 1995. In Europe, CEA is considered within the EIA process (EC 1999). In that form (i.e., at the project level), however, CEA has been found to be limited, and ways to integrate CEA with SEA instead of EIA are explored (Gunn and Noble 2011). Therefore, there is a need to perform CEA at a higher strategic level. Application of a CEA for multiple sectors is specifically required by regional policies like the European Marine Strategy Framework Directive (MSFD) and the European Habitats Directive. There is still need for improvement in CEA: definitions and conceptualizations of CEA are typically weak in practice, approaches to effect aggregation vary widely, and focus is more on single rather than multiple cause–effect relationships (Gunn and Noble 2011; Judd et al. 2015). Compared to EIA and SEA, the scoping and analyses phases in CEA requires additional effort addressing the spatial and temporal dimensions in which effects can cumulate (scoping phase) and the integration of multiple cause–effect relationships (analysis phase) (MacDonald 2000; Therivel and Ross 2007). Scoping is an important aspect of CEA and helps to avoid confusion in classifying, defining, assessing, and managing cumulative effects by defining the resources of concern and the spatial and temporal scales of the analysis (MacDonald 2000). Methods have been developed focusing on accumulation of effects of a single sector on a single ecosystem component (Stelzenmüller et al. 2011) or on accumulation of effects of multiple sectors on multiple ecosystem components (Halpern et al. 2008; Stelzenmüller et al. 2010; Fock 2011; Foden et al. 2011; Korpinen et al. 2012; Gimpel et al. 2013).

The field of environmental RA generally covers both human and ecosystem health. When focusing on ecological receptors it is referred to as ecological (or ecotoxicological) risk assessment (EEA 1998; USEPA 1998). Ecological risk assessment (ERA) can be defined as the process that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors (USEPA 1998). Ecological

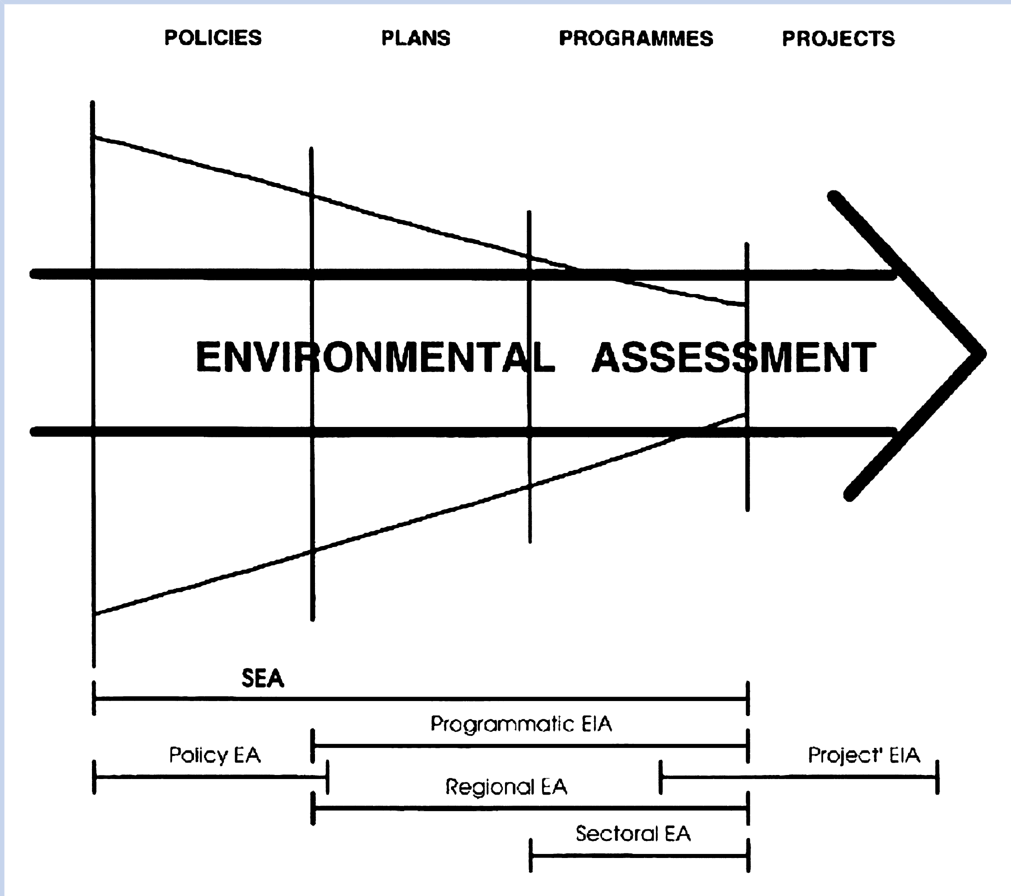

Figure 1. Focusing environmental assessments across sequential decision-making levels (Partidário 2000).

risk assessment is perhaps the most powerful framework for assessing anthropogenic changes to the environment (Gibbs and Browman 2015), although it is narrowly used for the assessment of impacts of chemical contaminants to the environment (i.e., in ecotoxicology). If ERA is applied to contaminants, the assessment will be based on the comparison of the exposure of (a part of) the ecosystem to a chemical with the sensitivity of (the same part of) the ecosystem for this chemical, that is, the dose–response method. The RA approach has recently been used as a method for CEA by evaluating risks from human activities to the marine ecosystem using semiquantitative (i.e., scoring) (Knights et al. 2015) as well as quantitative approaches (Stelzenmüller et al. 2010; Fock 2011). A review of (semi) quantitative ERA methodologies in the context of marine spatial management shows that at least 32 studies have been conducted since the year 2000, with most studies in recent years (Stelzenmüller et al. 2015).

In summary, we have identified and discussed 4 main types of environmental assessments serving different purposes with overlapping spatial and strategic scales (Table 1). Terminology varies greatly among environmental assessment studies, even in the same context of marine spatial management (Stelzenmüller et al. 2015). Furthermore, a need identified in literature, is to start EA on a high strategic level and to follow it across sequential decision-making levels (Partidário 2000; Gunn and Noble 2011) for which an overarching approach covering different purposes and assessment levels would be beneficial. To our knowledge, such an overarching approach is still lacking. Researchers are currently challenged to develop integrated ecosystem assessment methodologies and approaches that allow the use of both qualitative and quantitative data and that can be used to address both specific advisory questions and broader ecosystem issues (ICES 2014).

TOWARD CONSISTENCY IN ENVIRONMENTAL ASSESSMENTS: A GENERIC FRAMEWORK

Addressing the need for an overarching approach, we promote an environmental assessment approach that is both adaptable and consistent throughout the sequential levels of decision making. Based on the review of literature, we identified similarities and differences in EAs and define

- Basic elements, which are always part of an environmental assessment regardless of the purpose and level of assessment
- Characteristics, describing the context of the assessment
- Variables that could be adjusted according to the context of the assessment as defined by the characteristics

Basic elements

Although many different approaches exist, serving different purposes in various contexts, they all share the common goal of assessing the effect, impact, or risk of human activities on the environment. The link between human activities and impact on the ecosystem can be described using a simple hierarchy (Knights et al. 2013): activities can cause a range of pressures (e.g., shipping causes noise, pollution, disturbance. etc.), and

Table 1. Characteristics and options of various environmental assessments

Aspect	Environmental assessments			
	EIA	**SEA**	**CEA**	**ERA**
Purpose	Informing decision makers (permit application)	Informing decision makers, support consultation and governance (environmental policy and management)	Part of EIA or SEA and as stand-alone, providing insight for government and industry	Determining risk of substances (ecotoxicology) and other pressures (e.g., as methodology for CEA)
Decision-making level	Project	Plan, program	Project, plan, policy	Project, plan, policy
Need and/or requirements	Legally required in many countries	Legally required in many countries	Limited as part of EIA	Legally required for substances (ecotoxicology)
Spatial scale	Site, local	Local, regional	Variable, depending on purpose (from site to global)	Variable, depending on purpose (from site to global)
Temporal scale	Present and future	Present and future	Variable, depending on purpose	Variable, depending on purpose
Level of detail (data)	High	Low	Variable, depending on purpose	Variable, depending on purpose

CEA = cumulative effect assessment; EIA = environmental impact assessment; ERA = environmental risk assessment; SEA = strategic environmental assessment.

these pressures can affect a range of ecosystem components (e.g., marine mammals are affected by noise and pollution). Although Knights et al. (2013) acknowledge that activities can cause multiple pressures and these in turn can affect multiple ecosystem components, this is not completely visualized in their article (i.e., multiple activities and pressures are included in their schematic presentation but only affecting a single ecosystem component). Following their concept, but including the visualization of the links between multiple activities, pressures, and ecosystem components, we propose a generic framework for environmental assessment, the cumulative effects of offshore activities (CUMULEO) framework, originally developed by Karman and Jongbloed (2008) (Figure 2). The framework is based on a matrix containing the elements and their relationships. The ecosystem components are presented at the left side of the framework to express an ecosystem approach. Furthermore, the framework follows the principle of the dose–response method applied in ERA of contaminants as there are 2 parts distinguished in the links: one for intensity (dose) and one for sensitivity (response), which are integrated through the assessment process.

We argue that for each study or project, definitions should be clarified. In this study, based on the definitions of Cooper (2013), we define the elements of CUMULEO as follows:

Activity: an activity, process, or physical works intended to enhance human welfare; alternative terms used are e.g., driver, sector

Pressure: a means by which one or more activities cause or contribute to a change in an ecosystem component or components; alternative terms used may be stressor, impact, effect

Ecosystem component: an attribute or set of attributes of the natural environment; alternative terms used may be valued ecosystem component (VEC), ecological component, receptor, indicator

Sensitivity: the relation connecting ecosystem components to pressures, considering the vulnerability and recovery potential of the ecosystem component; alternative term used may be vulnerability

Intensity: the relation connecting pressures to activities, considering the type, duration, strength, and (spatial) extent of the pressure; alternative term used may be impact

In addition, we define risk as "the likelihood and severity of an adverse effect occurring to ecosystem component(s) following exposure to pressure(s)." Impact is defined as "any aspect of an activity that may cause an effect." Effect is defined as "any change that an activity may cause in the ecosystem component(s)."

According to these definitions, both pressure and impact are part of the link between an activity and an effect on an ecosystem component. It also implies that an effect results from impact, for example, wastewater discharge (activity) causing introduction of pollutants (pressure), could lead to polluted habitat (impact) and subsequently benthic mortality (effect), occurring with a certain likelihood and severity (risk). Although effect and impact are often used interchangeably (EC 2001), here the term impact is used to express the contribution to, or cause of, an effect when there is no specific pressure known or multiple pressures are involved. Besides these obvious synonyms ("effect" and "impact"), it is found that even terms such as "risk" and "vulnerability" have been used synonymously with the term impact in recent ERA studies for marine spatial management, as identified by Stelzenmüller et al. (2015). The broad acceptance and use of uniform terminology would greatly help to avoid misinterpretation and improve consistency in environmental assessments.

Characteristics

As described previously, the EA serves different purposes in various contexts and variables should thus be adjusted to derive

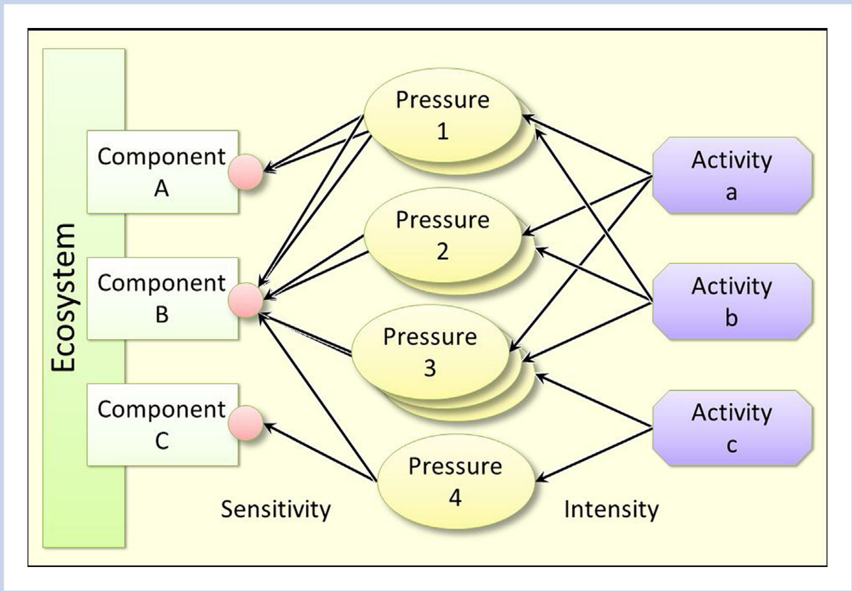

Figure 2. Generic outline of cumulative effect assessment (CEA) visualizing relationships between activities, pressures and ecosystem components based on Karman and Jongbloed (2008). For the ecosystem components, sensitivity determines the links with pressures, based on vulnerability and recovery. The links between activities and pressures are determined by the intensity, based on duration, extent, strength, and frequency of pressures caused by the related activity.

the "best fit for purpose." This process, determining the content and extent of the matters that should be covered in the environmental assessment, is also referred to as scoping. The variables can be structured according to different levels for the following characteristics (see also MacDonald [2000] and Therivel and Ross [2007]):

- Decision-making level, ranging from policy to project level
- Spatial scale, ranging from a global scale to site-specific
- Temporal scale, ranging from the present situation (current, ongoing activities and pressures) to inclusion of past and future activities and pressures
- Level of detail (information availability and requirement) ranging from field (monitoring) data to expert judgement

The purpose of the assessment determines at what level these different aspects should be addressed. For example, an EA could be applied as an industry initiative to generate insight and knowledge about the (potential) environmental impact of their (potential) activities or technology developments. This requires an assessment on a high strategic level. The spatial scale and level of detail depend on the specific case, but at a high strategic level generally a low level of detail is sufficient. An environmental assessment could also be conducted under legal requirements, for example, as part of a license application. This requires a site-specific, project-level assessment and generally a high level of detail.

Variables

Variables in the CUMULEO framework are:

- The selection of elements (i.e., which activities, pressures, and ecosystem components are to be included). This includes determining the aggregation level of the activities (e.g., "fishing" vs "benthic trawling"), pressures (e.g., "introduction of compounds" vs "introduction of heavy metals"), and ecosystem components (e.g., "sea mammals" vs "harbor porpoise"), that is, whether groups or specific elements are required and selected as it could affect the assessments' outcome. The availability of knowledge and supporting data (e.g., monitoring data, maps) that can be applied in the assessment and practicalities (time and budget constraints) are important aspects to consider in determining the aggregation level and subsequently the selection of elements.
- Spatial and temporal distribution of the elements, that is, determining whether geographic distribution of activities, pressures and/or ecosystem components is required (and in what level of detail) and determining whether temporal distribution of activities, pressures and/or ecosystem components should be considered (and in what level of detail, e.g., differentiate in seasons or months). The geographic distribution of activities, pressures, and ecosystem components could be implemented in the geographical information system (GIS), involving the following steps: implementing the distribution of activities in GIS, distribution of pressures per activity (cumulative pressures), distribution of ecosystem components, and combining pressures with ecosystem components (expressing the level of cumulative effects). Thus for each cell in GIS, the activities, pressures, and ecosystem components are either present or not present. This simple approach is similar to other studies found in literature (e.g., Halpern et al. 2008). A more refined approach would be to include the probability of pressures and ecosystem components being present, as demonstrated by Zacharias and Gregr (2005). A recent review indicates that the existing spatial data on human activities and ecosystem components can be greatly improved (Halpern and Fujita 2013). Temporal distribution could be implemented by adjusting the EA to a certain season, that is, use different data sets (maps) for the distribution of activities and/or ecosystem components for different seasons.
- Establishing the links between activities and pressures and between pressures and ecosystem components. A wide range of human activities in the marine environment have

already been linked to potential pressures and ecosystem components (Knights et al. 2013). This could be used as a basis. Whether or not to include indirect effects and interactions between elements (e.g., species interactions) should be clearly defined.

- Methodology used for assessing the relationships (sensitivity and intensity), ranging from:

1. Qualitative presentation, a simple presentation of the elements, and their relationships assuming all relationships are of equal weight
2. Semiquantitative scoring of intensities of pressures and sensitivities of ecosystem components; this is most suitable for a broad scale, low-detailed assessment on a high process (strategic) level, using available information and/or expert judgement and classification schemes; several criteria have been developed that could be used for such an assessment (Halpern et al. 2007; Gimpel et al. 2013; Knights et al. 2015)
3. Quantitative assessment of intensities of pressures and sensitivities of ecosystem components; this is most suitable for a focused, high-detailed assessment based on functional relationships
4. The assessment could also be a combination of 1 and 2, depending on data availability; most ERA methods derive a measure of sensitivity from model output that is based either on empirical data or expert judgement (Stelzenmüller et al. 2015); most methods assume linear relations without thresholds, although these relationships are thought hardly to occur (Halpern and Fujita 2013); other relationships (i.e., linear relation with threshold, logistic curve, probability function) could be considered but current information to establish these types of relationships is limited (Halpern and Fujita 2013).

- Methodology used for integrating the (semi-) quantified relationships; integration could be for instance by summation, multiplication, averaging, or by taking the maximum; most ERA methods assume additive effects when analyzing cumulative pressures (Stelzenmüller et al. 2015); other possible interactions (e.g., synergistic interactions) between pressures should also be considered, however, because of limited knowledge on possible interactions and when and why they occur, the default additive approach remains currently the only feasible option (Halpern and Fujita 2013).

DEMONSTRATION OF THE CUMULEO FRAMEWORK

We apply the CUMULEO framework for demonstration purposes to a selection of case studies from literature to cover the 4 types of environmental assessment discussed in this article and different purposes, spatial, and temporal scales, decision-making levels, and variable settings (Table 2).

The marine biological elements and linkages, identified as key effects in the Burbo Bank Extension offshore wind farm EIA (DONG Energy 2013), are visualized in the CUMULEO framework (Figure 3). The assessment is based on highly detailed input (e.g., site-specific monitoring studies), but a semiquantitative approach is used for the assessment of the relationships. The outcome of the assessment is the determination of the significance of the key effects against predetermined criteria (e.g., policy objectives).

On a higher strategic level, the Scottish Executive commissioned a SEA to examine the potential environmental effects of wave and tidal power generation (Scottish Executive 2007). Besides supporting strategy development, the results can also be used to inform renewable energy developers and serve as a reference source for project-level developments. The elements identified in the SEA relating to the marine biological environment are visualized in the CUMULEO framework (Figure 4). The methodology is very similar to the wind farm EIA, also using a semiquantitative approach. The SEA states, however, that the detail of the data is limited, as is appropriate for a high strategic level.

Three studies were selected to demonstrate CEA in the CUMULEO framework on a global (Halpern et al. 2008), regional (Knights et al. 2015), and local scale (Fock 2011). The purpose and strategic level of these studies are generally the same: driven by environmental policy, with the aim to inform governmental decision makers about the impact and risk resulting from human activities on the marine environment by using scientific knowledge. The studies by Halpern et al. (2008) and Knights et al. (2015) address a broad range of ecosystem components, pressures, and activities and use a semiquantitative approach to assess the relationships (Supplemental Data Figure S1 and Figure 5, respectively). Because of the great number of relationships included in these studies, the relationships are no longer distinguishable in the framework. In such a case, the framework can be used to zoom into specific elements (Figure 5). Because the figure is only a visualization of a matrix containing the elements and their relationships, another option would be to present the visualization after the (semi-) quantification of the relationships and show only those elements causing main effects on ecosystem components. The local study (Fock 2011) addresses a limited selection of elements (Figure S2) and uses a quantitative approach with a high level of detail (i.e., spatial distribution of activities and ecosystem components and functional relationships between pressures and ecosystem components). These seem logical choices as a more focused study allows more detail. However, considering the high strategic level, a detailed assessment is not required for addressing the purpose of the study. It could thus be questioned if such a highly detailed and quantitative assessment is the "best fit for purpose."

Knights et al. (2015) use a methodology to determine the relationships between the activities, pressures, and ecosystem components that is especially useful for marine management purposes (Piet et al. 2015). The methodology allows managers to focus on different time frames in their decision-making process, that is, focusing on measures targeting persistent pressures (e.g., marine litter) from past activities, measures targeting present activities (e.g., fisheries) that have a high likelihood of causing adverse impacts, or measures involving impacts that both have a high likelihood of an adverse impact as well as persistent pressures (Piet et al. 2015). Scores are determined for impact risk (a measure of the likelihood of an adverse ecological impact occurring following a sector–pressure introduction) and recovery lag (a measure of management potential given the persistence of a pressure and resilience of the impacted ecosystem component) (Knights et al. 2015).

To demonstrate ERA in the CUMULEO framework, a risk assessment for nontoxic pressures from drilling oil and gas wells was selected (Figure 6). Drilling oil and gas wells requires use of

Table 2. Studies selected for demonstration purposes including their characteristics and variable settings

Aspect	Environmental assessments: EIA	SEA	CEA	ERA
Reference	DONG Energy 2013	Scottish Executive 2007	Halpern et al. 2008; Knights et al. 2015; Fock 2011	Smit et al. 2008
Purpose	Informing governmental decision makers of the environmental impact of the proposal for an offshore wind farm	Informing government and developers of the environmental impact of the development of marine energy	Informing governmental decision makers of the impact and risk from human activities; requirement from European policy	Development of quantitative risk approach for nontoxic pressures
Decision-making level	Project	Plan and/or program	Policy	Plan and/or program
Spatial scale	Site (Liverpool Bay, UK EEZ)	Local (Scotland EEZ)	Global/regional (European seas)/ local (German EEZ)	Not spatially explicit
Temporal scale	Present, future	Present, future	Present	No temporal scale
Level of detail (data)	High	Moderate	Moderate/low/high	High
Elements (*n*)	17	17	37/47/14	7
Methodology	Semi quantitative, no integration	Semi quantitative, no integration	Semiquantitative, integration by summation/ semiquantitative, integration by multiplication/ quantitative, integration by summation	Quantitative, no integration
Spatial and/or temporal distribution	No	Spatial (some elements)	Spatial/no/spatial	No
Output	Indication of significance of effect (e.g. low, medium, high)	Indication of significance of effect (e.g. low, medium, high)	Total impact score/average risk score/total risk score	PAF of species
Visualized in CUMULEO framework	Figure 3	Figure 4	Figures S1, 5, and S2	Figure 6

CEA = cumulative effect assessment; CUMULEO = cumulative effects of offshore activities; EEZ = exclusive economic zone; EIA = environmental impact assessment; ERA = environmental risk assessment; PAF = potentially affected fraction; SEA = strategic environmental assessment.
Because EIA and SEA studies are usually published as publicly available reports (i.e., grey literature) and not in peer-reviewed journals, these were selected from a review (Smart et al. 2014; Phylip-Jones and Fischer 2015), ensuring sufficient quality of the environmental report.

drilling fluids (muds), which may be discharged to the sea provided that potential effects are acceptable. This study focuses on only one activity and a few pressures related to the emission of these particles with the aim to develop quantitative dose–effect relationships (Smit et al. 2008). The species sensitivity distribution (SSD) approach, which is commonly used in the risk assessment of toxicants (Posthuma et al. 2001), was applied to quantify the risk of these nontoxic pressures. The ecosystem components represent the groups of species on which the SSD is based. An important advantage of this methodology is the possibility to quantitatively combine effects from single pressures into one SSD for multiple pressures. The detailed quantitative risk assessment is well-suited for such a focused study intended for scientific development.

DISCUSSION AND CONCLUDING REMARKS

Recent political and scientific developments have enhanced the (number of) methodologies for assessing cumulative effects of human activities in the marine environment. There is, however, great variability in approaches and terminology. To move toward consistency, we introduce a generic framework for environmental assessment, CUMULEO, assuming that effects are a function of the intensity of pressures caused by activities and the sensitivity of recipient ecosystem components to those pressures.

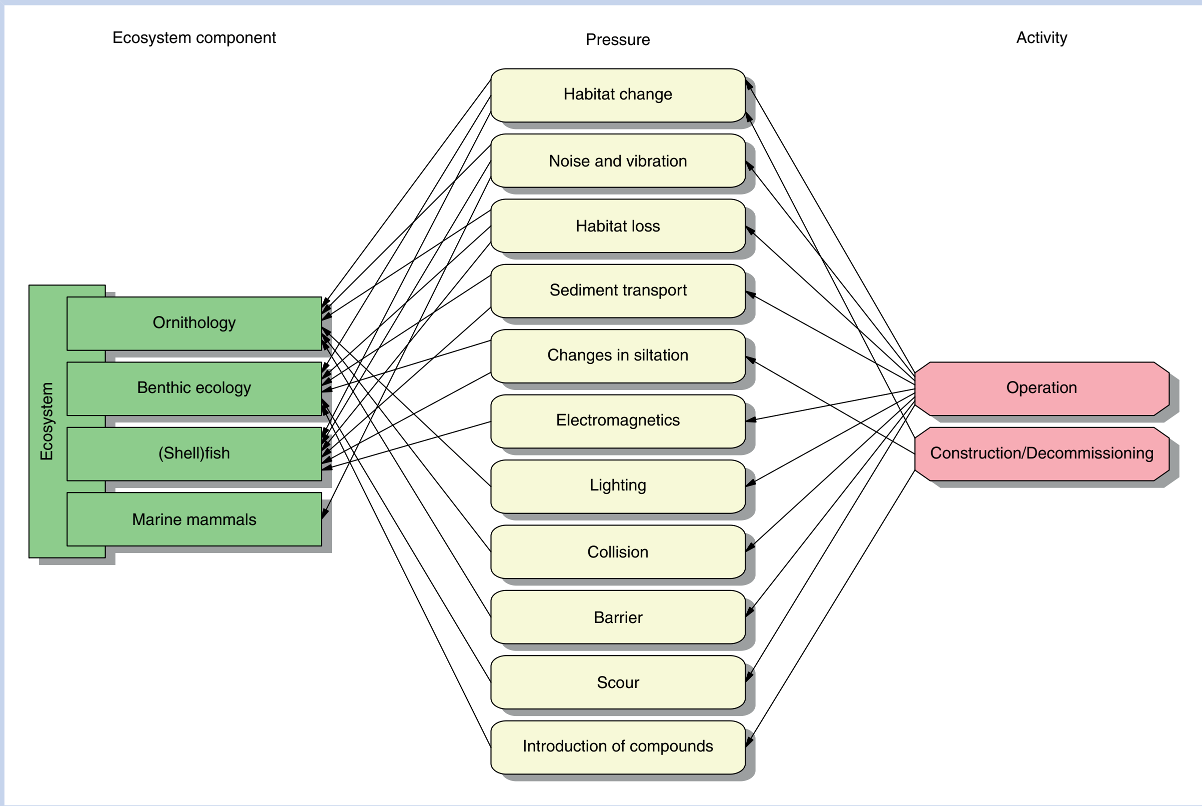

Figure 3. Generic outline of the EIA of an offshore wind farm in the UK EEZ, based on DONG Energy (2013). The assessment is based on highly detailed input (e.g., site-specific monitoring studies). The outcome of the assessment is the determination of the significance of the key effects for each ecosystem component against predetermined criteria (e.g., policy objectives). Significance is assessed by correlating the pressure intensity (based on spatial extent or size) and the sensitivity of the ecosystem component (based on vulnerability, recoverability, and value and/or importance of that component). The endpoint is a categorized indication (e.g., low, medium, high) of the significance of the effect.

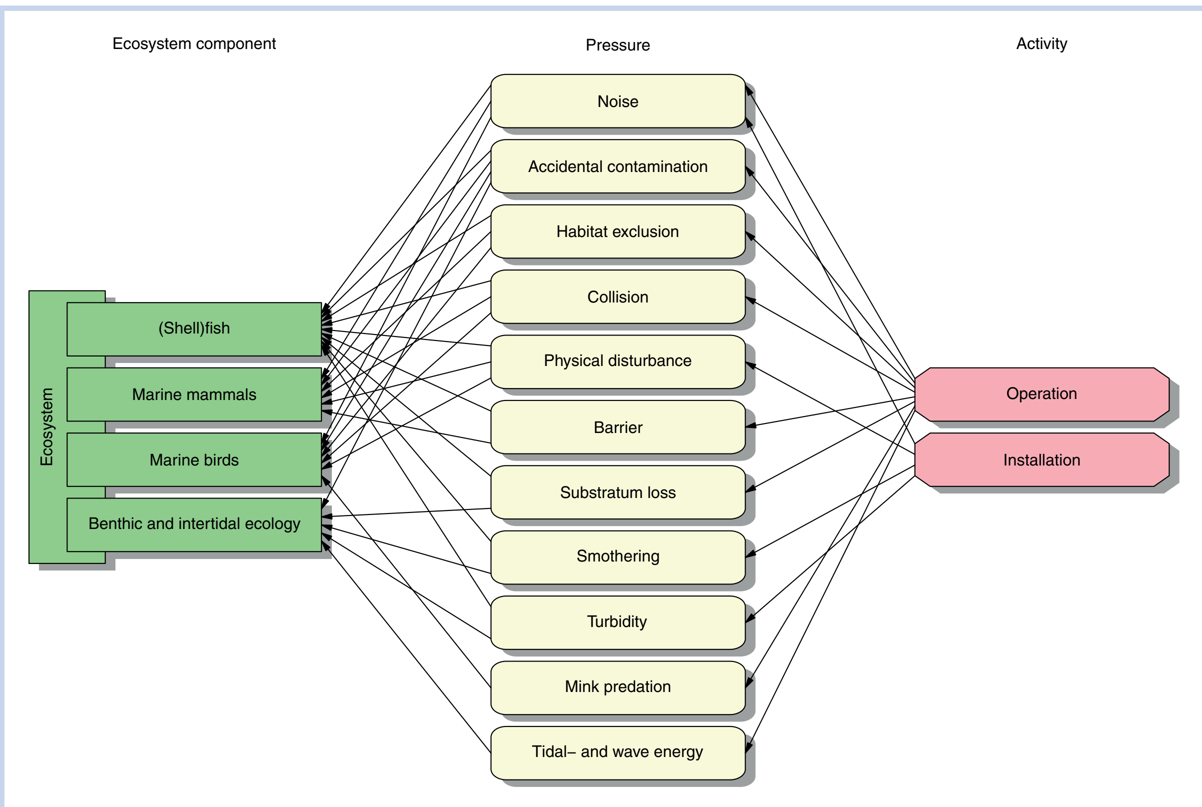

Figure 4. Generic outline of the SEA of developing wave and tidal power in the Scottish EEZ, based on Scottish Executive (2007). The assessment is based on classification of the intensity of pressures according to type, duration, and extent and the sensitivity of the ecosystem components to those pressures. The endpoint is a categorized indication (e.g., low, medium, high) of the significance of the effect.

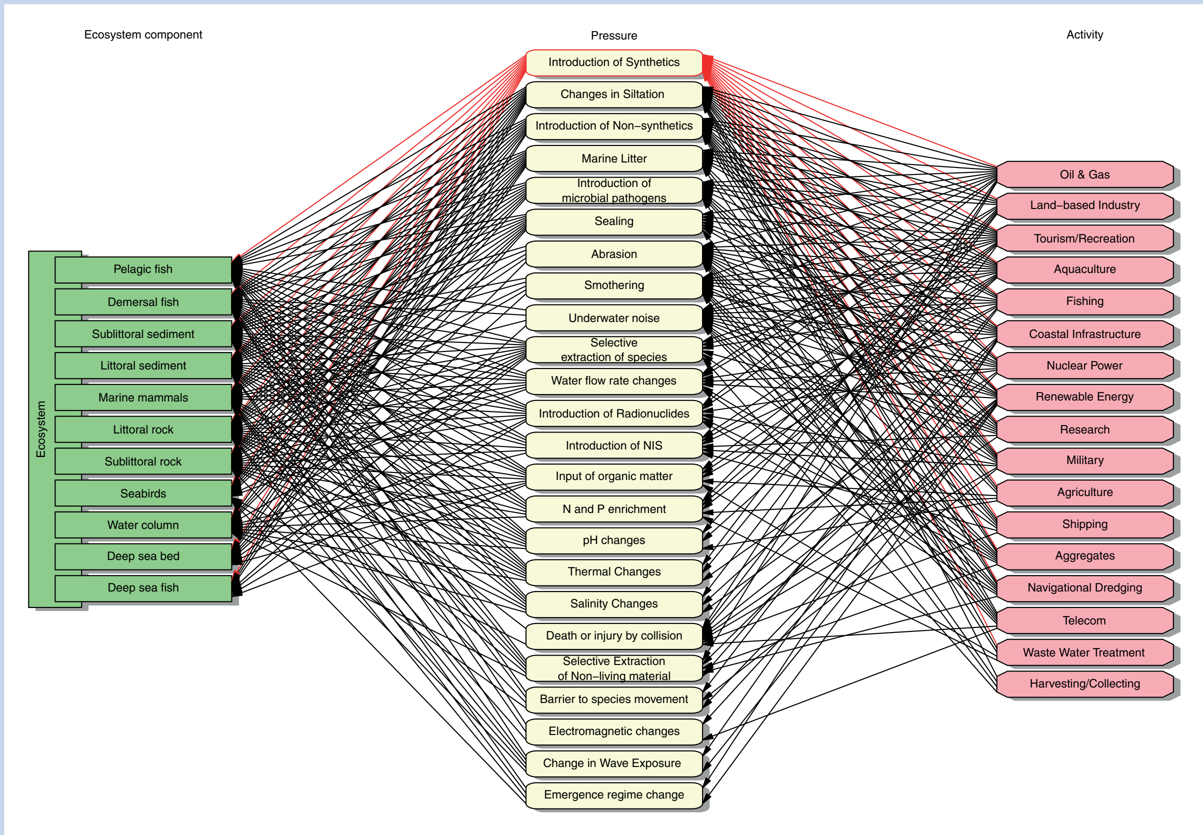

Figure 5. Generic outline of the CEA of human activities on a regional scale (North East Atlantic) based on Knights et al. (2015). Because of the great number of relations included in this study, these are no longer distinguishable in the framework. In such a case, the framework can be used to zoom into specific elements (example marked in red lines). Scores are determined by expert judgement for impact risk (based on the multiplication of scores for extent, frequency, and degree of impact) and recovery lag (based on the sum of persistence of a pressure and resilience of the impacted ecosystem component in years). This methodology does thus not distinguish between pressure intensity and ecosystem sensitivity but distinguishes different time frames. The total risk is the product of impact risk and recovery lag. Results are integrated as average risk, grouped per activity, pressure, and ecosystem components.

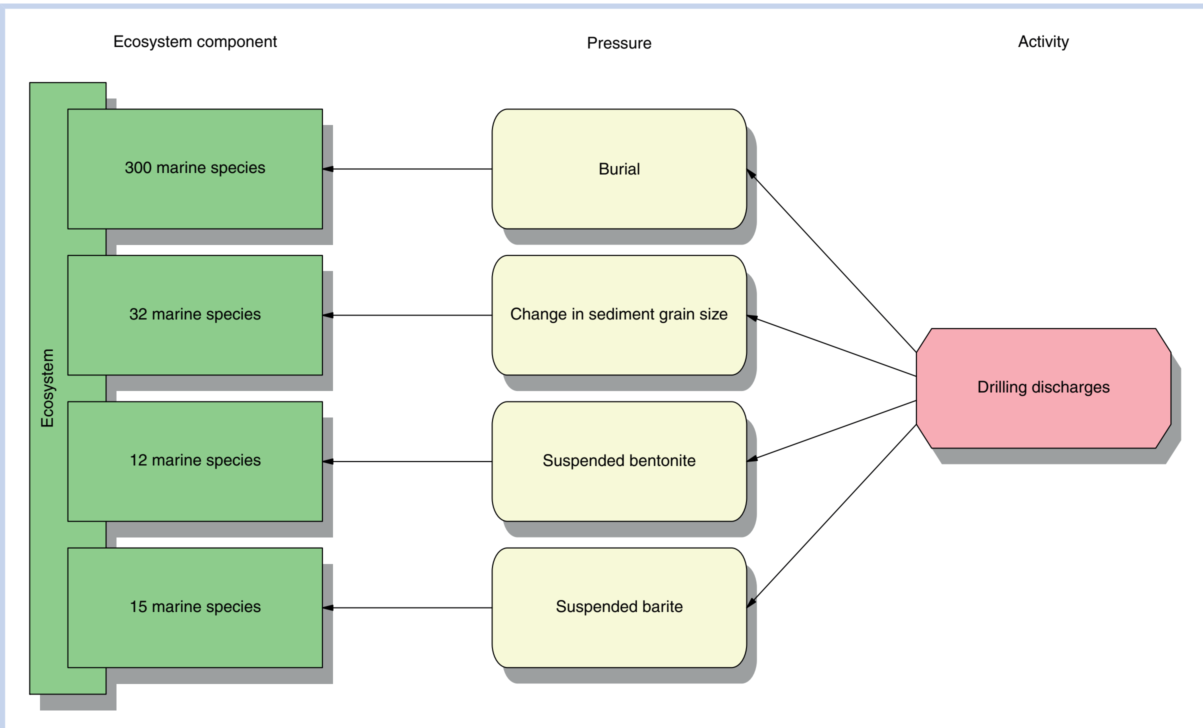

Figure 6. Generic outline of the ERA for nontoxic pressure from drilling discharges based on Smit et al. (2008). Four pressures are identified: suspended barite and bentonite, the change in grain size to represent the changing characteristics of the sediment, and burial by the deposited layer on the seabed. The study is based on a potential range of pressure intensities (exposure), and species sensitivity distributions (SSDs) were developed to represent the sensitivity. Each SSD includes a diversity of species representing an ecosystem (i.e., they are not intended to represent separate groups and overlap of species between SSDs is possible). The outcome of the assessment is the potentially affected fraction of species (PAF).

The framework is consistent throughout the sequential levels of decision making and comprises basic elements (always part of an environmental assessment regardless of purpose and level) and variables (adjusted according to the required purpose and level of the assessment, based on several characteristics).

Besides the consistency, the strength of the presented framework lies in its flexibility (allowing the use of both expert judgement and quantitative data and applicability for various purposes and levels), its transparency, and visualization. It is an approach that can be relatively easily understood, and the basic elements and simplicity make adjustments and extensions uncomplicated. Its visual aspects, combined with the ease of adjustments, makes it a powerful framework to support discussions with experts, stakeholders, and policymakers. Conceptual frameworks proved useful in synthesizing science into a visual format for multiple purposes, where an easy-to-interpret representation of a complex ecosystem was found beneficial within the decision-making process (Fletcher et al. 2014). The approach could thus be of great support in the process of marine spatial management and ecosystem-based management (Röckmann et al. 2015).

Applying the CUMULEO framework could identify the main issues of concern, i.e., deduce the strongest impacting activities, pressures, or impacted ecosystem components. Those main issues could subsequently be further assessed with more detail (i.e., using a quantitative approach) and/or be identified as knowledge gaps. The approach is therewith also useful to guide or focus future research and for relatively scarcely explored territories such as the Arctic or deep sea environments for both government and industry. Ad hoc decisions for industrial development could lead to an adverse impact on the environment at costs that are much higher than the benefits actually accrued. Applying the CUMULEO framework could be beneficial for industries in reducing time, costs, and risks involved with project developments through understanding the environmental sensitivities in an early phase of development. The framework could also contribute to a license to operate.

Although developed for the marine environment, the generic framework can be applied in other systems (i.e., coastal, freshwater, and terrestrial systems) as well, because the variables could be adjusted to the subjected environment. It also allows implementation in regions where the data availability varies (e.g., comprising both deep sea and coastal areas). Furthermore, including ecosystem services to the framework can be an important step toward maximizing social, economic, and ecological benefits from governmental and industrial developments (Allan et al. 2013). This topic (i.e., integrating ecosystem services in EA) needs additional research as indicated by Halpern and Fujita (2013). A recent study addressing ecosystem services assessed the effects of activities (trawling), via pressures (catches and gear effects) on ecosystem components (target species, benthic communities, and sediments) and subsequently on ecosystem functions and services (Muntadas et al. 2015). This approach also fits well in our generic CUMULEO framework.

It should be noted that the CUMULEO framework only presents the basic elements of CEA (i.e., activities, pressures, ecosystem components) and shows no space and time dimensions, whereas effects can only cumulate in space and time (MacDonald 2000). Although the framework shows all elements occurring in the same time and space, spatial and temporal scales can be addressed in the assessment by the variables. Furthermore, for reasons of simplicity, CUMULEO does not account for interactions between ecosystem components (e.g., species interactions, food web relationships), indirect effects, interactions between pressures, and interactions between activities. Such interactions are thought to be too complicated for inclusion in CUMULEO and are more likely to be addressed by ecosystem models. The following steps are foreseen in future development of CUMULEO:

- Spatial distribution of activities, pressures, and ecosystem components
- The CUMULEO framework has been applied in GIS and results are intended to be submitted for publication in the near future.
- Temporal distribution of activities and ecosystem components
- The option to include temporal distribution, as suggested in the description of the framework (under variables), will be further investigated.
- Intensity and spatial and/or temporal distribution of pressures
- Including the dependence of pressure intensity on distance to source and time. This would require additional knowledge and information on dispersion and/or propagation of pressures (e.g., models, thresholds). This option will be further investigated.

The generic framework proposed in this article is intended as a conceptual "umbrella" for the fragmented approaches to environmental assessment revealing the similarities and differences of these approaches. Stimulating the use of a generic framework and consistent terminology would enable better focus on (future research on) the variables within the assessment and therewith derive the "best fit for purpose."

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SUPPLEMENTAL DATA

Figure S1. Generic outline of the CEA of human activities on a global scale, based on Halpern et al. (2008). Activities and pressures are combined and referred to as drivers by Halpern et al. (2008). As our framework specifically distinguishes between activities and pressures, for demonstration purposes we divided these drivers into activities and pressures. Due to the great number of relations included in this study, these are no longer distinguishable in the framework. In such a case, the framework can be used to zoom into specific elements (example marked in red lines). The pressure intensity is a log-transformed and normalized value (0 to 1) of an activity-pressure combination at a certain location. The sensitivity is assessed (range, 0–4) per driver-ecosystem combination in Halpern et al. (2007) based on expert judgement. The impact per activity-pressure-ecosystem component combination is the product of the pressure intensity and the sensitivity. The total impact is summed per ecosystem component.

Figure S2. Generic outline of the CEA of human activities on a local scale (German EEZ), based on Fock (2011). The assessment uses distribution data of activities and ecological components and literature for model parameterization, results in a modelled quantitative risk score. Risk is the product of loss function (based on impact factor [0–1] and recovery derived from published data or estimated) and exposure. The total risk is summed per ecosystem component.

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