Science of the Total Environment 612 (2018) 1132–1140

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

A risk-based approach to cumulative effect assessments for marine management

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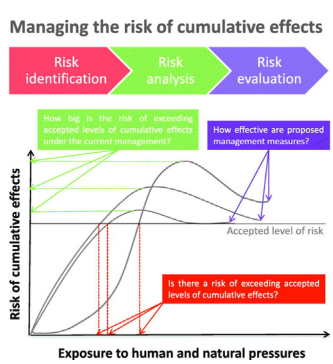
HIGHLIGHTS

- Cumulative effects assessments (CEAs) are inherently complex and seldom linked to real-world management processes
- A risk-based CEA contains risk identification, risk analysis and risk evaluation, revealing the risk of exceeding thresholds
- Embedding CEAs in a risk management process reduces complexity, streamlines scientific products, and increases transparency
- CEAs can be supported in practice by standardized terminology, procedures and the recent development of integrative methods

GRAPHICAL ABSTRACT



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http://dx.doi.org/10.1016/j.scitotenv.2017.08.289

ARTICLE INFO

Article history:
Received 13 July 2017
Received in revised form 28 August 2017
Accepted 29 August 2017
Available online xxxx

Editor: Jay Gan

Keywords:
Risk management process
Science-policy interface
Standardized framework
Terminology
Tools
Uncertainty

ABSTRACT

Marine ecosystems are increasingly threatened by the cumulative effects of multiple human pressures. Cumulative effect assessments (CEAs) are needed to inform environmental policy and guide ecosystem-based management. Yet, CEAs are inherently complex and seldom linked to real-world management processes. Therefore we propose entrenching CEAs in a risk management process, comprising the steps of risk identification, risk analysis and risk evaluation. We provide guidance to operationalize a risk-based approach to CEAs by describing for each step guiding principles and desired outcomes, scientific challenges and practical solutions. We reviewed the treatment of uncertainty in CEAs and the contribution of different tools and data sources to the implementation of a risk based approach to CEAs. We show that a risk-based approach to CEAs decreases complexity, allows for the transparent treatment of uncertainty and streamlines the uptake of scientific outcomes into the science-policy interface. Hence, its adoption can help bridging the gap between science and decision-making in ecosystem-based management.

Contents

1. Introduction

Environmental change driven by growing human pressures on marine ecosystems and their cumulative effects raises worldwide concerns. Integrated and spatially-explicit assessments of these effects are urgently needed to inform strategic planning and marine conservation (Giakoumi et al., 2015b; Halpern et al., 2008a; Katsanevakis et al., 2017; Korpinen and Andersen, 2017; Micheli et al., 2013). Cumulative effect assessments (CEAs) are defined as holistic evaluations of the combined effects of human activities and natural processes on the environment, and constitute a specific form of environmental impact assessments (EIAs) (Jones, 2016).

In marine realms, multiple policy drivers for CEAs exist from global and regional to national levels (Judd et al., 2015). For instance, the United Nations Convention on the Law of the Sea (UNCLOS; Articles 204–206) outlines a clear responsibility for Member States to assess potential threats to the marine environment and communicate the results of such assessments to other parties. While UNCLOS does not explicitly refer to CEAs, it is clear that cooperation and communication among States is essential to avoid the over-exploitation of resources. To best manage these resources, the most up-to-date, appropriate, and widely accepted methods of assessment and analysis should be used.

Despite their utility and critical need, the operationalization of CEAs in marine ecosystems remains one of the key challenges for scientists and policy makers worldwide. Although CEAs have long been recognized as an essential part of the impact assessment toolbox, debate remains with regard to the processes and frameworks to be used. The nature of the marine environment, in particular its vast openness with high connectivity of marine ecosystems, and the large heterogeneity and uncertainty in biophysical processes add additional complexities and challenges for CEAs (Carr et al., 2003; Stock and Micheli, 2016). A wide range of frameworks have been developed to assess cumulative effects on marine ecosystems, often also referred to as cumulative impact assessments (Halpern et al., 2008a; Stock and Micheli, 2016). This plethora of approaches has led to large variation of research agendas of CEAs (Foley et al., 2017) and makes comparisons among methods and the results they deliver difficult (Stock and Micheli, 2016).

Cause-effect pathways of multiple human activities on sensitive ecosystem components are often complex, involving a combination of additive, synergistic and antagonistic impacts on ecosystems (Crain et al., 2008). Thus dynamic research languages, methods and models spanning across disciplines are required. Although a unified and broadly applicable CEA methodology is most probably not feasible, the improvement of guidelines and best practices to facilitate CEA applications are urgently needed (Foley et al., 2017; Jones, 2016; Judd et al., 2015; Portman, 2011; Stelzenmüller et al., 2010).

The application of an environmental risk assessment framework to CEAs is a promising approach to align the assessment of the risk of cumulative effects with the required management actions (Judd et al., 2015). Here, we advance this thinking by entrenching CEAs in an overarching risk management process, comprising the core steps of risk identification, risk analysis and risk evaluation (Fig. 1) (Cormier et al., 2013). To support a practical implementation of this risk-based approach to CEAs, we provide a description of the required tasks and desired outputs for these steps, identify scientific challenges and synthesize practical solutions. In addition, we also provide a broad review of the types of tools useful to implement the respective CEA steps, recognizing the range of available types of data.

The development of a standard glossary of CEAs key terms is a prerequisite for the transfer of knowledge, assessment approaches and expertise across management boundaries, stakeholders, and organizations. In particular, an inconsistent use of terms can pose barriers to the communication of outputs (Foley et al., 2017; Judd et al., 2015). An example for linguistic ambiguity is the use of the terms “pressure”, “activity” or “threat” in EU marine policies (EU 2011/92). Here we offer a glossary of 37 terms which are both often used in CEAs e.g. (Korpinen and Andersen, 2017) and pertinent in a risk management process (ISO 31000 standard; International Organization for Standardization (ISO), www.iso.org) (Appendix A).

Another important aspect still insufficiently treated in CEAs is uncertainty, which can jeopardize the quality of CEA outputs and consequently their contribution to overarching management processes. Uncertainty can be rooted in inadequate knowledge, low predictive ability of ecosystem behavior, natural variability, measurement error, or changing policies (Halpern and Fujita, 2013; Opdam et al., 2009; Stelzenmüller et al., 2015). We address this gap and provide a synopsis of uncertainty treatment in CEAs.

In this study we present a comprehensive and standardized guidance for CEAs that allows the bridging of scientific approaches and defining of required outputs more precisely. Standardization facilitates informed decision-making in the management of the risk of cumulative effects in marine realms (Ban et al., 2010; Foley et al., 2010; Katsanevakis et al., 2011).

2. Recognizing and handling uncertainty in cumulative effect assessments

Building on a review of marine CEAs (Korpinen and Andersen, 2017), we assessed the current gaps and challenges for treating uncertainty in CEAs from a total of 41 peer reviewed studies and five project reports. Nine out of these 46 studies did not refer to uncertainty and thus were not further considered. We defined ten criteria related to methodological assumptions and data quality (based on Stock and Micheli, 2016) and evaluated (yes/no) the remaining studies (a) if uncertainty was acknowledged in the CEA, and (b) if its impact on overall CEA results was assessed (Table 1). While uncertainty was acknowledged in the vast majority of studies (36 out of 37), only 26 studies attempted (at least partly) to assess it (Fig. 2). Only six studies (out of 26) assessed more than two sources of uncertainty and overall not more than four sources. Different methodologies were applied to address uncertainty in CEA results, such as Bayesian models (e.g. McManus et al., 2014), expert judgment (Knights et al., 2015), Monte Carlo simulations and sensitivity analyses (Stelzenmüller et al., 2010). Also, the aggregation of uncertainty and its impact on CEA results were considered (Andersen et al., 2013; Halpern et al., 2015; Kelly et al., 2014; Knights et al., 2015). From our analysis three key messages can be distilled. First, there is a wide recognition of uncertainty sources, showing the awareness of the inherent complexity of the studied systems and the potential biases introduced by the chosen methods and data. Second, only a limited number of studies actually assess uncertainty related to generated outputs. Third, we revealed a clear gap between the sources of uncertainty recognized and the types of uncertainty assessed, and the need for further developing methodological frameworks and tools for adequate uncertainty assessments in CEAs.

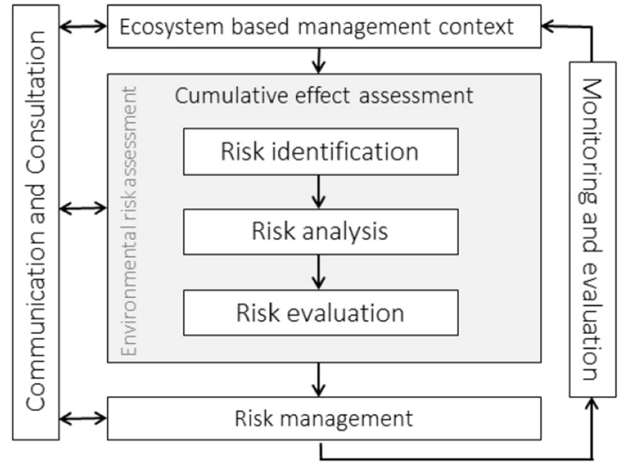

Fig. 1. Conceptual embedding of a cumulative effects assessment (CEA) into an ISO standard risk management process. The CEA forms an integral part of the framework, comprising the three basic steps of risk identification, risk analysis, and risk evaluation.

3. A risk-based approach to cumulative effect assessments

We emphasize embedding CEAs in an overarching ISO standard risk management process which comprises the three steps of risk identification, risk analysis and risk evaluation (see Fig. 1). The risk management process as a whole aims to reduce the risk of failing the management objective i.e. to manage cumulative pressures in such a way that cumulative effects do not exceed accepted thresholds (Fig. 3). A prerequisite for a risk-based CEA is an established risk management context that identifies clearly the relevant policy objectives. Without concrete policy objectives risk criteria and thresholds cannot be derived for the subsequent CEA. Hence CEA results should reveal the probability of occurrence and intensity of cumulative effects of multiple human activities and natural disturbances on defined ecosystem components. Moreover, the CEA step of risk evaluation should evaluate management procedures regarding potential failure to meet such management objectives (e.g. conservation targets for certain species or habitats). In other words, when following the standardized CEA, results should describe the risk of failing on the management objective to manage cumulative pressures in such a way that cumulative effects do not exceed accepted thresholds (see Fig. 3). Thus the proposed consistent procedure allows the linking of CEA outputs directly with the evaluation and implementation of management measures, regardless of the CEA context. The CEA context is defined by the management area, specific ecosystem components (ecological, social and economic) of concern and the likely causes of cumulative effects (human activities, but also natural disturbances). Throughout the overarching risk management process, communication is essential for the open exchange of explanatory information and opinions leading to better understanding and decision-making. Monitoring and evaluation is another key element allowing for adaptations of the entire process (see also Cormier et al., 2013).

We propose a framed CEA that builds upon defined standards, tasks and outcomes and which can explicitly address the severity of likely ecological, social, cultural, and economic impacts together with their legislative and policy implications. However, its practical implementation has challenges one of which is the identification and assessment of uncertainty in relation to data, methods, assumptions or outcomes. Although there is no “one fits all” solution regarding specific methods or data, we provide general guidance for the implementation of the proposed CEA process by indicating for each step: i) the required tasks and outcomes for the process, ii) scientific challenges, and iii) practical solutions.

Table 1
The treatment of uncertainty was evaluated for a total of 37 CEA studies using ten criteria (based on Stock and Micheli, 2016) related to model assumptions and data quality. The ten criteria refer to the following sources of uncertainty: (1) Pressure data: The effect of missing pressures data on CEAs; (2) Sensitivity weights: CEA models use sensitivity weights to estimate the effect of each pressure on each ecosystem component, often derived by expert judgment or models, and thus are often highly uncertain; (3) Spreading of effects from point sources: Uncertainty on how the effect from a point source decays with the distance from the source; (4) Non-linear responses to pressure: CEA models commonly assume linear responses to pressure intensity but often responses of ecosystems to pressures are non-linear, this assumption adds uncertainty to the CEA results; (5) Reduced analysis resolution: The effect of the spatial resolution of the CEA analysis on the result; (6) Reduced pressure resolution: The effect of low spatial resolution of some pressures (and thus the need of downscaling) on CEA results; (7) Mean or sum of effects: CEA calculate the human effect scores either as the sum of effects over all ecosystem components that are present in a given cell or as the mean effect across all ecosystem components, this decision affects the CEA outcomes; (8) Transformation type: Various transformations to make stressors comparable have been applied (e.g. log-transformation, P-transformation) – the selection of transformation type affects the final result; (9) Modelling multiple pressure effects: Commonly it is assumed that the effects of multiple pressures add up, yet, non-additive effects and interactions are common in nature and models that do not account for them affect CEA outcomes; (10) Spatial distribution of ecological features: Data gaps in the available maps of ecological features (habitats or species) often results in high uncertainty. For each criterion we explored whether the authors: (R) recognized relevant sources of uncertainty and (A) assessed the potential impact upon the results; yes = y; no = n.

	Pressure data		Sensitivity weights		Spreading of effects from point sources		Nonlinear responses to pressures		Reduced analysis resolution		Reduced pressure resolution		Mean or sum of effects		Transformation type		Modelling multiple pressure effects		Spatial distribution of ecological features	
	R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A
Andersen et al., 2013	y	n	y	y	y	n	y	n	n	n	y	n	n	n	n	n	y	n	y	n
Andersen et al., 2017	y	n	y	n	n	n	y	n	n	n	n	n	n	n	n	n	y	n	y	y
Aubry and Elliott, 2006	n	n	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
Ban et al., 2010	y	n	y	n	y	n	n	n	n	n	n	n	y	n	n	n	y	n	y	n
Batista et al., 2014	y	n	n	n	n	n	n	n	n	n	y	n	n	n	n	n	y	n	y	n
Clark et al., 2016	y	y	y	n	y	n	y	n	n	n	y	n	y	n	y	y	y	n	y	n
Murray et al., 2015	y	n	n	n	n	n	n	n	n	n	y	n	n	n	n	n	y	n	n	n
Coll et al., 2012	y	n	y	y	y	n	n	n	y	n	y	n	n	n	n	n	y	n	y	n
Coll et al., 2016	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	y	n
De Vries et al., 2011	y	n	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	y	n
Foden et al., 2011	y	n	y	n	y	n	n	n	n	n	y	n	n	n	n	n	y	y	y	n
Giakoumi et al., 2015a, b	n	n	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
Goodsir et al., 2015	y	n	n	n	y	n	n	n	n	n	y	n	n	n	n	n	y	n	y	n
Griffith et al., 2012	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
Halpern et al., 2008a, b	y	n	y	y	n	n	y	n	y	n	n	n	y	y	y	n	y	n	y	y
Halpern et al., 2009	y	n	y	n	n	n	n	n	y	y	y	n	y	y	n	n	n	n	y	n
Halpern et al., 2015	y	y	y	n	n	n	y	n	n	n	y	n	y	y	y	y	y	n	y	n
Hayes and Landis, 2004	y	y	y	y	y	y	n	n	n	n	n	n	n	n	n	n	n	n	y	y
Holon et al., 2015	y	n	n	n	n	n	y	n	y	n	y	n	n	n	n	n	y	n	y	n
Kappel et al., 2012	y	n	y	y	y	n	n	n	n	n	y	n	n	n	y	n	n	n	y	n
Katsanevakis et al., 2016	y	n	y	y	n	n	n	n	y	n	y	n	n	n	y	n	y	n	y	n
Kelly et al., 2014	y	y	y	y	n	n	n	n	y	n	n	n	n	n	n	n	y	n	y	n
Knights et al., 2015	y	n	y	y	y	y	y	n	y	y	n	n	n	n	n	n	y	n	y	y
Korpinen et al., 2012	y	y	y	y	n	n	y	n	y	n	y	n	n	n	n	n	n	n	y	y
Korpinen et al., 2013	y	n	y	y	y	n	n	n	y	n	y	n	y	n	n	n	y	n	y	n
Marcotte et al., 2015	y	n	y	n	y	y	y	n	y	n	n	n	n	n	n	n	y	n	y	y
Maxwell et al., 2013	y	y	n	n	n	n	n	n	n	n	n	n	n	n	n	n	y	n	y	y
McManus et al., 2014	y	n	y	y	y	y	y	y	n	n	n	n	y	y	n	n	y	n	y	n
Micheli et al., 2013	y	n	y	n	n	n	y	n	n	n	y	n	n	n	n	n	n	n	y	n
Moreno et al., 2012	y	n	y	n	y	n	y	n	n	n	y	n	n	n	n	n	y	n	n	n
Murray et al., 2016	y	n	y	y	n	n	y	n	n	n	n	n	n	n	n	n	y	n	y	n
Parravicini et al., 2012	y	n	y	y	y	n	y	n	n	n	n	n	n	n	n	n	y	y	y	n
Rodríguez-Rodríguez et al., 2015	y	n	y	n	n	n	n	n	n	n	n	n	y	n	n	n	n	n	y	n
Selkoe et al., 2009	y	y	y	y	n	n	n	n	y	y	y	n	n	n	n	n	y	n	y	n
Stelzenmüller et al., 2010	y	n	y	y	n	n	y	n	n	n	n	n	n	n	n	n	y	y	y	n
Van der Wal and Tamis, 2014	y	n	y	n	n	n	n	n	n	n	y	n	n	n	n	n	n	n	y	n
Wu et al., 2016	y	n	y	y	y	n	n	y	n	n	n	n	n	n	n	n	n	n	y	n

4. Synopsis of cumulative effect assessment tools

Each step of the CEA process calls for different scientific analyses and expertise, hence requiring a selection of appropriate tools. In turn, the selection of tools is determined by the ecosystem component/(s) and available input data (expert knowledge, qualitative or quantitative) being assessed in the CEA. We provide a synopsis of methods and tools applied in CEAs resulting from an extensive review of 154 studies and their subsequent quantitative classification regarding the input data, methods and tools applied in the respective risk management process (methods and results are described in Appendix C and classified references are provided in Appendix D). Our results (Table 2) demonstrated that: 1) expert knowledge and qualitative data are sporadically or moderately used across the CEA process; 2) the use of Geographic Information Systems (GIS) is almost a prerequisite for CEAs; 3) large gaps exist in addressing uncertainty in the risk analysis stage and when assessing the impacts of different management options in risk evaluation; and 4) novel integrative methods (e.g. a combination of qualitative data and qualitative modelling to assess ecosystem state and pressures) have been developed over the past decade to assess the status of marine ecosystems and some have been applied to fulfil the different components of CEAs.

5. Risk identification

5.1. Description

Risk identification is the process of finding, recognizing and describing risks (ISO guide 73). This involves the identification of risk sources, events (change of particular set of circumstances), and the determination of causes and consequences. Risk identification comprises also the identification of the main criteria to be used for the risk evaluation. Given the risk management and CEA context, risk criteria need to be specified in relation to specific management goals or policy objectives

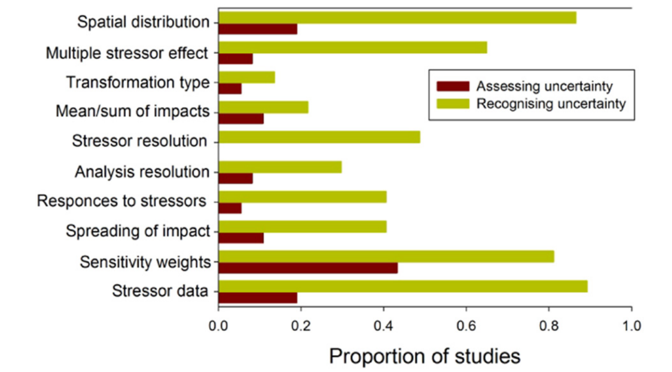

Fig. 2. Proportion of CEA studies recognizing and assessing uncertainty in respect to ten sources of uncertainty comprising spatial distribution, multiple pressure effect, transformation type, mean/sum of effects, pressure resolution, analysis resolution, responses to pressures, spreading of effects, sensitivity weights, and pressure data (based on Stock and Micheli, 2016; see Table 2).

for ecosystem components and services (see Cormier et al., 2013). In Fig. 4 and Appendix B an example of the adoption of risk criteria to assess the vulnerability of nursery areas of plaice (*Pleuronectess platessa*) in the Southern North Sea is shown. A key task to risk identification is the establishment of the cause-effect relationships or pathways of risks to describe the vulnerability of ecosystem components to pressures.

5.2. Scientific challenges

Pathways of risks are uncertain since spatio-temporal dynamics of ecological processes (e.g. sensitivity to a contaminant can be high in summer and low in winter) and the associated distribution and relation between effects (additive, synergistic or antagonistic) can alter the cause-effect relationships and therefore the pathways of risks (João, 2007; Tzanopoulos et al., 2013) (see Fig. 3). The lack of full coverage of spatial and temporal data for most CEAs adds to the challenge of deciphering cause-effect pathways. Most systematic monitoring rarely spans the past few decades failing to encompass the life spans of many species or important environmental disturbances such as e.g. El Niño–Southern Oscillation (Jackson and Hobbs, 2009). As a result, the definition of meaningful benchmarks or tipping points is often difficult, compromising the quantification of pressure-state relationships (Dayton et al., 1998; De Young et al., 2008). Hence, a deeper consideration of the non-linearity between pressures and their effects at different scales is critical for improving risk identification. Table 2 shows that the predictive ability of various models and CEA tools largely depends on the type and quality of the input variables. A key scientific challenge is outlining a transparent approach for the implementation of a standardized CEA assessment, acknowledging that assumptions might be insufficiently grounded (Halpern and Fujita, 2013).

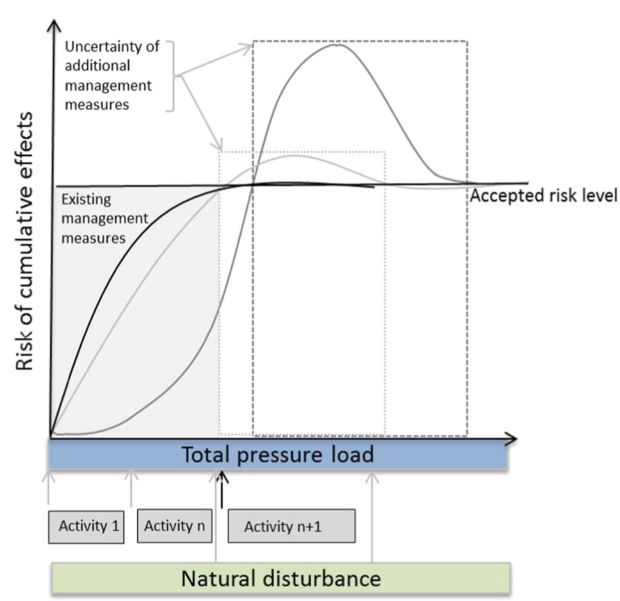

Fig. 3. Implemented management measures maintain the risk of cumulative effects resulting from human pressures and natural disturbance at accepted levels. Changes to the total pressure load e.g. due to a newly implemented activity (activity n + 1), can trigger deviations to cause-effect relationships (indicated by light grey, grey and black lines). Consequently the risk of cumulative effects can exceed accepted levels calling for new management measures. The uncertainty of cause-effect relationships can be transparently handled with a risk based approach to CEAs that entails structured risk evaluation.

5.3. Practical solutions

Disentangling cause-effect pathways is supported by a number of conceptual frameworks (e.g. Driver Pressure State Impact Response (DPSIR); Patrício et al., 2016) which provide guidance on how to link ‘driving forces’ to generic ‘pressures’ and to physical, chemical and biological attributes, and then translate the impacts into policy responses. Fundamental for the proximate assessment is the common understanding that the vulnerability of an ecosystem component is defined by the degree of exposure to a pressure, its sensitivity and recovery potential (De Lange et al., 2010) (see CEA glossary provided in Appendix A). The sensitivity to a pressure depends on structural properties, functions or trophic relations of the ecosystem components while recovery can be the result of population rebound, resilience, positive feedback loops and adaption (Tyler-Walters et al., 2001). As opposed to single ecosystem components, defining the vulnerabilities of ecosystem functions or services has received less attention in current CEAs. Some studies assessed the effects of single or multiple pressures on ecosystem function, goods and services with the help of functional trait approaches (Christensen et al., 2015; Froján et al., 2011; Hewitt et al., 2016). The adoption of these methods is often constrained by a lack of fundamental ecological information, even in very well studied ecosystems (Tyler et al., 2012). Therefore, promising initiatives collecting trait information and building data platforms (e.g. databases such as Biotic (www.marlin.ac.uk/biotic), WoRMS (www.marinespecies.org) or Arctic Trait Platform (www.sites.google.com/site/arctictraits/home/the-project)) are crucial for the development of trait-based approaches in CEAs and could offer a comprehensive alternative for risk identification.

Once the pathways of risk are identified, the risk criteria can be assessed with the help of qualitative data using, for instance, expert knowledge or published data (see Fig. 4 and Appendix B). Recent advances have been achieved in the development of models that directly implement risk criteria and thresholds (e.g. mortality rate is equal, larger or smaller as recoverability rate) using quantitative data to map the vulnerability of ecosystem components to specific pressures (e.g. seafloor communities to benthic trawling; Fock, 2011; Pitcher et al., 2017; Stelzenmüller et al., 2014). The use of such quantitative models is facilitated by the growing access to regional spatio-temporal data on ecosystem features and human activities via webportal warehousing and the provision of freely available data sets (e.g. such as Emodnet www.emodnet.eu at a European scale).

6. Risk analysis

6.1. Description

Risk analysis comprises the comprehension of the nature of risk and the determination of the level of risk (ISO Guide 73, 2009). This consists of determining the probabilities of identified risk events, taking into account the presence and effectiveness of control measures (IEC/ISO

Table 2
Result of the classification of 154 studies regarding the input data, methods and tools applied in the respective risk management process (all classified references are provided in Appendix D). Based on the number of references found in a literature review of these tools, we classified their use as: (1) Sporadic, when there were between 1 and 10 studies that used them; (2) Moderate, when we found between 10–20 studies, and (3) Frequent, when we found more than 20 studies.

CEA step	Tasks	Input data			Methods and tools						
		Expert knowledge	Qualitative	Quantitative	SA - GIS tools	SM-linear models	SM-no linear models	FWM - qualitative	FWM - quantitative	Integrative assessments	SP-Marxan
Risk identification	Description of ecosystem components	1	1	3	3	2	2	3	3	3	3
	Description of pressures	1	1	3	3	2	1	3	3	3	3
Risk analysis	Estimation of pressures	1	1	3	3	1	2	2	3	3	2
	Estimation of likelihood of impact		1	2	2	2	1	2	2	3	1
	Consideration of uncertainty			2	1	1	1	2	2	3	
Risk evaluation	Evaluation of impacts on ecosystem components	2	2	2	1	2	1	2	3	3	1
	Evaluation of different management options	1	1	2	1	1	1	2	2	3	3

Note: SA: spatial analysis, SP: spatial planning; SM: statistical modelling; FWM: food web modelling.

31010, 2009). Thus, risk analysis identifies the actual consequences of cumulative effects after accounting for the effectiveness of implemented management measures. Existing management measures are considered to be effective if they succeed in maintaining the risk of cumulative effects at levels which are compliant with the management objectives. This is analogous to fisheries management for which management measures are assessed in relation to fishing mortality and against population trends and defined allowable catches.

6.2. Scientific challenges

In the marine environment the sourcing and mapping of pertinent management measures is challenging due to complex governance structures (Buhl-Mortensen et al., 2017), often revealing mismatches in scales and in resolutions relative to the assessment at hand. Data of appropriate spatial and temporal resolution (monitoring data and/or predictive model output) are, similar to risk identification, a condition for a quantitative assessment of the effectiveness of implemented management measures. In the absence of empirical data, eliciting expert opinion is commonly used as a way to derive baseline information for conceptualizing the probability and magnitude of cumulative environmental effects or quantifying the effectiveness of management measures (Giakoumi et al., 2015a). In these cases a transparent assessment of uncertainty accounting for both the experts' context and opinion should be conducted (Stelzenmüller et al., 2015). The challenge is therefore twofold: a) to generate, collate, standardize and share data sets; and b) to develop and apply methods that combines various data sources and account for uncertainty.

6.3. Practical solutions

The analysis of existing management measures requires a comprehensive review of legislation, policy, and management practices, guidelines and thresholds. A "bow-tie" is a graphical model which could offer the ground for a wide-ranging analysis of the performance of a management system. This conceptual model is widely applied in risk analyses, but largely ignored so far in CEA; it allows mapping out cause-effect relationships that lead to an undesired event with the consequences of

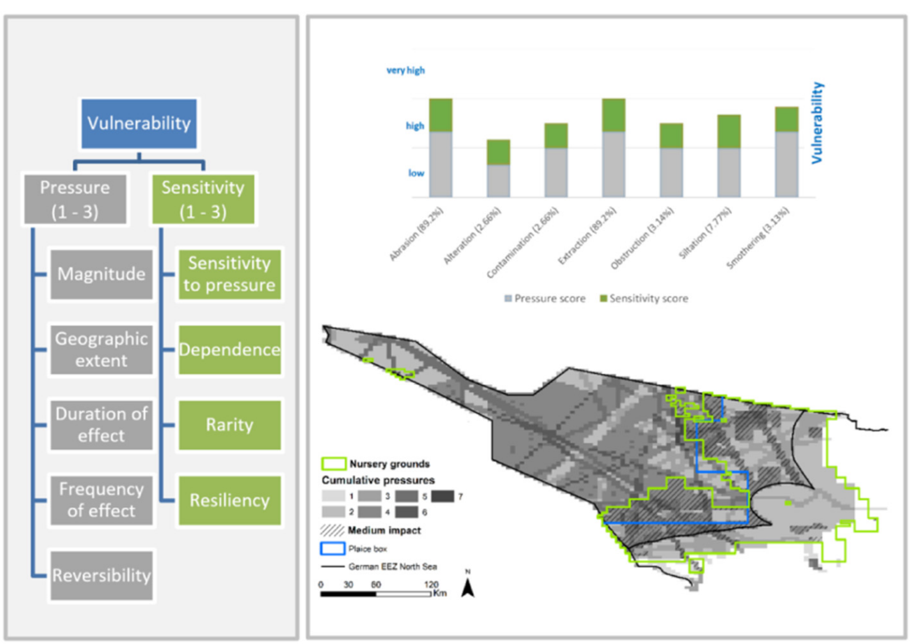

Fig. 4. Risk identification and risk analysis of the effects of human pressures on nursery grounds of plaice (*Pleuronectes platessa*) in the Southern North Sea (Gimpel et al., 2013) by qualitative scoring of nine risk criteria describing their exposure and sensitivity (1 to 3, 3 = high) (Appendix B). All scores (1 to 27, 27 = high magnitude of impact) were combined for the risk analysis. Alteration was identified to cause a medium level of risk (dashed lines) and the summation of all pressures per grid cell (*cumulative pressures*) showed an increased risk for nursery grounds (framed in green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

failure (Ferdous et al., 2013; Lu et al., 2015). Hence, a bow-tie analysis can help to order the complexity of relevant legislation measures in relation to the ecosystem components or ecosystem services of concern in the CEA (Cormier et al., 2013; Gerkensmeier and Ratter, 2016, IEC/ISO 31010, 2009). Our assessment of CEA tools (Table 2, Appendix C) highlighted that the use of Geographical Information System (GIS) and overlay analysis is very useful to reveal scale mismatches between existing management measures and areas with an increased risk for cumulative effects. Besides spatially explicit data, time series and baselines beyond the temporal limits of implemented monitoring programs are required. Recent examples show that palaeoecological data could offer information on ecosystem variability exceeding the length of most time series, and thus supporting marine risk assessments (Kosnik and Kowalewski, 2016).

7. Risk evaluation

7.1. Description

The prior risk identification identifies the risk of cumulative effects, while the risk analysis describes the risk of cumulative effects after accounting for the performance of existing management measures. In contrast, risk evaluation compares the results of the risk analysis with the established risk criteria and benchmarks to determine the significance of the level and type of risk (IEC/ISO 31010, 2009). Inconsistencies and gaps between the effectiveness of existing management measures, the specified risk criteria and the level of risk accepted by society (see Cormier et al., 2016) are identified. Risk evaluation assists in the decision about risk treatment and requires also a performance assessment of new measures. The CEA risk evaluation step delivers a recommendation to the competent authority on whether new measures need to be implemented or existing ones need to be enhanced to reduce the risk of cumulative effects. In a risk management process at this stage a decision has to be taken by the competent authority on the basis of probabilities and uncertainties (Cormier et al., 2016) and should build on a participatory process with jurisdictional partners and stakeholders (Cormier et al., 2013). The recommended measures are further assessed through risk management (see Fig. 1) where cost-effectiveness analyses can help to directly propose final management measures.

7.2. Scientific challenges

Risk analysis and risk evaluation involve comprehensive and interdisciplinary approaches to evaluate the performance of existing or new management measures that might represent ecological, social and economic targets (Katsanevakis et al., 2011; Stelzenmüller et al., 2013). These approaches often deliver very specific and technical results, and their communication to responsible authorities and stakeholders is a key challenge in risk evaluation. The challenge is the delivery of particular science products to the science-policy interface and the following rendering of the outcomes of this participatory process into technical advice. Different views on evaluating the quality of the provided evidence often result in scientific and societal debate (Gluckman, 2016); thus, scientific input is most needed by policymakers where science is complex, multidisciplinary, and incomplete. Discrepancies can arise between scientific recommendations and political solutions highlighted by cases where the implementation of management measures is based on concrete factors (Portman et al., 2012), for instance when protected areas are designated in resource-poor locations because there are little or no claims by other sectors. In addition, some pressures are much easier to regulate (or mitigate) than others (Prugh et al., 2010). The degree to which a pressure is manageable depends on the scale of measured implementation and the jurisdiction of the authority responsible for the uptake of the management action (Judd et al., 2015; Tulloch et al., 2015). For example, a local government that has supported and contributed to the CEA may not be in a position to take the necessary steps to regulate a pressure (e.g. trawling activities that take place outside of jurisdictional waters).

7.3. Practical solutions

There are a number of tools and methods that facilitate the performance assessment of existing and new management measures (Appendix C). For instance, a framework for structured decision making proposed by Tulloch et al. (2015) can help to evaluate potential management measures and as such supports a more cost-effective decision process. Mechanistic ecosystem models (Christensen and Walters, 2004; Fulton et al., 2015a) enable the incorporation of current or future control or mitigation measures for the assessment of spatial explicit cause-effect relationships between e.g. fishing and single ecosystem components (e.g. commercial species) or ecosystem functions (such as reproduction grounds). Also end-to-end models such as Atlantis can assess management options as requested for a CEA analysis (Fulton et al., 2011). Another modelling approach that has been successfully used for environmental risk assessments (Marcot et al., 2006) and the assessment of management scenarios (Pascual et al., 2016) is the use of Bayesian belief networks. The latter enables the incorporation of prior knowledge allowing for different data sources (e.g. expert judgment, data from preliminary studies or other locations) and levels of uncertainty, which may be particularly valuable when data are scarce. This is a powerful approach for CEA analyses, especially from an adaptive management perspective. Our analysis showed that the use of GIS and specifically the use of planning tools, such as Marxan and Zonation, enable a spatially explicit evaluation of management options (Table 2 and Appendix C). In any case, effective communication of candidate management measures and building consensus on clear recommendations require participatory processes (Fulton et al., 2015b) so that the simple use of a spatial explicit decision support tool may not be enough or may be only the start of the evaluation of management options. Other example tools for structured science-based stakeholder dialogues are rational actor paradigm, Bayesian learning (Pascual et al., 2016), organizational learning (see Welp et al., 2006), and qualitative modelling (Dambacher et al., 2015) (see Appendix C).

8. Conclusions

Worldwide policy mandates at different jurisdictional levels and scales call for CEAs in marine realms. As a result, there have been an increasing number of CEA endeavors across regions and ecosystems. Despite methodological advancements, they often lack some key features. For instance, our review revealed a clear divergence between the sources of uncertainty evident in CEAs and the ones actually addressed. More importantly, we highlighted a lack of standardization of processes when conducting CEAs. The risk-based approach to CEAs proposed here helps to standardize procedures and allows treating uncertainty in a more transparent manner since our framework comprises key definitions of terms, criteria, standards, and required outputs. Our approach specifically acknowledges uncertainty in cause-effect relationships and highlights the need to account for management measures in such analyses. We show that entrenching CEAs in a risk management process reduces complexity, allows for the transparent treatment of uncertainty and streamlines the uptake of scientific outcomes for an improved the science-policy interface. In conclusion, a risk-based approach to CEAs can help bridge the gap between theory and practice in ecosystem based management.

Acknowledgements

This article is based upon work from COST Action 15121 'Advancing marine conservation in the European and contiguous seas (MarCons) - supported by COST (European Cooperation in Science and Technology, CA15121).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.08.289.

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