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Review

Operationalizing risk-based cumulative effect assessments in the marine environment

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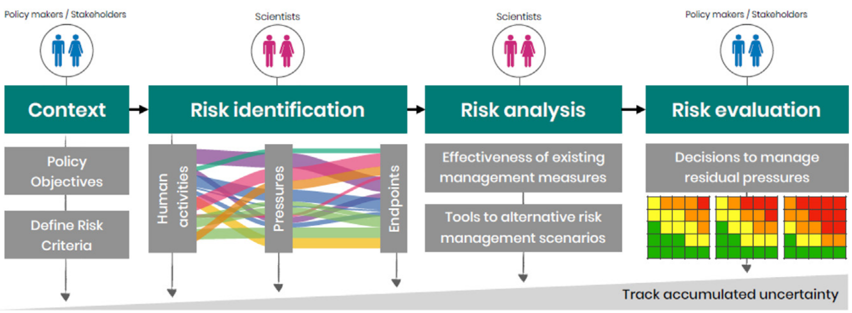
HIGHLIGHTS

- Eleven contrasting case studies reveal key issues for the operationalization of a risk-based CEA framework
- General need to better define CEA context, risk criteria and the roles of scientists, managers and stakeholders
- Customized tools for the communication of uncertainty and trade-offs of knowledge and data are demonstrated
- Need to differentiate CEA by purpose informing either governance advice, marine spatial planning or regulatory processes
- Well-framed CEA as a strategic tool to integrate ecosystem considerations across sectors

GRAPHICAL ABSTRACT



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ABSTRACT

Ecosystem-based management requires an assessment of the cumulative effects of human pressures and environmental change. The operationalization and integration of cumulative effects assessments (CEA) into decision-making processes often lacks a comprehensive and transparent framework. A risk-based CEA

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framework that divides a CEA in risk identification, risk analysis and risk evaluation, could structure such complex analyses and facilitate the establishment of direct science-policy links. Here, we examine carefully the operationalization of such a risk-based CEA framework with the help of eleven contrasting case studies located in Europe, French Polynesia, and Canada. We show that the CEA framework used at local, sub-regional, and regional scales allowed for a consistent, coherent, and transparent comparison of complex assessments. From our analysis, we pinpoint four emerging issues that, if accurately addressed, can improve the take up of CEA outcomes by management: 1) framing of the CEA context and defining risk criteria; 2) describing the roles of scientists and decision-makers; 3) reducing and structuring complexity; and 4) communicating uncertainty. Moreover, with a set of customized tools we describe and analyze for each case study the nature and location of uncertainty as well as trade-offs regarding available knowledge and data used for the CEA. Ultimately, these tools aid decision-makers to recognize potential caveats and repercussions of management decisions. One key recommendation is to differentiate CEA processes and their context in relation to governance advice, marine spatial planning or regulatory advice. We conclude that future research needs to evaluate how effective management measures are in reducing the risk of cumulative effects. Changing governance structures takes time and is often difficult, but we postulate that well-framed and structured CEA can function as a strategic tool to integrate ecosystem considerations across multiple sectorial policies.

Contents

1. Introduction

Over the last decade scientific effort on the categorization and description of human pressures on marine ecosystems has increased (Borgwardt et al., 2019; Knights et al., 2015) together with a better understanding of the dynamics of global patterns of human activities at sea (Allan et al., 2013; Halpern et al., 2019; Halpern et al., 2015). However, in light of increasingly rapid changes of direct and indirect pressures on biodiversity and ecosystem services, pathways towards a sustainable future still remain uncertain (Harrison et al., 2019; Lindegren et al., 2018; O'Neill et al., 2017). In particular, an improved detection of tipping points in social-ecological systems is key to prevent the coupled human-nature systems to shift into undesirable states (Bates et al., 2018; Hodgson and Halpern, 2019; Rilov et al., 2019).

Management frameworks exist that aim to explicitly avoid such undesired changes in marine socio-ecological systems. Marine ecosystem-based management (EBM) (Katsanevakis et al., 2011) or integrated marine management (Stephenson et al., 2019) can effectively inform policies to meet sustainable development goals. A sound understanding of cause-effect pathways describing the link from human pressures causing potential state changes of ecosystem components, processes or functions should form the backbone for such management frameworks (Stelzenmüller et al., 2018). Thus, despite uncertainty such a knowledge base can help to implement appropriate programs, measures, procedures, and control actions (Cormier et al., 2017; Stephenson et al., 2019).

Cumulative effects assessments (CEAs) aim to explore these causal pathways and should deliver advice for the implementation of management measures for human uses to maintain or restore ecosystem states while balancing conservation and restoration with social and economic objectives (Cormier et al., 2019). 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 (Jones, 2016). As a consequence, CEA results can, therefore, directly inform regulatory processes (Willsteed et al., 2017), marine spatial planning (MSP) (Liversage et al., 2019; Menegon et al., 2018; Stelzenmüller et al., 2010) or the implementation of environmental policies such as the European Union Marine Strategy Framework Directive (MSFD; EC, 2008/56/EC). Although the numbers of CEA case studies are increasing in the marine realm (Korpinen and Andersen, 2016; Menegon et al., 2018; Murray et al., 2015), the formal uptake of CEA results in management processes is yet to be evidenced (Willsteed et al., 2018).

Thus, this underlines the need on guidance and best practices for the operationalization of CEA in a management context. Stelzenmüller et al. (2018) suggested a risk-based CEA framework (dividing the process into risk identification, risk analysis and risk evaluation), which structures complex analyses and facilitates the establishments of direct science-policy links, highlighting the fact that CEAs should not only be scientifically driven (see also Cormier et al., 2018). By applying standardized risk analysis along with a unified glossary and terminology (Stelzenmüller et al., 2018; Appendix A), the framework outcomes should allow, independent of the context, to address the likelihood of exceeding accepted risk of ecosystem state changes together with the potential effectiveness of new management measures. Thus, this risk-based CEA framework can support the operationalization of CEA as a strategic tool in ecosystem-based management, being an integral part of the management process, where the roles of scientists and decision-makers are clearly defined.

Here, we shed light on the challenges and opportunities of the operationalization of such a risk-based CEA at different spatial scales and in diverse settings. We identified eleven case studies in Europe, French Polynesia, and Canada at local, sub-regional, and regional management scales. In each case study, we used the framework described by Stelzenmüller et al. (2018) to identify the main outcomes and challenges for a better uptake of CEA into management and decision-making. Furthermore, we developed and applied a structured evaluation of uncertainty in CEA outcomes and facilitated its application for management advice. Based on the here compiled knowledge base, we derived some key recommendations on how to overcome the main challenges for the operationalization of the risk-based CEA framework. Ultimately, these recommendations will help scientists and managers alike to foster the dialog between key players at the science-policy interface.

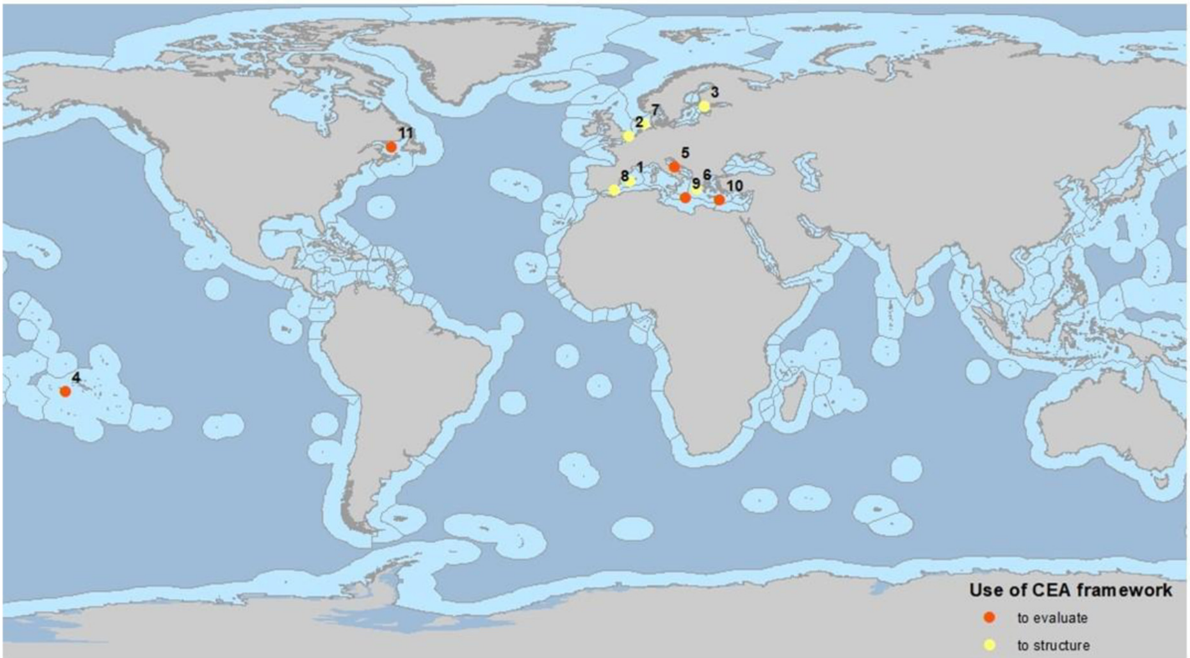
2. Comparative analysis of CEA case studies

The precondition for a case study to be included in our analysis was the capability to either conduct a risk based CEA or decompose an existing CEA with the help of the risk-based CEA framework. We primarily included CEA case studies that participated in the EU MARCONS program to account for the contrasting northern and southern European conditions. Furthermore, we enlarged the geographical scope and included the island of Moorea and the Gulf of St. Laurence cases since these cases add to the variation of context. Hence, we conducted a qualitative comparison among eleven CEA case studies (Fig. 1, Appendix A), which either used the risk-based CEA framework to structure a subsequent assessment or used it as a lens for evaluating existing CEA. For this we designed a standardized questionnaire containing thirteen open questions (see Appendix B), which were answered by each of the eleven case studies. In the following sections we present a synthesis of observed key outputs in relation to the context, knowledge, data, approaches, and outcomes of the case studies and provide corresponding recommendations and solutions to advance the operationalization of CEA.

2.1. CEA drivers and assessment endpoints

Our comparison revealed that in most of the cases, scientists had initiated CEAs with the aim of producing meaningful results to inform a respective management context. Thus, with only one exception, management bodies or governance institutions have not commissioned such an analysis as part of e.g. marine spatial planning process. Hence, only the Canadian case was initiated by a management body in the course of the implementation of an integrated management plan. Across case studies, the CEA management context spanned from regional policies such as the MSFD, marine spatial planning processes to sectoral regulations (Fig. 2). Based on the case studies, we also observed that targeted assessment endpoints were broad, and comprised of biological entities such as species (e.g. sea turtles, dolphins), ecosystem types (e.g. coral reefs), ecosystems state (e.g. ecosystem health), and ecosystem services (e.g. sustainable resource use) (Fig. 2). The diversity of assessment endpoints and assessment scales demonstrated clearly that the proposed risk-based CEA framework is flexible and context independent.

In addition to biological components, case studies also reported assessment endpoints in relation to the effectiveness of conservation and management measures such as marine protected areas. The capacity, functioning and the achievement of a Good Environmental Status (GES) of marine waters, as requested by the MSFD, was targeted by two case studies (see Fig. 2). These CEA examples integrated an ecological state assessment with an evaluation of cost-effective management processes. Thus, choosing GES as the endpoint of an assessment requires the consideration of policy context, thresholds, and ecological state assessment. Two case studies targeted the broader effects of sectoral plans of the energy sector. Another example from the Adriatic Sea highlighted that management needs to bring together not only the



ID	1	2	3	4	5	6	7	8	9	10	11
CS	Western Mediterranean	Belgian North Sea	Coastal Baltic Sea	Moorea French Polynesia	Adriatic Sea	Zakynthos MPA	German North Sea	Alboran Sea	Mediterranean LME	Aegean Sea	Gulf of St. Lawrence

Fig. 1. Spatial distribution of the eleven local, sub-regional and regional case studies applying the risk based cumulative effects assessment framework (Stelzenmüller et al., 2018) either to evaluate an existing CEA process or to structure a CEA. Note that the exact spatial expansion of respective case study area is not shown.

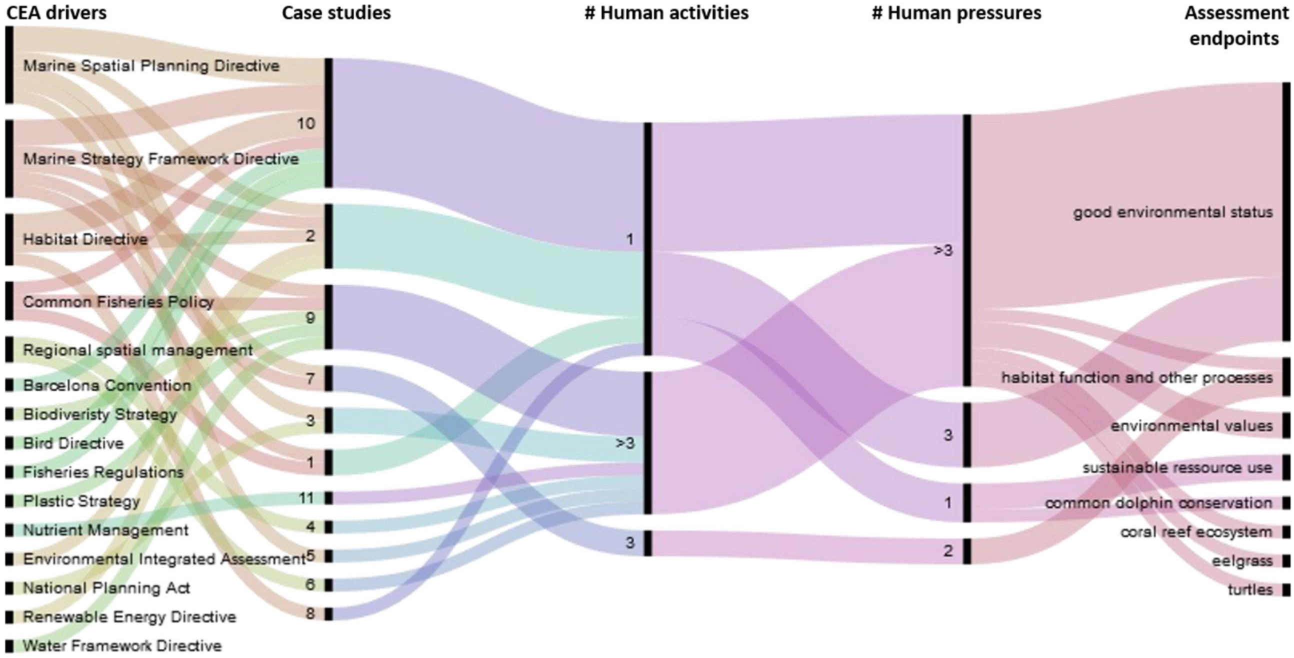


Fig. 2. Alluvial plot showing the frequencies of the relationships between the CEA drivers, number of human activities, pressures, and the assessment endpoints considered by the eleven cases studies . The width of the back nodes and colored lines is proportionally to the flow quantity (produced with RAWGraphs Visualization Platform; Mauri et al., 2017).

biological components and the relevant human pressures with their management measures, but also has to take into account the inherent complexity of the responsible authorities and sector policies (Gissi et al., 2017). The studied cases exemplified the breadth of the drivers for CEA, assessment endpoints and their envisioned strategic setting in specific management processes. This underlines the need for an integrative setting of the risk base CEA framework application between policy and science.

2.2. Establishing cause-effect pathways

Applying the risk-based CEA framework entails the initial establishment of the linkages between human activities, the corresponding pressure categories, and the effects on the respective ecosystem components, processes and functions (Stelzenmüller et al., 2018) (Fig. 3). As described by the framework this is part of the risk identification entailing also an assessment of the degree of spatial and temporal

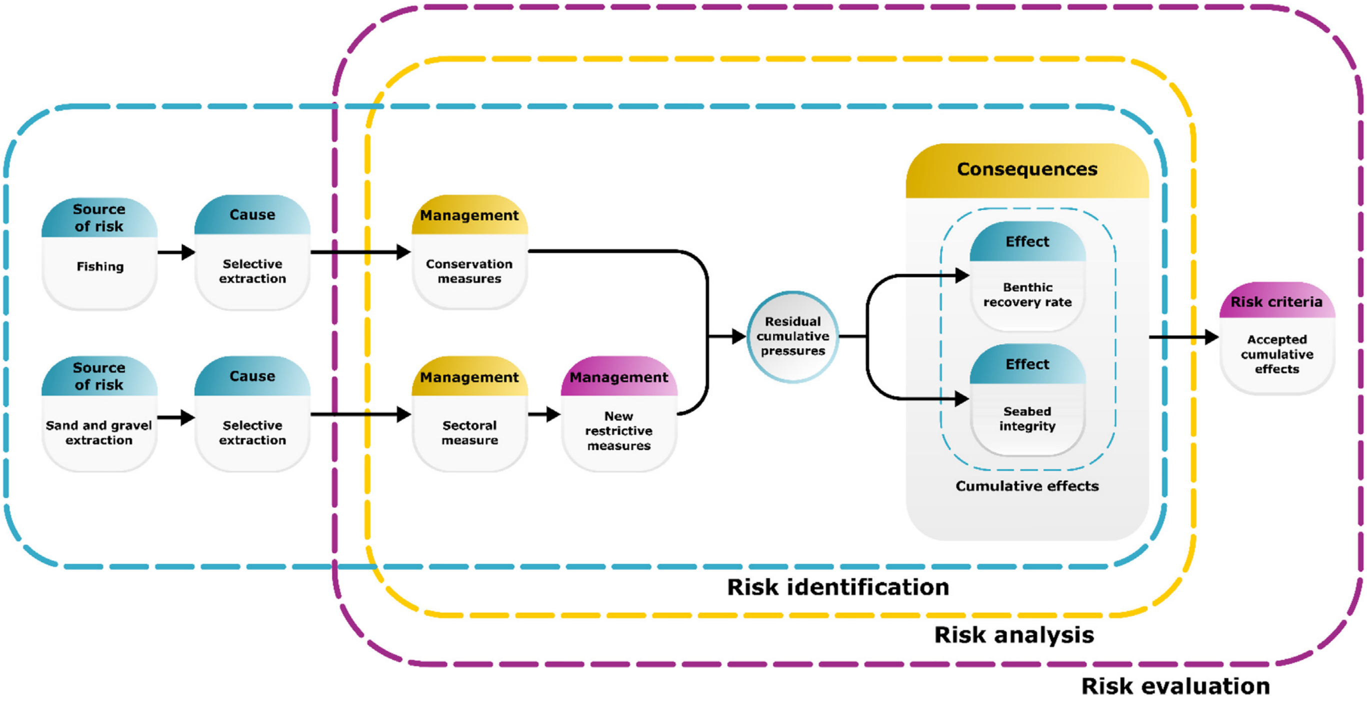


Fig. 3. General illustration of the elements and interlinkages of the steps of risk identification, risk analysis and risk evaluation. Two theoretical cause-effect pathways showing the links between two human activities (e.g. fishing and aggregate extraction), their common pressure (e.g. selective extraction), sector specific management measures (e.g. conservation measures, sectoral measure), cumulative residual pressures (total selective pressure load in the system despite management measures) and measurable state change of ecosystem components (e.g. benthic recovery, seabed recovery).

overlap of the assessment endpoint with a certain pressure. A generic pressure such as e.g. abrasion or siltation describes the actual mechanism of change or alteration to the ecosystem component (Elliott et al., 2017). Further, more than one human activity can cause the same type of pressure (Menegon et al., 2018). The general linkages between human activities and respective pressures is an established concept in environmental effects assessment (Borgwardt et al., 2019).

The total pressure load to which an ecosystem component is exposed to will contribute to its overall vulnerability. Vulnerability is a function of the exposure of the ecosystem component to a given pressure and the susceptibility of the ecosystem component to that specific pressure (Piet et al., 2015; Stelzenmüller et al., 2015a). The overall susceptibility or sensitivity of an ecosystem component to a pressure depends on its general resilience and adaptive capacity (Alliance, 2010). The assessment of vulnerabilities is the foundation for defining cause-effect pathways that in turn are necessary to prioritize human activities requiring regulation to prevent an increase of adverse effects on the system. As illustrated in Fig. 3, measurable cumulative effects are caused by the amount of pressures (referred to as residual pressures), that still exists despite management measures or restrictions implemented within management boundaries (Cormier et al., 2018). This implies that, those implemented measures can technically not reduce the pressure loads to levels, which are not causing adverse effects on ecosystem components. Despite differences in the definitions of vulnerability, we noted that this general concept has been embraced by most case studies. Further, we observed that all case studies identified general cause-effect pathways between an ecosystem component at risk and the respective pressures generated by human activities or at least identified the link to relevant human activities (see Fig. 2).

When establishing cause-effect pathways, case studies encountered difficulties with regard to both the quality of the human pressure data and the confidence in the assumed causality. For instance reported data gaps related to the description of ecosystem components and functions (e.g. species richness, pelagic compartment, benthic habitats, non-commercial species, movement patterns), occurrence of human activities (e.g. aquaculture and energy extraction plans) and their pressures (e.g., plastic pollution, noise, climate change). Furthermore, data limitations (e.g. water circulation, high resolution habitats, artisanal and recreational fisheries) held up the application of modelling tools and introduce uncertainty in the representability of data (e.g. available information not capturing well inter-annual variation or different spatial scales). In fact, reconciling data of different geographic scales (local to regional), seasonal dimensions (spawning, secondary production) and temporal resolutions (past and current dynamics) seemed to be the main challenge for most case studies. Further, several cases have been very explicit about data needs and identified knowledge gaps that should be addressed by future monitoring schemes, research programs and initiatives aiming to provide standardized and accessible data systems.

In addition, the consideration of connectivity among the terrestrial, freshwater and marine realms, and cross-realm pressures to ecosystems was also highlighted as a challenge due to data requirements from different sectors (e.g. agricultural use of pesticides and fertilizers). This underlines the recently described gap on knowledge and research on connectivity across realms (Pascual et al., 2016). Further, not including climate change was also mentioned frequently as an important limitation of CEA case studies contributing to the increase of uncertainties in the results. These observed challenges correspond well with recent work that highlighted that uncertainty in the data resolution on human-induced pressures can have significant effects on the interpretation of cause-effect pathways and respective vulnerability assessments (Amoroso et al., 2018; Stock et al., 2018).

The key requirements for establishing cause-effect relationships are knowledge on the causality and data to support such conclusions. Both aspects introduced uncertainties in the interpretation and communication of CEA results. However, uncertainty is part of any decision making process and therefore requires a transparent and explicit handling of knowledge and data. We developed and applied a confidence matrix that facilitates a general communication of uncertainty with regard to knowledge on the causality and quality of pressure data (Fig. 4). The four quadrants of the matrix allow for a quick ranking of the produced CEA outcomes in relation to their potential use in a specific management context. We work from the premises that science advice of a CEA that underpins a regulatory process requires the highest confidence, as opposed to scientific advice for policy processes (Fig. 4). There is a greater need for confidence in the established causal relationships between activity, pressure and effect at a regulatory process since this entails technical advice on how to regulate human activities or

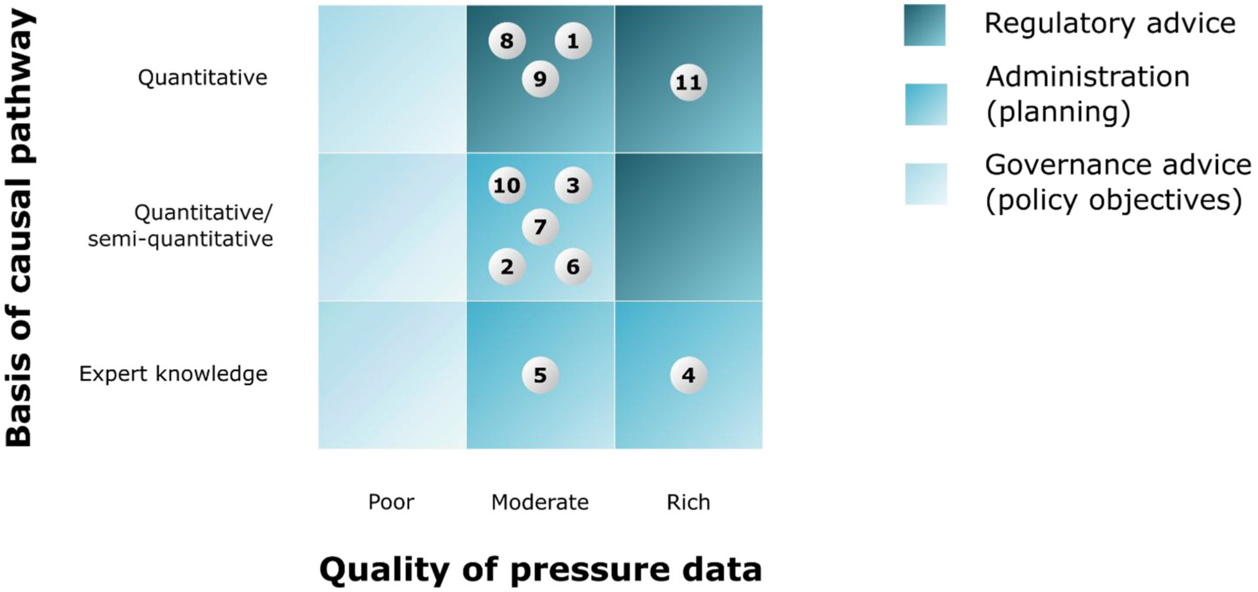


Fig. 4. Confidence matrix which ranks the quality of the pressure data as poor (spatiotemporal resolution showing a mismatch with spatiotemporal data on ecosystem components), moderate (spatiotemporal resolution showing a partial overlap with spatiotemporal data on ecosystem components), and rich (spatiotemporal resolution showing a sufficient overlap with spatiotemporal data on ecosystem components). Causal pathways can be derived from expert knowledge, semi-quantitative, or quantitative assessments; numbers correspond to the cases studies shown in Fig. 1.

requirements such as environmental quality standards. Less confidence may be sufficient in a marine spatial planning context when developing planning objectives for multiple activities. When data on pressures are of poor quality in terms of e.g. a mismatch between spatiotemporal resolutions of pressure and ecosystem components data, CEA outcomes should at most underpin strategic processes, such as the development of policy objectives. Hence, dark blue implies that a rather low level of uncertainty of scientific evidence should be provided to a regulatory process, middle blue implies that a medium level of uncertainty in scientific evidence could still underpin a planning process and that scientific results with a rather high level of uncertainty (light blue) would still be sufficient when advising the implementation of e.g. environmental policies. Fig. 4 shows how the eleven cases mapped their confidence across the quadrants. Interestingly, none of the cases studies reported a poor quality of human pressure data, indicating that most of the case studies can inform spatial planning processes.

2.3. Understanding the need of risk criteria

We noticed that most case studies were confined to the risk identification stage, where the human activities, their pressures and the respective vulnerable ecosystem components are being described. This is also in accordance with the majority of the CEA published over the last years (Korpinen and Andersen, 2016; Menegon et al., 2018; Murray et al., 2015), which mainly identified priority areas of concern for management processes. However, from the risk-based CEA framework perspective, all these cases were missing the essential ingredients that allow moving from risk identification to the analysis of effectiveness of management measures and then risk evaluation processes. Hence, they were missing the identification of the level of risk of adverse effects that would be tolerated in a given management setting. The tolerated risk should be reflected in risk criteria, such as definitions of effect sizes (e.g. defining the degree of change of an ecosystem state due to a certain amount of exposure) or thresholds in relation to acceptable levels of pressures remaining within management boundaries after considering existing management measures (see also Fig. 3). Risk criteria should not only define different levels of ecosystem state change, they should also enable assessing in the risk evaluation the overall risk of not achieving policy objectives. Hence, the CEA should be founded on established risk criteria reflecting the selected policy objectives to maximize the advice a CEA can deliver in the management process. Further, in alignment to the procedures of classical risk assessments, risk criteria should be developed prior to initiating the CEA within the context and the scope of the policies involved and in consultation with stakeholders (Rozmus et al., 2014). Without risk criteria individual personal objectives and values become the basis of debate of what is risky given the different perceptions of the level of risk and individual tolerances to risk when making a decision (Cormier and Londsdale, 2020).

We found that, in general, case studies responded to national policies, informed marine spatial planning processes and have been well framed in the context of regional policies (Fig. 2). Some cases referred to the European Blue Growth policy (Buhl-Mortensen et al., 2017) and designed the CEA to assist the allocation of new uses while managing conflicts between them, and between uses and the environment, according to the MSP Directive (EU, 2014/89/EU). However, most of them did not mention specific risk criteria.

2.4. Accounting for the effectiveness of management measures and trade offs

Risk analysis means determining the actual consequences of cumulative effects; thus the consequences that will occur when a state change of an ecosystem component, function or process has occurred. This entails an analysis of the effectiveness of management measures that exist to regulate the pressures (Fig. 3). The case studies showed that with only a few exceptions, the existence and effectiveness of management measures have not been considered as part of the CEA (Appendix A). Further, we detected quite some confusion across case studies on how to assess the effectiveness of management measures and how to incorporate it within the respective studies. One exception is the Western Mediterranean case study, which did consider the effectiveness of management measures. With a help of an ecosystem model the effects of different management measures were tested. Those management measures corresponded to categories of marine protected areas reflecting different levels of protection (Horta e Costa et al., 2016). The assessment of potential management measures revealed that only a high level of protection will likely be effective in achieving management objectives (Zupan et al., 2018).

A few case studies also mentioned the importance to acknowledge the complex social-ecological dimensions in a CEA, hence pointing to the fact that conflicts and trade-offs between human activities need to be analyzed in relation to the risk of cumulative effects. Hence, trade-off analysis might need to consider both positive and negative effects of pressures since some human activities may counter-balance the effects of pressures, while others may amplify them. Mechanistic models can be used to quantitatively identify such trade-offs (Christensen and Walters, 2004; Coll et al., 2008).

When cumulative effects are occurring in a given area, there are several factors at play that cannot be managed by measures taken locally. Hence, cumulative effects can also be driven by natural variability, the effect of climate change or pressures that are generated from outside the planning or management area. In the latter case, regulatory options that can address these external factors require cross-jurisdictional or cross-boundary coordination in the implementation of management measures to reduce the pressures in each jurisdiction equivalently. This makes a strong case for the recognition of climate change induced effects and their contributions to cumulative effects in regulatory frameworks for human activities and their pressures. This comprises the consideration of such external effects in marine spatial planning processes, therefore complementing conservation and restoration efforts.

Other aspects concerning the assessment of the effectiveness of implemented measures is the level of conformity to the implementation specification of the measure, the compliance of those that have to implement the measures and the reliability of the measures to perform adequately over time (Cormier et al., 2019). Due to the lack of studies and research designed to determine by how much a given measure contributes to the reduction of a specific pressure, the quantification of effectiveness remains challenging.

An analysis of the effectiveness of management measures should allow defining the amount of residual pressure as an undesirable outcome of a measure or measures (e.g. level of contaminant reduction in an effluent, the reduction of the spatial extent or frequency of sedimentation, etc.). From a methodological perspective, for instance, modelling tools can be used to simulate different levels of effectiveness of an action linked to different pressure levels and compare prediction with observational data (Coll et al., 2008; Piroddi et al., 2015). Further, Cormier et al. (2018) presented a modelling framework which permits to quantify the residual pressure and how it contributes to the management effectiveness. A sound understanding of the cause-effect pathways should then help assessing the contribution of the reduction of the pressure to achieve the desired ecosystem state.

2.5. Providing scientific evidence for risk evaluation

The risk-based CEA framework considers risk evaluation as a process where management and stakeholders evaluate what could be done to reduce the detected risks of cumulative effects. In the risk evaluation step the decision is taken to maintain or improve existing measures or implement additional ones. Hence, the decision in risk evaluation is about choosing the management strategy that would reduce the risks as low as reasonably practicable given that risk can never be zero (Baybutt, 2014). Risk evaluation is where the results of the risk analysis are brought into the policy realm of decision-making, which is actually the interface between the science and the policy (Cormier et al., 2018). Up to this point, risk identification and risk analysis have primarily a scientific and technical role in the provision of independent scientific advice without any value judgement such as e.g. "serious", "harmful", "impacting" or "severe" (Fig. 5; left). Thus, only the levels of the likelihood of the effect occurring and the magnitude of consequences are discussed in relation to the source of the risk, as outlined by the cause-effect pathways. In risk evaluation, the scientific advice is provided to the managers and stakeholders to underpin their decisions as to what to do in terms of management measures required to reduce the risk considering the severity of those risks. Given that visualization is a key communication tool to non-technical managers and stakeholders (Stelzenmüller et al., 2018), risk matrices are typically used in risk evaluation as a graphical representation of the likelihood and consequence combinations that are less to more tolerable given the policy context (Cormier and Londsdale, 2020). In risk evaluation, tolerable refers to the likelihood or risk of not achieving stated management objectives. Hence, it is important to note here that the use of such matrices goes beyond the simple identification of the severity of the risk as commonly presented in ecological risk assessments (Astles and Cormier, 2018). As shown in Fig. 5, in a CEA context risk matrices should show how the combinations of the levels of the likelihood of the effect of cumulative residual pressures occurring and the severity of consequences are mapped to different risk tolerance levels (e.g. high, moderate, low). In the examples of Fig. 5, the likelihood of the consequence of the existing management measures (P_{EM}) is compared to the likelihood of the consequence for the proposed improvements to existing measures (P_{EP}). Thus, improvements and additional measures should reduce the likelihood of the cumulative residual pressures and/or the severity to a level that is tolerable in terms of reaching stated objectives given the scientific, management and operational uncertainties. The different color scheme of the three example matrices simply reflects different levels of risk tolerance by the managers. For instance, there are more red boxes for cases of low tolerance to risk compared to matrices reflecting higher tolerances. This requires prior definitions; red could mean that the likely consequences are not tolerable because the management measures are not effective enough to reach defined objectives, while orange or yellow could mean that there are uncertainties as to whether management measures will lead to the achievement of targets, which would imply for instance extensive monitoring and review. Finally, green would imply that the management measures are considered effective in the sense that policy objectives would be reached. Matrices should avoid using qualifiers such as high, medium or low or 1, 2, 3 because they do not explicitly convey the severity of the risks to managers and stakeholders (Baybutt, 2018). If the risk of cumulative residual pressures is assessed for more than one assessment endpoints (e.g. species, functions, processes), each causal concern should also have its own matrix because decisions regarding such risks would weight different combinations of likelihood and consequences.

Given the iterative aspects of CEA, decision makers, managers and stakeholders could submit new management options to risk analysis that would then be analyzed by scientific and technical experts. As explained above, technically, scientists should not be part of the risk evaluation, but in practice, they are often consulted when it comes to actual decision making. Across our case studies, we identified examples where there have been processes to clarify the roles of science and management (e.g. Gulf of St. Lawrence case study) up to cases where roles have been mixed. Therefore, scientists should be prepared to develop and deploy tools in risk identification and risk analysis to determine the effectiveness of various management options. In risk evaluation, scientists can only provide insight into uncertainties and assumptions involved in determining the likely consequences of various management scenarios. The decision about the tolerability of the risks not to meet the objectives should be left to the decision-makers, managers and stakeholders during the risk evaluation phase. Some ready to use tools to provide informative results to managers and to help them find alternatives or information about risk already exist (Stelzenmüller et al., 2018). This is linked to the "being proactive" in the assessment of alternative scenarios of management advice and "being prepared" to present results in a science-policy context.

3. Unfolding uncertainty in CEA

The spatial and temporal distribution of ecological components, multiple pressures operating at various scales, their potential effects upon assessment endpoints, and the effects of proposed management actions are fundamental pieces of information for a CEA. Like in any environmental impact assessment, many assumptions and predictions have to be made, thus making it difficult to estimate the overall uncertainty of the analysis outcomes (Tenney et al., 2006). Hence, considering and treating the uncertainty that is inherent to the various steps of an environmental impact assessment is critical for conveying a comprehensive understanding of the limitations and accuracy of the generated outputs. Towards this direction, previous studies (Gissi et al., 2017; Stelzenmüller et al., 2015b; Stock and Micheli, 2016) offered insights on the potential sources of uncertainty linked with causality and data, and proposed technical solutions on how to deal with it.

Apart from dealing with uncertainty in risk identification and risk analysis, it is also critical to disclose the degree and sources of uncertainty associated with risk evaluation process. In risk evaluation as described above, proposed management actions are contrasted to the likelihood of achieving policy objectives. Here an additional layer of uncertainty is introduced, which could influence the transparency

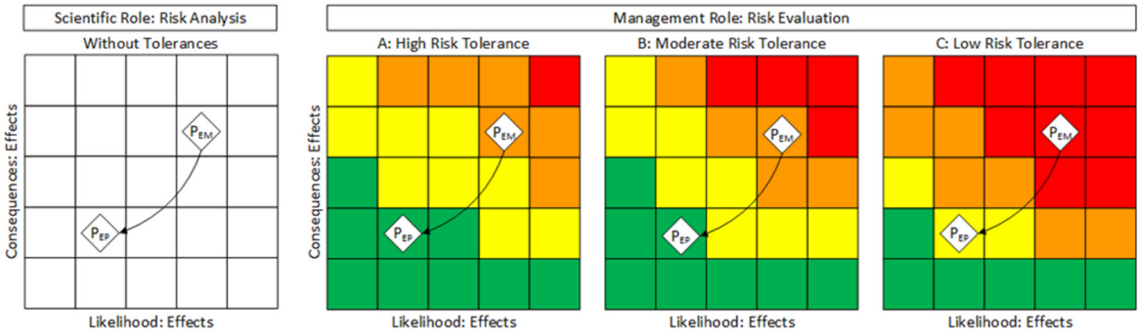


Fig. 5. A risk matrix without tolerance levels (left) derived from the results of the risk analysis of the effectiveness of the management measures in contrast to risk matrices colored by the tolerance levels in risk evaluation (right). The existing management measures (P_{EM}) are compared to the likelihood of a given consequence for the proposed improvements to existing measures or additional measures (P_{EP}).

throughout the decision-making process and therefore affect capitalization of the outputs (Leung et al., 2015; Tenney et al., 2006) .

From our case studies, we observed that many cases acknowledged uncertainty, but often in an unstructured fashion. Only for the Adriatic case a substantial effort was undertaken to transparently assess uncertainty (Ansong et al., 2017). In an attempt to unfold the dimensions of uncertainty associated to the risk-based CEA framework and to offer a systematic guidance for improving the treatment of uncertainty, we followed the approach presented in Ansong et al. (2017) and Gissi et al. (2017) and elaborated a Walker-type matrix (Walker et al., 2003). We defined a total of eight uncertainty descriptors: context uncertainty, cause-effect model uncertainty, data input uncertainty, statistical uncertainty, scenario uncertainty, recognized ignorance, epistemic or knowledge-related uncertainty and inherent variability (Table 1 and Appendix C). These descriptors represent uncertainty in a structured way, synthesize sources, causes and needs across the three dimensions: location, level and nature (Walker et al., 2003). Such a comprehensive reporting of uncertainty allows for a better understanding of the overall level of uncertainty associated with the assessment outcomes and is key for an informed decision-making.

We found a great variation of sources of uncertainty across the eleven CEA cases (Appendix C). Hence, we often observed that policies and measures that were identified in the CEA context setting could often not be translated into clear operational objectives with explicit criteria and targets. Comparing the eleven cases showed that the efficiency and adequacy of policies and measures identified at local (e.g. through the managing authority responsible for the protection of sea turtle nesting habitats), national (e.g. Belgium national policies on blue growth and offshore renewable sources) or international scales (e.g. the CFP and the MSP in the case of fisheries in the western Mediterranean or as the potential determinants for protecting habitats and key ecosystems in the Adriatic-Ionian sea) were often defined both as the assessment endpoints and uncertainty of the case study context.

Factors contributing to the uncertainty of the cause-effect modelling processes include the limited knowledge of the spatiotemporal dynamics of ecological processes, the lack of a precise understanding of the mechanism of cumulative effects (e.g. additive, synergistic or antagonistic), and the gaps and incomplete information on the distribution, dynamics and magnitudes of pressures. To overcome these gaps, inputs have been generated from models, expert assessments, and extrapolations from patchy datasets. In some cases, efforts have been made to statistically quantify uncertainty by using sensitivity analyses (Ansong et al., 2017) or by incorporating variability to ensure that model structure is adequate, such as in the Western Mediterranean case. Still, in many of the case studies a further exploration and description of sources of uncertainty through e.g. statistical tools was missing. In relation to scenario uncertainty, identified sources of uncertainty comprised the management measures tested and the magnitude of their future effectiveness and reinforcement. Following the complexity of ecological, environmental and social-political dimensions involved in the CEA process and the focus and spatial scale of the cases, contributors identified uncertainty, which they did not further address. Examples of such recognized ignorance included the spatio-temporal variability of different pressures (e.g. noise pollution, fishing pressure, tourism activities) but also the cumulative effect of invasive species and climate change. Therefore, environmental variability, the multi-dimensional interactions at the ecosystems level or complex ecosystem responses due to climate change reflect sources of uncertainty that are often acknowledged, but rarely defined, quantified or addressed.

4. Recommendations for CEA operationalization

From our CEA case study comparison and analysis, we derive four key recommendations to strengthen the implementation of CEA into management through a risk-based CEA framework:

1) *Framing the context and setting risk criteria* – The operationalization of a CEA requires a well-framed context comprising the identification of the drivers, management objectives, and targets. In the absence of clear objectives that address the avoidance or mitigation of cumulative effects, the CEA process should still formulate or lay out the aspired objectives regarding the tolerance of cumulative effects. Only then, risk criteria can be defined. Risk criteria need to be set prior to the assessment, which requires the involvement of stakeholders and decision-makers.
2) *Defining the roles* – Throughout a CEA a clear separation and allocation of the roles and expected tasks of decision makers, various stakeholder groups and scientists is fundamental. This helps to build trust when sharing and interpreting data and knowledge.
3) *Reducing and structuring complexity* – CEAs are context-dependent, resource intensive and complex. There are unavoidable trade-offs among the level of complexity, available resources and timelines, but they should be reached in a transparent and well documented manner, as cause-effect pathways have to be assessed for each identified link between human activities, pressures, and assessment endpoints.
4) *Communicating assumptions and uncertainty* – A cross-cutting issue in successful CEAs is a clear communication of assumptions made throughout the process and types and levels of uncertainty. Emphasis should be put on the selection of tools to present the different dimensions of uncertainty, which accumulates along a CEA process.

5. Conclusions

Our analysis of the context, approaches, and implementation of eleven CEA case studies, which aligned their analyses or evaluation to a risk-based CEA framework, revealed the large variation in CEA drivers, objectives and assessment endpoints. A single recipe on how to conduct a CEA does not exist, but the application of a standardized framework facilitated a consistent and coherent comparison of the key issues to operationalize such complex assessments. Here we underline the urgent need to differentiate CEA in light of the different clients or processes such as governance advice, marine spatial planning or regulatory advice. Thus, laying out the context, assessment objectives and criteria, and roles of those involved, is fundamental to allow for the take up of CEA outcomes in management processes. We suggest that future CEAs should move towards this direction to maximize the advice a CEA can provide in an EBM context. Further, we conclude that it is crucial to communicate uncertainty throughout the various assessment steps in a transparent and structured manner, which helps build confidence and trust in the derived scientific evidence. One of the reasons why CEA have not been formally operationalized yet is their complexity and limitations of knowledge and evidence and the difficulty in identifying which human activity and pressure should be reduced. Applying the risk-based CEA framework together with a strategy of communicating uncertainty should help to overcome bemoaning of imperfect knowledge on the sensitivity of ecosystem components to distinct pressures, and embrace uncertainty around the scientific evidence. Our results underlined the need for further research on the effectiveness of management measures to improve current practices or to develop new ones to reduce the effects of specific human activities. Finally, risk evaluation comprises trade-off analysis of the cost and benefits of additional management measures. Here the final decision on management strategies should be left to the decision makers; scientists should only provide technical advice to such a process. We postulate that if the description and quantification of uncertainty and trade-offs becomes a routine in CEA, then decision makers will more likely understand the potential repercussions of their decisions. In summary, our study makes a strong case that CEA should be well framed and recognized as cross-cutting tools that could bridge different management objectives. We acknowledge that

Table 1
We developed a Walker-type matrix (Ansong et al., 2017; Gimpel et al., 2015; Walker et al., 2003) with eight uncertainty descriptors: context uncertainty, cause-effect model uncertainty, data input uncertainty, statistical uncertainty, scenario uncertainty, recognized ignorance, epistemic or knowledge-related uncertainty and inherent variability. This allows assessing the dimensions of uncertainty associated to the risk-based CEA framework and offers a systematic guidance for improving the treatment of uncertainty.

Uncertainty dimensions	Location - identifies where uncertainty establishes within the methodological approach applied for the risk-based CEA. Location can refer to the context, model and input			Level - encompasses statistical uncertainty, scenario uncertainty and recognized ignorance			Nature - the nature of uncertainty can be distinguished as knowledge related and variability related uncertainty	
Uncertainty descriptors	Context	Cause-effect model	Input	Statistical uncertainty	Scenario uncertainty	Recognized ignorance	Knowledge related	Variability related
	Policy drivers for CEA (e.g. problem framing stage or boundaries determined by policies, legislations) and defined risk criteria (i.e. benchmarks) against which the evaluation of cumulative effects is being performed	Uncertainty in assessing cause-effect pathways can relate to (i) the description of causal relationships, (ii) externalities outside the CEA context	The data input relates to pressures and their related effects. It also comprises the data used for assessing the effectiveness of management measures	Uncertainty that can be statistically quantified	The range of possible outcomes of the management measures being considered to reduce pressures and the risk of cumulative effects	A fundamental uncertainty about the mechanisms and functional relationships considered in the CEA	Uncertainty which refers to the imperfection of knowledge; which may be reduced by conducting more research	Uncertainty related to the variability inherent in the studied system

resolving mismatches in governance structures takes time and is often difficult, but we suggest that CEA can be one strategic approach to integrate ecosystem management considerations across multiple sectorial policies.

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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