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Operationalising risk-based cumulative effect assessments in the marine environment

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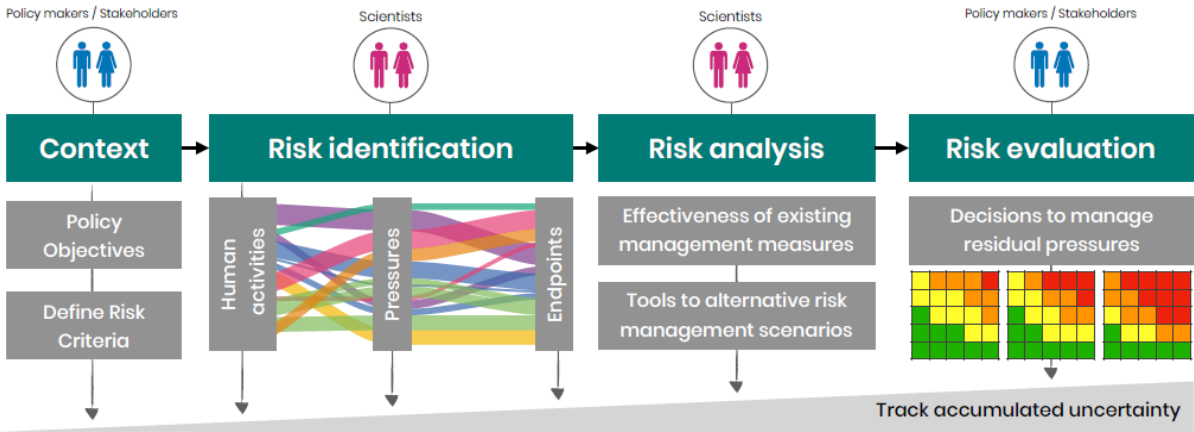
Abstract

Ecosystem-based management requires cumulative effect assessments. However, how those assessments should be operationalised and integrated into decision-making processes still lack a comprehensive and transparent framework. A risk-based cumulative effect assessment (CEA) framework (dividing the process into risk identification, risk analysis and risk evaluation) could structure complex analyses of XXX and facilitate the establishments of direct science-policy links. Here, we shed light on the current operationalisation of such a risk-based CEA framework at different spatial scales and in diverse settings. Using 11 case studies in Europe, French Polynesia, and Canada at local, sub-regional, and regional management scales, we show that a single recipe on how to conduct a CEA does not exist, but the application of a standardised framework facilitates a consistent, coherent, and transparent comparison of the key issues to operationalise such complex assessments. We illustrate the large variation in CEA drivers, objectives, and assessment endpoints. We identify four key recommendations to better strengthen the implementation of CEA into management: 1) Framing the context and setting risk criteria; 2) Defining the roles; 3) Reducing and structuring complexity; 4) Communicating assumptions and uncertainty. We reveal the need for more research on the effectiveness of existing management measures to improve these measures or the development of new ones to reduce the cumulative effects through the reduction of pressures generated by individual activities. Key to the whole process is to consider that the risk evaluation comprises a trade-off analysis of the cost and potential benefits of alternative or additional management measures, which should be clearly separated from the provision of technical advice by scientists. Our study makes a strong case that CEA should be well framed and recognised as a cross-cutting tool that could bridge different management objectives and could be a strategic approach to integrate ecosystem management considerations across multiple sectorial policies.

Highlights

- How to bridge the gap between theory and practice in ecosystem-based management
- Well-structured CEAs is a solution for effective EBM
- 11 case studies demonstrate a large variation in CEA drivers, objectives, and assessment endpoints
- Framing the CEAs context and risk criteria, and defining clear roles are recommended for larger impact
- Reducing/structuring complexity and communicating uncertainty are essential for CEAs

73 **Graphical abstract**



1. Introduction

Over the last decade scientific effort on the categorization and description of human pressures on marine ecosystems has increased (Knights et al. 2015, Borgwardt et al. 2019) leading to a better understanding of the globally increasing footprint and intensity of human activities at sea (Halpern et al. 2015). However, in front of increasingly rapid changes in direct and indirect pressures on biodiversity and ecosystem services, pathways towards a sustainable future still remain uncertain (Lindegren et al. 2018) {O'Neill, 2017 #370; Harrison, 2019 #371}. In particular, better detecting the risk of current and future changes of social-ecological systems is key to prevent the coupled human-nature systems to shift into undesirable states (Bates et al. 2018, Rilov et al. 2019) (Hodgson and Halpern 2019).

In marine social-ecological systems, management frameworks exist that aim to explicitly avoid undesired changes in the coupled systems. Marine ecosystem-based management (EBM) (Katsanevakis et al. 2011) and integrated marine management (IMM) (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 decision making in EBM or IMM (Stelzenmüller et al. 2018) and 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, 2019 #339;Cormier, 2019 #342}. 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). As a consequence, CEA results should therefore directly inform regulatory processes (Willstead et al. 2017), marine spatial planning (MSP) (Stelzenmüller et al. 2010, Menegon et al. 2018, Liversage et al. 2019) or the implementation of environmental policies such as the European Union Marine Strategy Framework Directive (MSFD 2008/56/EC). Although the numbers of CEA case studies are increasing in the marine realm (Murray et al. 2015, Korpinen and Andersen 2016, Menegon et al. 2018), the formal uptake of CEA results in management processes is yet to be evidenced (Willstead et al. 2018).

Therefore, the operationalisation of CEA should be facilitated. 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, 2018 #327}. By applying standardized risk analysis along with a unified glossary and terminology, the framework outcomes should allow, independent of the context, addressing the likelihood of exceeding accepted ecological threshold and the 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 EBM, 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 operationalisation 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 applied 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 provide some tailored tools that allow for the evaluation of the uncertainty around CEA assessment results and facilitate the use of CEA outcomes for management advice. Based on the here compiled knowledge state, we derived some key recommendations on how to overcome the main challenges for the operationalization of the risk-based CEA framework. Ultimately, those should help scientists and managers alike to foster the dialog between key players at the science-policy interface.

2. Comparative analysis of CEA case studies

We conducted a qualitative comparison among eleven CEA case studies (Figure 1, Appendix 1), which either used the risk-based CEA framework to structure an assessment or used it as a lens for evaluating existing CEA. We therefore designed a standardised questionnaire containing thirteen open questions (see Appendix 2), which were answered for each of the eleven case studies. In the following sections we present a synthesis of observed key outputs in relation to the context, knowledge and data, approaches, and outcomes of the case studies and provide corresponding recommendations and solutions to advance the operationalisation of CEA.

2.1. CEA drivers and objectives

With one exception, all case studies reported that CEAs were not commissioned by management bodies, but had rather been initiated by scientists with the aim of producing meaningful results to inform a

respective management context. 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 targeted management context spanned from implementation of regional policies such as the European MSFD, Marine Spatial Planning (MSP) to sectoral regulatory processes and regional spatial management plans (Figure 2). The selection of the general management goals or policy objectives determined the ecosystem components, functions and processes for which the assessment of cumulative effects was conducted. Based on the case studies, we also observed that targeted assessment endpoints were broad, and comprised 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) (Figure 2).

This diversity in assessment targets and assessment scales demonstrated clearly that the proposed risk-based CEA framework is flexible and can be applied in different contexts. Further, the studied cases exemplified the breadth of both assessment objectives and their strategic setting within specific management processes, thus underlying the integrative setting of the framework between policy and science.

As opposed to biological components, case studies reported also assessment targets 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 in two additional case studies (e.g. Aegean, Med LME). These are CEA examples where an ecological assessment was integrated with the evaluation of cost-effective management processes. 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 (e.g. Belgian North Sea). Another example showing that sector management needs to bring together not only the 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 (e.g. Adriatic Sea, see {Gissi, 2017 #304}{Cormier et al. 2019}).

2.2. Establishing cause-effect pathways

Applying the risk-based CEA framework entails the 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) (Figure 3). Hence, well-established

cause-effect pathways play a central role enabling the identification of key activities that need to be regulated to prevent an increased impact on the system. It is important to understand that a pressure such as abrasion or siltation can be caused by different activities (Menegon et al. 2018) {Knights, 2015 #322} and that the pressure describes the actual mechanism of change or alteration to the ecosystem component (Elliott et al. 2017). Thus, the general linkages between human activities and respective pressure characteristic is an established concept (Borgwardt et al. 2019) when aiming to assess environment effects. Measurable cumulative effects are caused by the amount of pressures (referred to as residual pressures, see Figure 3), which still exists despite the implemented management measures or restrictions (Cormier et al. 2018). This implies that, depending on the human activities and type of measures, employed measures could be technically not capable and/or not effective enough at reducing the pressure loads to levels, which are not deemed to cause adverse effects on ecosystem components.

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 Figure 2). The total pressure load to which an ecosystem component is exposed to will contribute to its overall vulnerability. Therefore, vulnerability estimates are a result of the exposure of the ecosystem component to a given pressure and the sensitivity of the ecosystem component to that specific pressure (Piet et al. 2015, Stelzenmüller et al. 2015). We noted that this general concept of vulnerability has been embraced by most case studies. In other cases, environmental vulnerability profiles were e.g. calculated as an aggregated product of the distribution of essential nature values (habitat-forming benthic macroalgal and invertebrate species, benthic species richness, birds and seals as top marine predators) and their sensitivity to disturbances (Aps et al. 2018).

One of the key issues encountered by case studies in relation to the establishment of the cause-effect pathways were limitations with regard to both the quality of the human pressure data and the confidence in the assumed causality. Reported data gaps related to ecosystem components and functions (e.g. species richness, pelagic compartment, benthic habitats, non-commercial species, movement patterns), data to develop modelling tools (e.g. water circulation, high resolution habitats, artisanal and recreational fisheries), data on emergent activities (e.g. aquaculture and energy extraction plans) and pressures (e.g., plastic pollution, noise, climate change) or 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 with regard to data needs and identified knowledge gaps that should be addressed by future monitoring schemes, research programs and initiatives aiming to provide standardised 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 fertilisers). This underlines the recently described gap on knowledge and research on connectivity cross-realms {Giakoumi, 2019 #372}. 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).

Working from the basis that uncertainty is part of any decision making process, and that it is key to deal with uncertainty in a transparent and explicit manner in terms of the knowledge and data available in risk identification, we developed a confidence matrix which facilitates a general communication of uncertainty at this step (Figure 4).

Science advice of a CEA that underpins a regulatory process requires the highest confidence, as opposed to scientific advice of CEA that supports policy processes (Figure 4). Hence, 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 requirements such as environmental quality standards. Less confidence may be sufficient in a marine spatial planning context when developing planning objectives for multiple activities. Here the confidence in estimated ecosystem vulnerabilities forms the basis to identify the cumulative pressures that need to be addressed through for instance a regional planning process. The matrix adopts the above rationale and recognises the importance of human pressures data. It indicates that 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 rather underpin strategic processes e.g. such as the development of policy objectives. The eleven cases applied the confidence matrix and the aggregated results are shown in Figure 4. Interestingly, none of the cases except for the Mediterranean LME case study reported a poor quality of human pressure data, indicating that most of the case studies should be geared to advice e.g.

MSP processes. Hence, communicating the aggregated uncertainty should help building trust and allowing to move towards a more transparent and informed decision-making process.

2.3. Understanding the need of risk criteria

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 (Murray et al. 2015, Korpinen and Andersen 2016, Menegon et al. 2018), which mainly identified priority areas to be of concern for management processes. However, from the risk-based CEA framework perspective, all these scientific initiatives were missing the essential ingredients that allow moving from risk identification to the analysis of effectiveness of management measures to feed this advice in risk evaluation and risk treatment processes. Hence, they were missing the identification of risk that would be tolerated.

To maximize the advice a CEA can deliver in the management process, the assessment should be founded on established risk criteria reflecting the selected policy objectives. This is key to transparently set the scope and context for the assessment, while delineating the level and resolution of information needed to define cause-effect relationships. 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). Thus, risk criteria should be used to express different levels of state change and the overall risk of not achieving policy objectives. Both need to be specified in relation to the identified management goals or policy objectives addressing ecosystem components, functions and processes. We found that, in general, case studies responded to national policies, informed MSP processes and have been well framed in the context of regional policies (Figure 2). Some cases referred to the European Blue Growth policy {EU, 2017 #374} 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 #136}. However, most of them did not mention specific risk criteria in terms of 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 Figure 3). Examples of defined risk criteria can be found in Gimpel et al. (2013) or Cormier and Lonsdale (2019). The former is an example for a semi-quantitative case where exact thresholds were not known but the acceptable risk for an ecosystem component had been predefined

along clear criteria. A prerequisite for doing this is to well define the CEA context and the policy objectives that are being addressed. 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 Lonsdale (2019) (IEC/DIS, 2017)).

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 (Figure 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 2). Further, we observed 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, which considered the effectiveness of management measures. In this case, simulations of an ecosystem model were used to vary the levels of protection of different marine protected areas located in the study area. The case study used a marine protected area classification introduced by Horta e Costa et al. (2016), which classifies marine protected areas according to the impacts of species and habitats the uses allowed within their boundaries can have. Out of the five classes, only the two more strictly protected prove to be effective (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 analysed in relation to the risk of cumulative effects. Hence, trade-off analysis might need to consider both positive and negative effects of (cumulative) 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. Cumulative effects can also be related to natural variabilities, 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 often require cross-jurisdictional or cross-boundary coordination in the implementation of management measures that can reduce the pressures in each jurisdiction equivalently. This makes a strong case for the recognition of

e.g. climate change induced effects and contributions to cumulative effects in regulatory frameworks for human activities and their pressures (e.g. limits to spatial use of an activity such as spatial allocation for specific types of fishing gear or where dredging spoils can be disposed). This also requires the consideration of such external effects in marine spatial planning processes, therefore complementing conservation and restoration efforts. The effectiveness of the implemented measures is also influenced by 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. 2018; Cormier et al. 2019). Due to the lack of studies and research designed to determine by how much does a given measure contribute to the reduction of a specific pressure the quantification of effectiveness remains challenging. This is why the residual pressures remaining in the system after the implementation of a measure, or a suite of measures to manage specific human activities, can be considered as a metric of measures' effectiveness (REF). An analysis of the effectiveness of management measures must be able to characterize 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, 2015 #373). Further, Cormier et al. (2018) present a modelling framework which allows to quantify the residual pressure and how it contributes to the management effectiveness. A sound understanding of the pressure-state relationship should then help assessing the contribution of the reduction of the pressure to achieve the desired environmental 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. Risk evaluation is where the decision is taken to maintain or improve existing measures or implement additional ones. In other words, 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 is primarily a scientific and technical role in the provision of independent scientific advice without any value judgement such as "serious", "harmful", "impacting", "severe", etc. (Figure 5; left). Thus only the levels of the likelihood of

the effect occurring and the severity 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 Lonsdale, 2019). 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 Figure 5, in a CEA context risk matrices show the combinations of the levels of the likelihood of the effect of cumulative residual pressures occurring and the severity of consequences are mapped to three different risk tolerance levels (high, moderate, low). In the examples of Figure 5, the likelihood of the consequence of the existing management measures (EM) is compared to the likelihood of the consequence for the proposed improvements to existing measures (PM). 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 colour scheme of the three matrices simply reflects different levels of risk tolerance. 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 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 many ecosystem components (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, managers and stakeholders could submit new management options to risk analysis that would then be analysed 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. Canadian CS) 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 provide insight into uncertainties and assumptions involved in determining the likely consequences of various management scenarios leaving the decision about the tolerability of the risks not to meet the objectives to the managers and the 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 be ready to present results in a science-policy context.

3. Unfolding uncertainty in CEA

The spatial and temporal distribution of ecological components, the causalities of 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. Throughout any environmental impact assessment, including CEA, many assumptions and predictions often take place, thus making it difficult to estimate the overall uncertainty of the analysis {Tenney, 2006 #305}. Thus 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, 2017 #304;Stelzenmüller, 2015 #50;Stock, 2016 #49} offered insights on the potential sources of uncertainty linked with causality and data and proposed technical solutions on how to deal with it.

The risk-based CEA framework structures the evaluation of cumulative effects on ecosystem components, considering the effectiveness of existing or proposed management measures, in relation to levels accepted to reach policy objectives (Stelzenmüller et al. 2018). In this context, 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 where proposed management actions are contrasted to the likelihood of achieving policy objectives. Hence, introducing an additional layer of

uncertainty which could influence the transparency throughout the decision-making process and therefore affect capitalization of the outputs {Leung, 2015 #306; Tenney, 2006 #305}.

From our case studies, we observed that many cases acknowledged uncertainty, but often in an unstructured fashion. Only for the Adriatic case a considerable effort was undertaken to assess the sources of uncertainty in a transparent manner {Gissi, 2017 #360}. 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 {Stelzenmüller, 2015 #52; Gissi, 2017 #360} and elaborated a Walker-type matrix {Walker, 2003 #193}. Building on {Walker, 2003 #193} 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 Annex 3). These descriptors represent uncertainty in a structured way, synthesise sources, causes and needs across the three dimensions: location, level and nature.

We applied this approach to explore uncertainty in the eleven CEA cases (Annex 3) and found a great variation of sources of uncertainty. 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) often defined both the assessment endpoints and case study context uncertainty. Thus, results revealed that policies and measures identified in the context setting are often not translated to clear operational objectives with explicit criteria and targets.

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 or by incorporating variability to ensure that model structure is adequate, such as in the Western Mediterranean case. Still, in most of the case studies a further exploration and description of sources of uncertainty through e.g. statistical tools was missing. In relation to management scenarios

that have been considered, sources of uncertainty comprised mainly the management measures tested and the assessed or described 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. Thus, environmental variability, the multi-dimensional interactions at the ecosystems level or complex ecosystem responses due to climate change {Rilov, 2019 #324} reflect some of these uncertainty types which are often acknowledged, but still hardly defined, quantified or addressed.

4. Recommendations for the operationalisation of a CEA

Stemming from our analysis, we synthesize here 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 operationalisation 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 and requires the involvement of stakeholders and decision-makers.

2) Defining the roles – 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 accumulate 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 standardised framework facilitated a consistent and coherent comparison of the key issues to operationalise such complex assessments. With this study 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 operationalised 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 and should be clearly separated from the provision of technical advice by scientists. 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 recognised as cross-cutting tools that could bridge different management objectives. We acknowledge that mismatches in governance structures can often not be changed, but we suggest that CEA can be one strategic approach to integrate ecosystem management considerations across multiple sectorial policies.

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600 Table 1. Following the approach of {Stelzenmüller, 2015 #52; Gissi, 2017 #360} we expanded a Walker-type matrix {Walker, 2003 #193} with
601 eight uncertainty descriptors: context uncertainty, cause-effect model uncertainty, data input uncertainty, statistical uncertainty, scenario
602 uncertainty, recognized ignorance, epistemic or knowledge-related uncertainty and inherent variability. This allows assessing the dimensions of
603 uncertainty associated to the risk-based CEA framework and offers a systematic guidance for improving the treatment of uncertainty.
604

Uncertainty dimensions	Location - Identifies where uncertainty establishes within the methodological approach applied for the RB-CEA. Location can refer to the context, model and input.			Level - Encompasses statistical uncertainty, scenario uncertainty and recognised 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	Recognised 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

Figure legends

Figure 1. Spatial distribution of the eleven local, sub-regional and regional case studies which applied the risk based cumulative effects assessment framework (Stelzenmüller et al. 2018) either to evaluate an existing CEA process or to structure a CEA. The latter represent cases where the CEA is still in progress. Note that the exact spatial expansion of respective case study area is not shown.

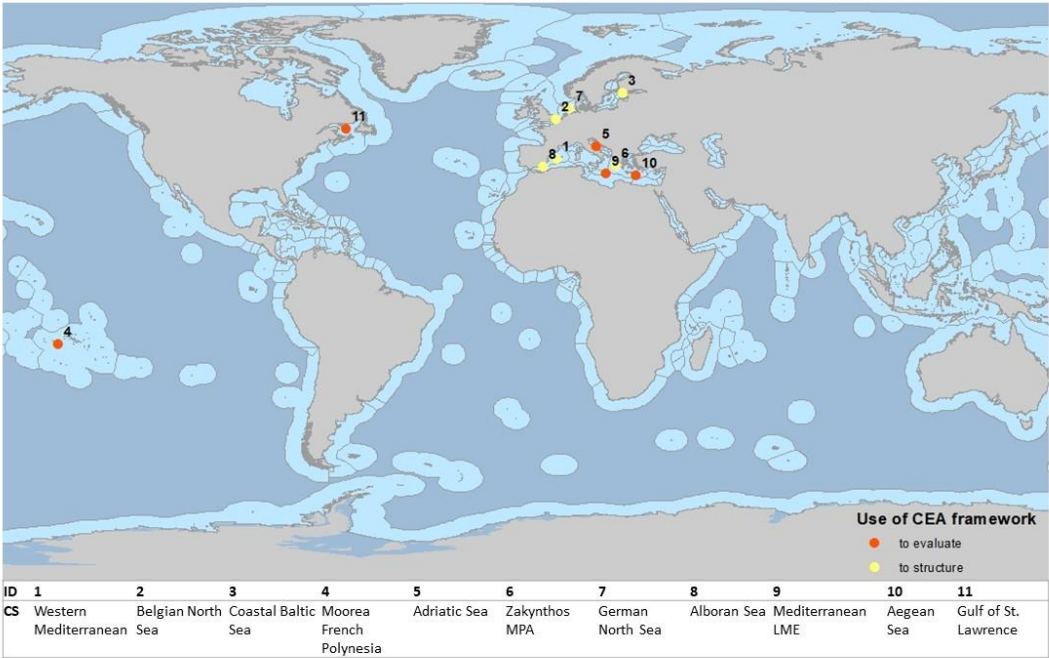
Figure 2. Alluvial plot showing the frequencies of the relationships between the CEA drivers, number of human activities, pressures, and the assessment endpoints considered by the eleven cases studies .

Figure 3. Representation of the logical chain between example human activities (e.g. fishing and aggregate extraction), their corresponding pressures (e.g. selective extraction), sector specific management measures (e.g. conservation measures, sectoral measures), cumulative residual pressures (total selective pressure load in the system despite management measures) and measureable state change of ecosystem components (e.g. benthic recovery, seabed recovery). Further the steps of risk identification, risk analysis and risk evaluation are superimposed to indicate the required elements.

Figure 4. Confidence matrix for a transparent representation of the quality of pressure data and the confidence of the applied causal pathways. The numbers correspond to the cases studies shown in Figure 1. At the risk identification step the quality of the pressure data can be categorised ranging from 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). The assessment used to derive causality in the relevant cause-effect pathways can be either based on expert knowledge, semi-quantitative, or quantitative assessments. 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 environmental policies e.g. EU MSFD.

Figure 5. Risk matrix without tolerance levels (left) in risk analysis versus tolerance levels in risk evaluation. The existing management measures (EM) is compared to the likelihood of a given consequence for the proposed improvements to existing measures or additional measures (PM). Such matrices are used as policy support tool to classify the combination of likelihood and consequences that would be considered as undermining defined policy objectives (red colours) following a gradient of colours (tolerance) to combinations that are considered as not undermining such objectives (green) (Rozmus et al., 2014). These matrices compare the risk of existing management measures versus new or improved management measures. These matrices can only inform managers and stakeholders as to how “bad” things are or could be. They must be derived from the results of the risk analysis of the effectiveness of the management measures given that 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).

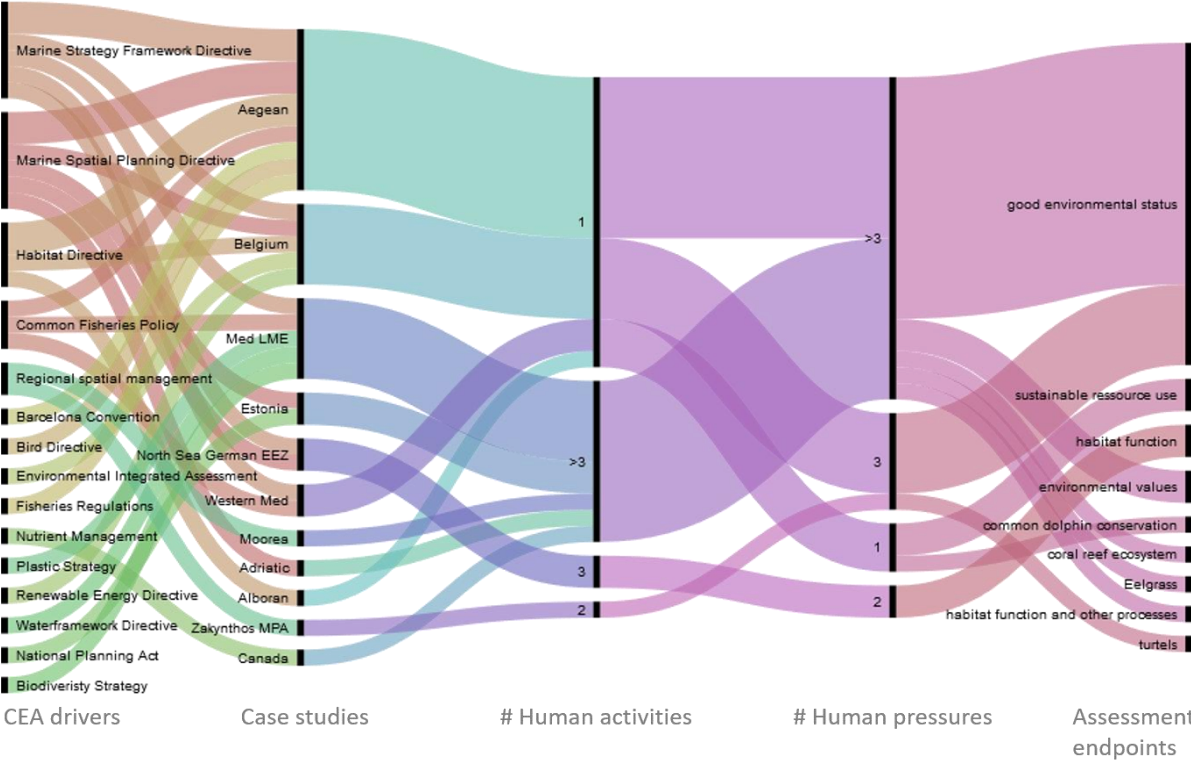
651 Figure 1



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654 Figure 2

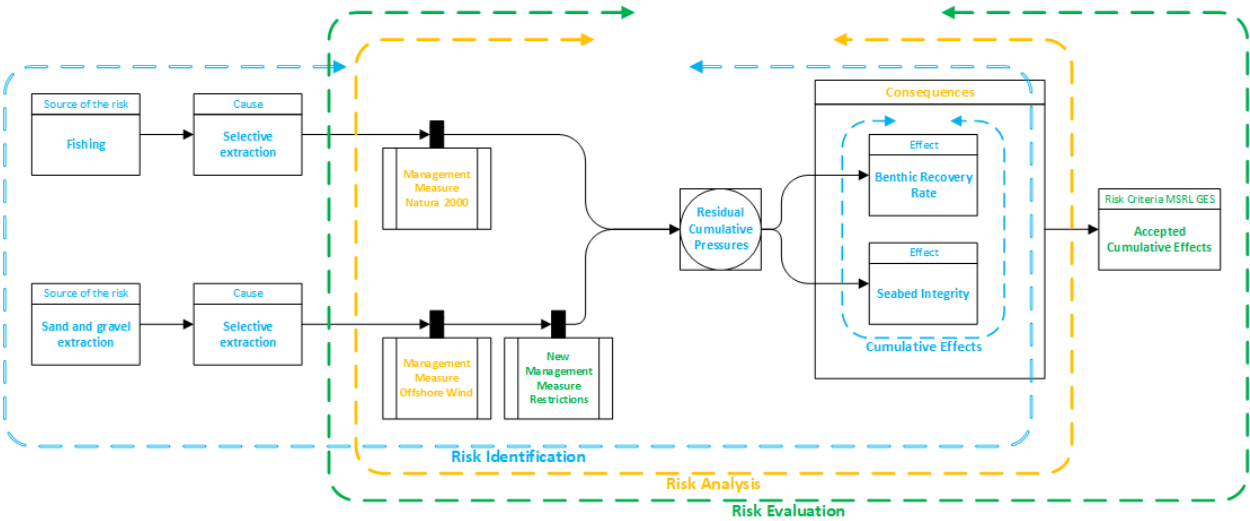


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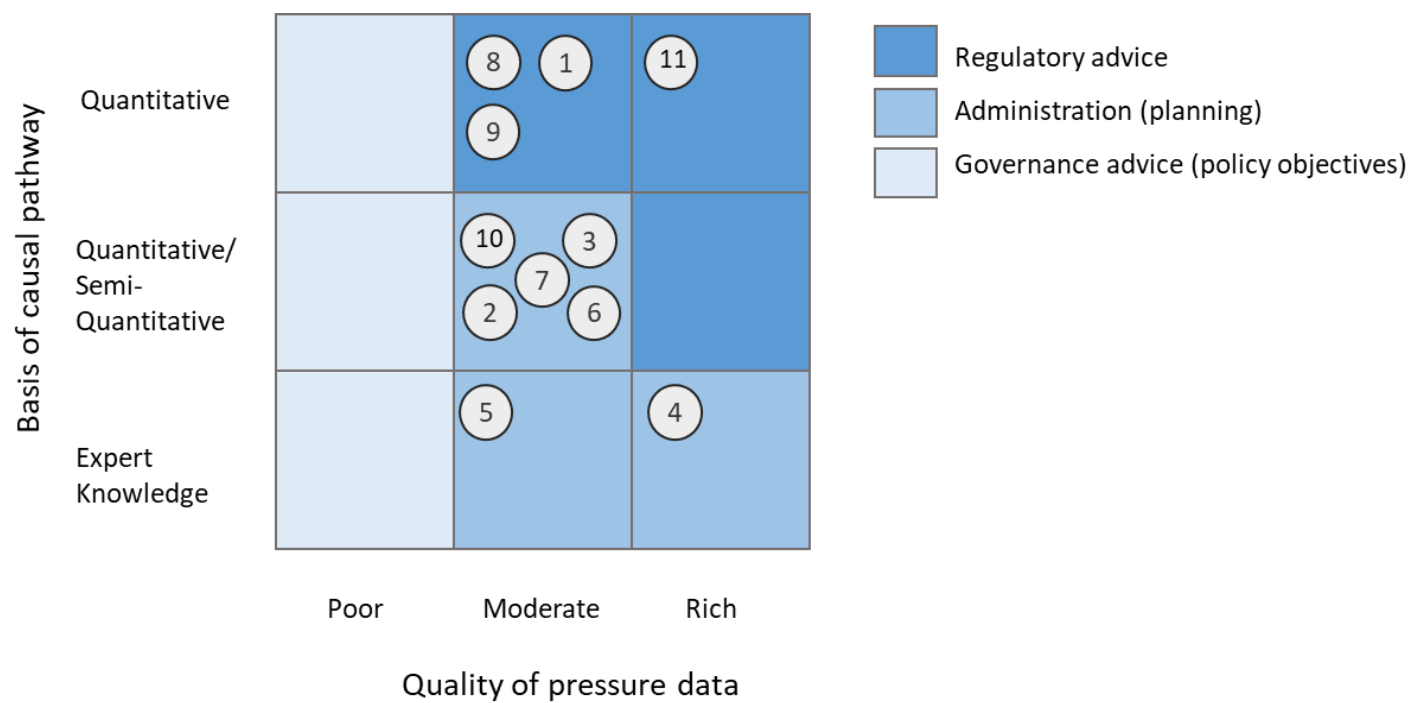
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Figure 3



662 Figure 4



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Figure 5

