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Review

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Advances in cumulative effects assessment and application in marine and coastal management

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Abstract

Quantifying and managing the cumulative effects of human activities on coastal and marine environments is among the foremost challenges in enabling sustainable development in the twenty-first century. As the speed with which these environments are changing increases, there is greater impetus to resolve the evident problems facing governance systems responsible for managing cumulative impacts. Policymakers and regulators recognise the need to assess and manage cumulative effects, as evidenced by widespread legislation requiring cumulative effects assessment (CEA). Yet there is ample evidence that we are not turning the tide in terms of balancing good environmental health with increasing demands of already degraded coastal and marine spaces that are increasingly impacted by climate change. This paper reviews the current state of knowledge regarding scientific and practical advances in CEA, assesses whether these advances are being applied in decision-making and identifies where challenges to implementation exist. Priority research questions are formulated to accelerate the inclusion of effective CEA in marine and coastal planning and management.

Impact statement

Our ability to assess cumulative effects underpins our capacity to manage cumulative effects. If we want to know how multiple human activities are interacting with and impacting our ecosystems and societies, we need good cumulative effects assessments (CEAs). These tools enable decision-makers and stakeholders to understand what impact existing activities and proposed development are likely to have on a changing environment. Good CEAs, therefore, are a prerequisite for sustainable development. This paper reviews advances in CEA in marine and coastal environments, assesses whether these advances are linked to decision-making and identifies where implementation challenges exist. Our review shows that research into how effects accumulate continues, but that there is much less evidence of research investigating how to bring that science into decision-making. The review intends to support efforts to accelerate the inclusion of CEA into marine and coastal planning and management. To that end, we propose research directions to bridge the gap between science, policy and delivery. While our paper focuses on marine and coastal systems, it is straightforward to find evidence of the continuing need for good CEAs in terrestrial and freshwater systems also. To that end, we hope that our review of recent research and proposed research directions will be of international interest and relevance.

Introduction

There is tension between the drive to develop coastal and marine environments and the need to protect our coastal and marine ecosystems. Demands to develop blue economies and to use these environments to support net zero targets mean that further development of coastal areas, seas and the ocean is inevitable. The outcome of that development is not inevitable, however. If ocean governance can move beyond the historically siloed approach to marine management and monitoring, there is the potential for development to be sustainable. Sustainable development depends on our ability to manage coastal and marine spaces holistically, which requires that decision-makers and stakeholders are supported by assessments of how multiple activities and processes cumulatively shape the environment, that account for how diverse actors use and value these spaces, and that permit identification of effective strategies for managing these cumulative effects to benefit ecosystems, societies and economies.

If we are concerned about sustainable development, we are concerned about the cumulative effects of human activities (Duinker, 2020). Cumulative effects impact the sustainability of elements of the environment that human societies care about, called *valued components*

(VCs; Beanlands and Duinker, 1984). VCs could include, for example, populations, species, habitats or ecosystem services. VCs never experience causal agents (entities, actions or occurrences) in isolation. Instead, VCs' condition and resilience reflect a range of causal agents acting on VCs at multiple scales (Segner et al., 2014). For future development to be sustainable, policy-makers and planners must be aware of the current status of VCs, how vulnerable VCs are to change and have robust predictions of how VCs respond to causal agents (Sinclair et al., 2017). Decision-makers need an understanding of which spatial and temporal scales are relevant to VCs, as well as insight into how VCs connect into a wider socio-ecological system.

Decision-makers also need to consider the pace at which environmental parameters are changing due to human activities such as climate change. Cumulative effects assessments (CEAs) should support decision-making by systematically identifying and evaluating the significance of effects from multiple sources/activities and providing estimates of the overall expected impact to inform management measures (Judd et al., 2015). Truly effective sustainable management of our coastal and marine environments requires CEAs that are a trusted source of information facilitating sustainable development and shaping policy, planning and management.

This review enquires into the state of knowledge about how we assess and address cumulative effects in coastal and marine environments. These environments are undergoing significant cumulative change as human activities are altering land- and seascapes, and as climate change alters ecological systems. Some coastal and marine areas are recovering or are protected where strong management is in place, but, broadly speaking, the resilience of coastal and marine ecosystems is in decline (IPCC, 2022). Uncertainties about the impacts of human activities on VCs are exacerbated by the challenges of monitoring and quantifying interactions and change in tidal and subtidal environments. There is, however, an active community of researchers investigating the space where net zero, the blue economy and ecosystem functioning collide, providing a pool of literature to support inquiry into the current state of knowledge regarding the application and use of CEA in marine and coastal spaces.

The legal requirement to assess and manage cumulative effects in coastal and marine environments

We first touch on examples of national and regional legislation that explicitly or implicitly call for CEA to highlight that there is a legal, as well as scientific, imperative to implement ecologically sound and politically functional CEA. In these regions (Table 1), the assessment and management of cumulative effects has been intentionally incorporated into multiple legislative acts. This legislation requires planning and management of coastal and marine environments to be informed by CEAs. Given the ethos and rationale behind environmental impact assessment (EIA), nations with legislation requiring EIA (more than 140 in 2013; Glasson et al., 2012) could be argued to legally require CEA. However, multiple authors have flagged difficulties in integrating CEA into policy, planning and delivery (e.g., Judd et al., 2015; Van Roon et al., 2016; Davies et al., 2020), including inconsistent CEA approaches and quality, fragmented legislation, mismatches between political and ecological scales and the need for long-term data and funding.

Reviewing recent coastal and marine CEA research

Methodology

We assessed the current state of CEA research in marine and coastal environments by examining new evidence, building upon previous reviews (Judd et al., 2015; Willsteed et al., 2017) to update and reflect on past and emerging observations and challenges in their implementation. We applied a variation of the systematic mapping method described by James et al. (2016), which is detailed in the extended methodology in the Supplementary Material.

Systematic mapping collates, describes and catalogues available evidence relating to a topic or question of interest, and is useful for identifying evidence for policy-relevant questions, knowledge gaps and knowledge clusters (James et al., 2016). We limited the literature search to the Scopus publications database, which while not exhaustive, provides a comprehensive spread of source journals from which to investigate and reflect on progress in the use and effectiveness of CEA.

We asked: *what is the current state of knowledge regarding CEA in marine and coastal environments?*

And defined search parameters as:

i. The title, abstract or keywords (where 'keywords' is a combined field that searches the author-selected keywords, index terms and trade names) of the paper must contain one of the phrases 'cumulative effect(s) assessment' or 'cumulative impact(s) assessment'.
ii. The title, abstract or keywords of the paper must contain one of the words 'marine', 'coast' or 'sea'.
iii. The publication year is after 2014.
iv. The document type must be either an article (ar), review (re) or conference paper (cp).

Full details of the search process, the treatment of the initial list of literature returned by the search, the coding fields and the review process can be found in the Supplementary Material.

Literature mapping results and observations

The initial Scopus search returned 296 results that were reduced to 91 following the rapid review of titles and abstracts. This number increased to 118 once supplemented with papers added by the review team. Following the more detailed review of included papers, 78 papers and articles were included in the mapping exercise. The mapping database can be found in the Supplementary Material. The coding exercise flagged instances where coding required interpretation, introducing potential subjectivity. Capacity constraints limited our ability to test for and reduce subjectivity to relying on second reviews and discussions across the team, so we limited reported observations to those results where clear trends were identified.

The count and distribution of CEA research

Research into cumulative effects and impact assessments continues apace (Figure 1). All the papers scoping into the review flagged the importance of assessing cumulative effects relative to environmental protection and conservation goals. Each published CEA concluded that cumulative effects pose a risk to VCs and ecosystems, adding further weight to the argument that we urgently need to bridge the gap between identifying, quantifying and managing cumulative effects. CEAs that provided estimates of the significance of impacts were few in number (discussed in a later section).

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Table 1. Examples of nations and regions with legislative frameworks requiring CEA

Jurisdiction	Example legal requirements to conduct CEA
Australia	The Commonwealth Environment Protection and Biodiversity Conservation Act 1999 may require an impact assessment when proposed activities may affect matters of national environmental significance, and this has been interpreted by the courts to include cumulative effects (Franks et al., 2010).
Canada	The Canadian Council of Ministers of the Environment (CCME 2014) emphasises that cumulative effects assessment (CEA) should consider effects that accumulate across space and time (potentially encompassing all causal agents affecting a valued component).
European Union	Directive 2008/56/EC (Marine Strategy Framework Directive) specifies the assessment and management of the collective pressures of human activities. Directive 2001/42/EC (SEA Directive) specifies assessment of the effects of plans and programmes, including cumulative effects.
United Kingdom	The Marine Works (Environmental Impact Assessment) and Marine Strategy (Amendment) Regulations 2018 (2018 No. 287) retain the Marine Strategy Regulations 2010 requirement to apply ecosystem-based management ensuring that the collective pressures of human activities are compatible with Good Ecosystem Status and do not compromise the capacity of marine ecosystems to respond to human induced changes.
United States of America	The National Environmental Policy Act (1969) stipulates the requirement to assess cumulative effects.
New Zealand	The Resource Management Act 1991 includes provision for CEA, and the New Zealand Coastal Policy Statement (NPS Coastal) mentions cumulative effects in relation to integrated management approaches and strategic planning (Van Roon et al., 2016).

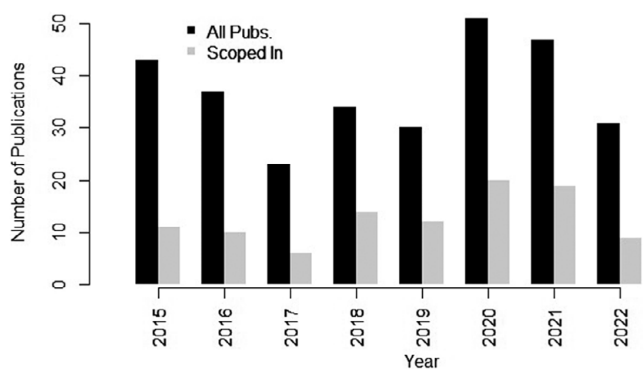

Figure 1. Number of CEA publications per year between 2015 and 2022 included within the Scopus database of peer-reviewed literature using the search term defined, and those scoped into the literature review. Note 2022 is a partial year.

Of the papers mapped, the majority originated in Europe (50%), followed by North America (20%) and Oceania (12%), with research also originating from South America (Brazil) and Asia (China, including Hong Kong, and South Korea) (Figure 2). Just one example of CEA research relating to Africa was identified, stemming from research considering the effects of energy infrastructure on bird species migrating between Africa and Europe (Gauld et al., 2022). Two studies included proof of concept examples or considered case studies that were distributed in multiple regions of the globe (Tamis et al., 2015 and Stelzenmüller et al., 2020, respectively).

Drivers behind CEA research

Coding the drivers behind each CEAs revealed clear links between drivers. For example, Marine Spatial Planning (MSP) was frequently discussed in conjunction with Ecosystem-Based Management (EBM), and Energy was often discussed in combination with MSP. A handful of papers included two drivers (e.g., Gauld et al., 2022) where energy and species conservation were given equal importance. Acknowledging this blurring of drivers, it is nonetheless apparent that over the period reviewed, MSP has motivated the majority of CEAs in Europe, whereas EBM has been the leading driver elsewhere (Figure 2). Interestingly, given the scale of current concerns about the cumulative environmental effects of offshore wind expansion in Europe, North America and beyond, CEAs assessing the cumulative impacts of offshore energy generation were less well represented in recent literature.

The prevalence of MSP as a driver in Europe may reflect the influence of the Marine Strategy Framework Directive (2008/56/EC) and the Marine Spatial Planning Directive (2014/89/EU), which are closely linked with the former introducing the concept of ecosystem-based MSP (Douvere, 2008). During the review, it was difficult to determine whether CEAs were responding to specific policy or legislative drivers because few papers (about 10%, $n = 78$) could be unambiguously categorised as responding to a specific legislative need. Signposting CEAs to specific policy and/or legislative needs would be useful from an implementation perspective, providing a clear link between assessment and intended goals.

Definitions, methods and focus

Linking CEAs to legislative needs may also be helpful in effectively using CEA in decision-making. A range of authors noted the importance of framing CEAs, of being explicit about a CEA's intentions and objectives, and of clearly defining what the term 'cumulative effects' refers to in each CEA (Judd et al., 2015; Foley et al., 2017; Stelzenmüller et al., 2020). Within the literature mapped, we found that half of the papers reviewed (39 of 78) did not clearly define 'cumulative effects/impacts' (Figure 3a). In some

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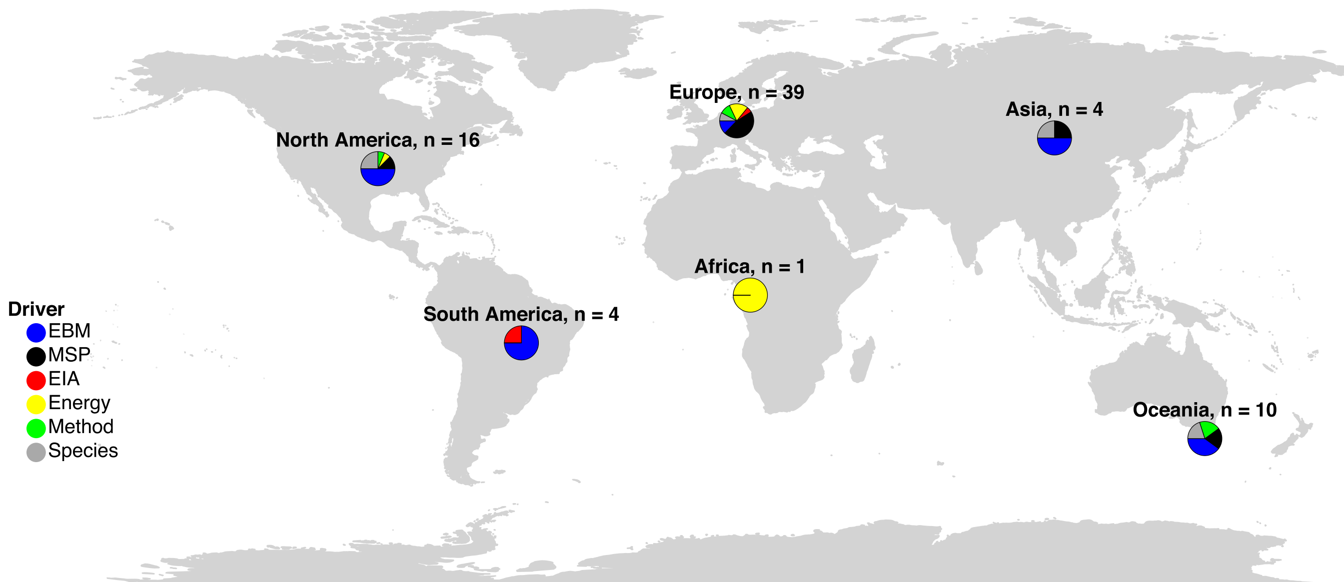

Figure 2. Map of geographic regions to which papers covered by the review relate with pie charts indicating the policy drivers linked to CEAs scoped into the review.

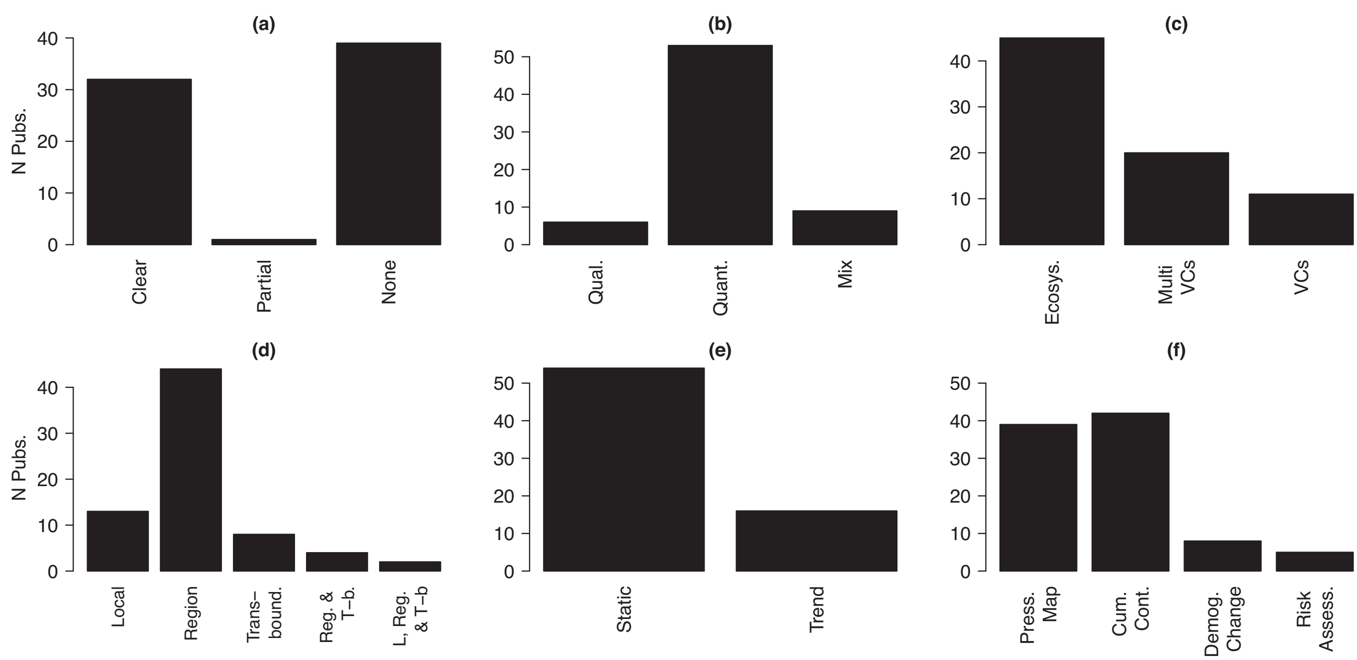

Figure 3. Selection of literature mapping results. 3a) number of CEAs with a clear definition of cumulative effects/impacts or no definition; 3b) number of CEAs applying qualitative (Qual.), quantitative (Quant.) or mixed approaches (Mix); 3c) number of CEAs assessing cumulative effects on ecosystems (Ecosys.), multiple VCs (Multi VCs), or individual VCs; 3d) number of CEAs investigating effects over local, regional, transboundary (Trans-bound.), regional and trans-boundary (Reg. & T-b.) or local, regional and trans-boundary (L, Reg & T-b.); 3e) number of CEAs presenting a snap-shot of cumulative effects (static) or where temporal trends are incorporated; 3f) number of CEAs with outputs coded as pressure maps (Press. Map), where the cumulative contribution of stressors were estimated (Cum. Cont.), where demographic change was estimated (Demog. Change), or where the risk of cumulative impacts were assessed (Risk. Assess).

cases, authors' interpretation of cumulative effects could be deduced from the methodology sections, but clear, unambiguous definitions and statements of purpose would aid transparency.

About 75% of CEAs (excluding papers relating to methods or reviews, $n = 68$) applied quantitative methods that emphasised the use of and reliance on data to support models of cumulative impacts and mapping of overlapping pressures and VCs (Figure 3b). Expert opinion continues to play an important role in many quantitative CEAs to overcome the lack of empirical data about pressures, VCs and the effects of pressures on VCs. Broadly speaking, all CEAs reviewed flagged that better data would increase confidence in CEA findings by decreasing uncertainty. Calls for better data were also found in relatively data-rich CEAs (e.g., Stockbridge et al., 2020). Murray et al. (2019) provide one example of the scale of data requirements required to deliver a scientifically robust CEA designed to inform marine managers about measures designed to aid species recovery.

The need to quantify and reduce uncertainty remains a common thread between CEAs. CEAs applying qualitative and quantitative–qualitative approaches indicate a range of methods to advance this aim. These include: (1) applying evidence-based review methods and combining multiple lines of evidence (Diefenderfer et al., 2016); (2) explicitly accounting for expert uncertainty and combining uncertainty scenarios to identify more robust outputs (Jones et al., 2018) and (3) the use of risk-based approaches to reduce complexity and bridge the gap between theory and practice (Stelzenmüller et al., 2020) and to overcome 'paralysis by analysis' (Brignon et al., 2022, p. 273).

In terms of focus, the majority of CEAs investigated cumulative effects acting on ecosystems, followed by multiple VCs, followed by individual VCs (Figure 3c). Several CEAs investigated effects on ecosystems through assessing multiple VCs as proxies for ecosystem change.

Scale, treatment of time and outputs

Scale is critical to CEA, from the geographical and temporal scales required to understand the range of pressures impacting VCs over distributions and life cycles, to the political scales that manage regional and often transboundary impacts. Of the papers detailing specific applications of CEA, the majority considered impacts at the regional scale (Figure 3d). This is a positive trend given the need for CEAs to inform regional policy and delivery processes, including MSP and EBM. Sutherland et al. (2016) note the emerging consensus that regional approaches are essential for CEA to become a useful strategic tool. One challenge in this regard is that data collection at regional scales is often too coarse to provide the detail required to inform management measures and that significant local impacts may be missed or obscured at regional scales (Gkadolou et al., 2018). This highlights the need for CEA to consider a multi-scale approach, capable of identifying and evaluating both local and regional impacts. The importance of evaluating cumulative effects at local scales was highlighted by CEAs applying empirical data. Field observations identified significant variation in local-scale responses to different combinations of anthropogenic pressures (Guarnieri et al., 2016), and significant differences between modelled predictions of cumulative impacts and observed ecosystem condition (Stockbridge et al., 2021). Validating modelled and expert-opinion-derived CEAs is key if these assessments are to be used in decision-making.

The inclusion of time in CEA continues to lag behind analysis of spatial characteristics of cumulative effects (Figure 3e). The most common CEA application was to a specific moment in time (about 75%), as opposed to CEAs that explicitly considered how pressures, VCs or ecosystem status are changing over time. The value of static CEAs can be increased through regular updates (Halpern and Fujita, 2013; Murray et al., 2015), but this is dependent on the underlying datasets being maintained consistently (Murray et al., 2015) or CEAs being linked to ongoing monitoring programmes, ideally for indicators across regional scales (Sutherland et al., 2016). Unsurprisingly, CEAs that identify demographic change in VCs incorporate temporal analysis (e.g., Brabant et al., 2015; Marcotte et al., 2015; Otto et al., 2020; Bozec et al., 2022).

Previous research has identified variability in CEA approaches (Hodgson and Halpern, 2018; Stelzenmüller et al., 2018). This was also observed in our review. An investigation of CEAs within EIAs identified high variability between approaches even when focussed on the same VC in the same region (Hague et al., 2022). Within the papers reviewed here, some approaches were more common, such as the use of GIS to derive spatial analyses of overlapping pressures and VC distributions (about 55%), and the driver–pressure–state–impact–response model framework used to support the identification of cause–effect pathways between pressures and VCs. Expert opinion was often used to score the importance of pressure–VC pathways.

The frequent use of Geographic Information System (GIS) meant that outputs were commonly maps (Figure 3f), primarily of the cumulative pressures acting on a system, but also of risk, connectivity and recovery, and the identification of areas for potential management interventions. Such outputs are relevant to regional MSP but struggle to provide quantitative estimates for specific pressures and local impacts. More advanced outputs were derived in some CEAs where estimates of the contribution of specific pressures or stressors to the state of VCs were derived (e.g., to estuaries, Van Roon et al., 2016; to coral reefs, Loiseau et al., 2021), enabling the identification of key leverage points or focal points for management measures (Loiseau et al., 2021). Only rarely were CEAs found to deliver estimates or measures of demographic change to VCs, which are valuable when estimating the significance of cumulative impacts, either *ex post* (e.g., on coral reefs; Bozec et al., 2022) or *ex ante* (e.g., on coastal and riparian habitats; Sutherland et al., 2016). Such quantification of cumulative impacts on demographic rates allows for a more dynamic understanding of current and future impacts of pressures, enabling the use of modelling projections to derive impact forecasts on key populations. As noted previously, CEAs indicating demographic change inevitably include temporal data as well as spatial data. Appropriate spatial delineation of populations is key to this approach. Another relevant research area when determining how significant effects are to VCs is the identification of thresholds (Brabant et al., 2015). Studies that advance knowledge about integrating quantitative management targets into coastal and marine planning (e.g., noise budgets; Merchant et al., 2018) are important.

Cumulative effects assessments in decision-making today

Our review reveals limited evidence that research applying CEA methods (as opposed to research contributing to methodological advances) is allied to decision-making. Studies concluding that cumulative effects pose a risk to ecological resilience frequently recommend that CEAs are incorporated into decision-making but rarely identify how to do so.

Notable examples of research that support CEA implementation do exist. For instance, CEA research originating in Canada offers lessons, with CEAs stimulated by the need for species at risk recovery plans (Murray et al., 2019) and being explicitly linked to the need to support Federal regulators tasked with responding to new legislative demands (Lieske et al., 2020). In both examples, VCs are placed at the centre of the CEA, discussion of results is placed in the context of planning and management decision-making and the value of robust underlying data is evident. Diggon et al. (2022) provide important insight into the broader decision-making, conflict resolution and technical architecture required to develop collaborative marine plans informed by CEA. These approaches provide guidance to ensure CEA research contributes to the design and delivery of policy, which should be emphasised in future assessments.

Judd et al. (2015) observed that CEA consistency and robustness are critical if CEA is to become a trusted tool for informing decision-making. Calls for consistency are repeated in recent studies (e.g., Stelzenmüller et al., 2020; Tamis et al., 2021), and the wide variety of approaches to CEA observed in this review lead us to echo this call. Examples of research that potentially progress consistency include Tamis et al. (2015), Stelzenmüller et al. (2020) and Piet et al. (2021), who propose and test frameworks that can be replicated at different scales and for different VCs and pressures. Notably these frameworks apply risk-based approaches that simplify complexity, promote transparency regarding the treatment of uncertainty and can be iterated to make use of improved evidence. Notable also was research by Griffiths et al. (2019), which adapted a tried and tested species vulnerability assessment approach to investigate the cumulative impacts of fisheries to investigate the suitability of biological reference points to support ecosystem-based fisheries management.

Also relevant to implementation is research that supports CEA at strategic scales. Tamis et al. (2021) provide a consistent approach to project-level assessments that can be integrated into strategic planning and that specifically estimate cumulative impacts, offering support to efforts to address project-level CEA shortcomings (see Willsteed et al., 2018a; Hague et al., 2022). Sutherland et al. (2016) systematically selected indicators for strategic CEA, which offers a transferable approach to forecasting present and future indicator condition. CEAs that identify the significance of individual pressures also support implementation by informing management measure design; for example, Tulloch et al. (2022) identified that addressing priority threats to keystone VCs reduces risks across an ecosystem.

Finally, we highlight examples of research that offer insights into how to bridge the gap between CEA science and its application in policy and delivery. Common obstacles observed include fragmented legislation, poor alignment between ecological scales relevant to CEA and political scales relevant to management of cumulative effects and the need for reliable, long-term datasets and the problem of shifting baselines (Van Roon et al., 2016; Davies et al., 2020; Hollarsmith et al., 2022). Enabling integrated coastal and marine planning and management involves long timescales, highlighting the need for long-term engagement and funding (Van Roon et al., 2016; Diggon et al., 2022). The need to include diverse values, including those of indigenous peoples, into decision-making is discussed by Davies et al. (2020) and Diggon et al. (2022). Collaboration and inclusion of diverse sources of knowledge enable progress and support stakeholder buy-in (Diefenderfer et al., 2016; Diggon et al., 2022; Hollarsmith et al., 2022).

Research directions to integrate CEA in decision-making

Reflecting on the findings of the review and the review teams experiences with CEA, we briefly touch on research directions to progress the integration of CEA into coastal and marine planning and management. We echo previous studies that stressed the need for consistency, explicit contextualisation of CEAs, careful use of terminology, explicit identification and treatment of uncertainty and the potential for adaptive, risk-based frameworks to enable coherence and progress. Beyond this, we pose a series of research questions that respond to other common barriers to implementation.

Enabling strategic CEA: CEA applied at strategic levels and scales is likely to be most beneficial in delivering to policy needs (Jones, 2016; Sutherland et al., 2016; Sinclair et al., 2017; Willsteed et al., 2018b), but there is also compelling evidence for the need for fine-scale assessments capable of identifying and quantifying localised impacts, for instance, on key-protected populations (e.g., Guarnieri et al., 2016; Gkadolou et al., 2018; Stockbridge et al., 2021). Key research questions include:

- Can alternative CEA approaches bridge different spatial and temporal scales, and how can resulting increased data requirements be adequately met?
- How transferable are indicators across different activities, and can VC indicators be correlated to aid in their quantification and prediction in less well-studied systems (e.g., Sutherland et al., 2016)?
- Which modelling frameworks best support testing and evaluating different management measures?
- What testing and validation of CEA frameworks are necessary to meet planning and regulatory thresholds for evidence and proportionality?

Investigating data needs: Broadly speaking, while there are always some data available to support CEA, a common theme running through environmental literature more widely is that there are never enough data. Therefore, key research questions are:

- What are the minimum data requirements to adequately quantify shifting baselines, and to gain sufficient knowledge to quantify and predict cause–effect pathways?
- In situations where data and analytical complexity are high, how can CEAs avoid 'paralysis by analysis' and deliver assessments that enable decisions?
- Which statistical frameworks can be used to ensure that uncertainty arising from data limitations is captured and expressed coherently in CEA outputs?
- Recognising the importance of nested scales, what information storage systems would be required to enable open access to coherent long-term data, and who is responsible for inputting to and maintaining these structures?

Evaluating effect significance, thresholds, integrating diverse values and trade-offs: For CEA to best support sustainable development, progress is needed in answering the 'so what?' questions.

- What are the implications of coinciding pressures and VCs from the perspectives of VCs, of stakeholders, and of regulators?
- At what point are impacts significant, and what are the thresholds beyond which additional impacts will be unacceptable?
- How can diverse values and trade-off analyses be integrated into CEA? By way of example, this research theme is a priority in the North Sea in Europe, where offshore wind expansion, depleted VCs, competing interests and a complex policy and delivery environment collide. There is growing recognition that project-by-project mitigation and compensation will not address the risks of cumulative impacts to ecological and social VCs caused by widespread construction of offshore wind farms. Progress relative to the questions posed here and advances in CEAs are urgently required to inform if compensatory measures are likely to be adequate.

Understanding the delivery landscape: Noting the observation that CEA should remain independent of decision-making (Stelzenmüller et al., 2020), there is a clear need for CEA research to have greater interaction with decision-makers, to align with policy and delivery information needs (Jones, 2016; Van Roon et al., 2016). Therefore, key research questions are:

- Relative to CEA, how coherent are existing governance systems?
- What research would be appropriate to test CEA approaches on people involved in policy, planning and delivery to identify implications from regulatory and legal perspectives?
- Recognising the iterative nature of CEAs and the need for adaptive management approaches, how would adoption of CEA frameworks impact the need for regulatory stability and to maintain investor confidence?
- What are the capacity building needs within decision-making institutions and participating stakeholder groups to support integration of CEA into decision-making and enhance understanding of the implications of uncertainty (or of inaction)?
- What is the appetite for regulatory change to deliver standardised data collection as part of the approvals and post-consent processes, and for data to be provided open access in government databases?

Fast-tracking CEA in developing nations: Perhaps the most pressing question is: what is 'good enough CEA'? While this is a relevant question in all jurisdictions, it is especially pertinent in regions where rapid coastal and marine development is forecast, but legislative frameworks are less developed and governance systems are seriously constrained by capacity shortfalls. Key research questions to address this shortfall are:

- How transferable is global CEA research, covering the technical, policy and legal and participatory lens (Sinclair et al., 2017), and can this be simplified and packaged to support developing nations to leapfrog the decades of incremental progress in more advanced jurisdictions?
- Can CEA research be applied to support strengthening of environmental and social accountability of developers and investors? For example, by providing technical advice to clarify CEA commitments contained in standards for private investment in developing countries, such as the International Finance Corporation Performance Standards.

Conclusion

The leading role that cumulative effects have in shaping environmental change coupled with the need for sustainable development has led to high expectations of CEA. However, assessing cumulative effects in complex adaptive systems is challenging and the intricacies of governance challenge application. Our review suggests that aspirations remain high, that scientific challenges are well discussed, but implementation challenges much less so, and that despite decades of CEA research, there is little evidence that 'good' CEA informs decision-making. The pace of development in coastal and marine systems suggests that aspirations need to be balanced by pragmatism.

Our review suggests that while CEA research continues, there is a parallel and urgent need to bridge the gap between science and policy, planning and delivery. We recommend stepping back to identify the technical, political and participative lenses (see Sinclair et al., 2017) that could coordinate CEA efforts within regions, overcoming mismatches between ecological, social and political scales. Defining common ground across policies, delivery bodies and industries would aid coordination, collaboration and communication and accelerate progress towards 'good enough CEA'.

Recognising that change in governance systems takes time but that we need change now, we suggest that existing coastal and marine policy provides a sufficiently robust policy and legislative lens to focus CEA. For example, ecosystem-based MSP *sensu* (Ansong et al., 2017) is mandated in parts of Africa, Asia, the Americas, Europe and Oceania. We need more CEAs that specifically focus on delivering existing marine and coastal policy. We urgently need trusted and robust CEAs that support reconciliation of net zero and blue economy aspirations with responsibilities to protect socio-ecological systems.

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References

Ansong J, **Gissi E and Calado H** (2017) An approach to ecosystem-based management in maritime spatial planning process. *Ocean and Coastal Management* **141**, 65–81. https://doi.org/10.1016/j.ocecoaman.2017.03.005.

Beanlands GE and Duinker PN (1984) An ecological framework for environmental impact assessment. *Journal of Environmental Management* **18**(3), 267–277.

Bozec Y-M, **Hock K**, **Mason RAB**, **Baird ME**, **Castro-Sanguino C**, **Condie SA**, **Puotinen M**, **Thompson A and Mumby PJ** (2022) Cumulative impacts across Australia's Great Barrier Reef: A mechanistic evaluation. *Ecological Monographs* **92**(1), e01494. https://doi.org/10.1002/ecm.1494.

Brabant R, **Vanermen N**, **Stienen EWM and Degraer S** (2015) Towards a cumulative collision risk assessment of local and migrating birds in North Sea offshore wind farms. *Hydrobiologia* **756**(1), 63–74. https://doi.org/10.1007/s10750-015-2224-2.

Brignon JM, **Lejart M**, **Nexer M**, **Michel S**, **Quentric A and Thiebaud L** (2022) A risk-based method to prioritize cumulative impacts assessment on marine biodiversity and research policy for offshore wind farms in France. *Environmental Science and Policy* **128**, 264–276. https://doi.org/10.1016/j.envsci.2021.12.003.

CCME (2014) Canada-wide definitions and principles for cumulative effects. Available at https://ccme.ca/en/res/cedefinitionsandprinciples1.0e.pdf; https://www.ccme.ca/en/resources/canadian_environmental_quality_guidelines#Specific.

Davies KK, **Fisher KT**, **Couzens G**, **Allison A**, **van Putten EI**, **Dambacher JM**, **Foley M and Lundquist CJ** (2020) Trans-Tasman cumulative effects management: A comparative study. *Frontiers in Marine Science* **7**, 25. https://doi.org/10.3389/fmars.2020.00025.

Diefenderfer HL, **Johnson GE**, **Thom RM**, **Buenau KE**, **Weitkamp LA**, **Woodley CM**, **Borde AB and Kropp RK** (2016) Evidence-based evaluation of the cumulative effects of ecosystem restoration. *Ecosphere* **7**(3), e01242. https://doi.org/10.1002/ecs2.1242.

Diggon S, **Bones J**, **Short CJ**, **Smith JL**, **Dickinson M**, **Wozniak K**, **Topelko K and Pawluk KA** (2022) The marine plan partnership for the North Pacific Coast – MaPP: A collaborative and co-led marine planning process in British Columbia. *Marine Policy* **142**, 104065. https://doi.org/10.1016/j.marpol.2020.104065.
Douvere F (2008) The importance of marine spatial planning in advancing ecosystem-based sea use management. *Marine Policy* **32**(5), 762–771. https://doi.org/10.1016/j.marpol.2008.03.021.
Duinker, P. (2020) Cumulative effects: The only effects that matter! Presentation. Available at https://ec.europa.eu/newsroom/mare/document.cfm?doc_id=64787.
Foley MM, **Mease LA**, **Martone RG**, **Prahler EE**, **Morrison TH**, **Murray CC and Wojcik D** (2017) The challenges and opportunities in cumulative effects assessment. *Environmental Impact Assessment Review* **62**, 122–134. https://doi.org/10.1016/j.eiar.2016.06.008.
Franks DM, **Brereton D and Moran CJ** (2010) Managing the cumulative impacts of coal mining on regional communities and environments in Australia. *Impact Assessment and Project Appraisal* **28**(4), 299–312. https://doi.org/10.3152/146155110X12838715793129.
Gauld JG, **Silva JP**, **Atkinson PW**, **Record P**, **Acácio M**, **Arkumarev V**, **Blas J**, **Bouten W**, **Burton N**, **Catry I**, **Champagnon J**, **Clewley GD**, **Dagys M**, **Duriez O**, **Exo KM**, **Fiedler W**, **Flack A**, **Friedemann G**, **Fritz J**, … **Franco AMA** (2022) Hotspots in the grid: Avian sensitivity and vulnerability to collision risk from energy infrastructure interactions in Europe and North Africa. *Journal of Applied Ecology* **59**(6), 1496–1512. https://doi.org/10.1111/1365-2664.14160.
Gkadolou E, **Stithou M and Vassilopoulou V** (2018) Human pressures and carbon assessment of *Posidonia oceanica* meadows in the Aegean Sea: Limitations and challenges for ecosystem-based management (conference paper). *Regional Science Inquiry* **10**(3), 73–86.
Glasson J, **Therivel R and Chadwick A** (2012) *Introduction to Environmental Impact Assessment*, 4th Edn. Abingdon, Oxon, UK: Routledge.
Griffiths SP, **Kesner-Reyes K**, **Garilao C**, **Duffy LM and Román MH** (2019) Ecological assessment of the sustainable impacts of fisheries (EasI-FiSh): A flexible vulnerability assessment approach to quantify the cumulative impacts of fishing in data-limited settings. *Marine Ecology Progress Series* **625**, 89–113. https://doi.org/10.3354/meps13032.
Guarnieri G, **Bevilacqua S**, **de Leo F**, **Farella G**, **Maffia A**, **Terlizzi A and Fraschetti S** (2016) The challenge of planning conservation strategies in threatened seascapes: Understanding the role of fine scale assessments of community response to cumulative human pressures. *PLoS One* **11**(2), e0149253. https://doi.org/10.1371/journal.pone.0149253.
Hague EL, **Sparling CE**, **Morris C**, **Vaughan D**, **Walker R**, **Culloch RM**, **Lyndon AR**, **Fernandes TF and McWhinnie LH** (2022) Same space, different standards: A review of cumulative effects assessment practice for marine mammals. *Frontiers in Marine Science* **9**, 822467. https://doi.org/10.3389/fmars.2022.822467.
Halpern BS and Fujita R (2013) Assumptions, challenges, and future directions in cumulative impact analysis. *EcoSphere* **4**(10), 1–11. https://doi.org/10.1890/ES13-00181.1.
Hodgson EE and Halpern BS (2018) Investigating cumulative effects across ecological scales. *Conservation Biology* **33**(1), 22–32. https://doi.org/10.1111/cobi.13125.
Hollarsmith JA, **Therriault TW and Côté IM** (2022) Practical implementation of cumulative-effects management of marine ecosystems in western North America. *Conservation Biology* **36** (1), e13841. https://doi.org/10.1111/cobi.13841.
IPCC (2022) *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds.). Cambridge University Press (in press).
James KL, **Randall NP and Haddaway NR** (2016) A methodology for systematic mapping in environmental sciences. *Environmental Evidence* **5**(1), 7. https://doi.org/10.1186/s13750-016-0059-6.
Jones AR, **Doubleday ZA**, **Prowse TAA**, **Wiltshire KH**, **Deveney MR**, **Ward T**, **Scrivens SL**, **Cassey P**, **O'Connell LG and Gillanders BM** (2018) Capturing expert uncertainty in spatial cumulative impact assessments. *Scientific Reports* **8**(1), 1469. https://doi.org/10.1038/s41598-018-19354-6.
Jones FC (2016) Cumulative effects assessment: Theoretical underpinnings and big problems. *Environmental Reviews* **24**(2), 187–204. https://doi.org/10.1139/er-2015-0073.
Judd AD, **Backhaus T and Goodsir F** (2015) An effective set of principles for practical implementation of marine cumulative effects assessment. *Environmental Science & Policy* **54**, 254–262. https://doi.org/10.1016/j.envsci.2015.07.008.
Lieske DJ, **Tranquilla LMF**, **Ronconi RA and Abbott S** (2020) Seas of risk': Assessing the threats to colonial-nesting seabirds in eastern Canada. *Marine Policy* **115**, 103863. https://doi.org/10.1016/j.marpol.2020.103863.
Loiseau C, **Thiault L**, **Devillers R and Claudet J** (2021) Cumulative impact assessments can show the benefits of integrating land-based management with marine spatial planning. *Science of the Total Environment* **787**, 147339. https://doi.org/10.1016/j.scitotenv.2021.147339ï.
Marcotte D, **Hung SK and Caquard S** (2015) Mapping cumulative impacts on Hong Kong's pink dolphin population. *Ocean and Coastal Management* **109**, 51–63. https://doi.org/10.1016/j.ocecoaman.2015.02.002.
Merchant ND, **Faulkner RC and Martinez R** (2018) Marine noise budgets in practice. *Conservation Letters* **11**(3), e12420. https://doi.org/10.1111/conl.12420.
Murray C, **Agbayani S**, **Alidina HM and Ban NC** (2015) Advancing marine cumulative effects mapping: An update in Canada's Pacific waters. *Marine Policy* **58**, 71–77. https://doi.org/10.1016/j.marpol.2015.04.003.
Murray CC, **Hannah LC**, **Doniol-Valcroze T**, **Wright B**, **Stredulinsky E**, **Locke A and Lacy R** (2019) *Cumulative Effects Assessment for Northern and Southern Resident Killer Whale (Orcinus orca) Populations in the Northeast Pacific*. DFO Canadian Science Advisory Research Document 2019/056, x + 88 pp.
Otto SA, **Niiranen S**, **Blenckner T**, **Tomczak MT**, **Müller-Karulis B**, **Rubene G and Möllmann C** (2020) Life cycle dynamics of a key marine species under multiple stressors. *Frontiers in Marine Science* **7**, 296. https://doi.org/10.3389/fmars.2020.00296.
Piet GJ, **Tamis JE**, **Volwater J**, **de Vries P**, **van der Wal JT and Jongbloed RH** (2021) A roadmap towards quantitative cumulative impact assessments: Every step of the way. *Science of the Total Environment* **784**, 146847. https://doi.org/10.1016/j.scitotenv.2021.146847.
Segner H, **Schmitt-Jansen M and Sabater S** (2014) Assessing the impact of multiple stressors on aquatic biota: The Receptor's side matters. *Envirnmental Science & Technology* **48**, 7690–7696. https://doi.org/10.1021/es405082t.
Sinclair AJ, **Doelle M and Duinker PN** (2017) Looking up, down, and sideways: Reconceiving cumulative effects assessment as a mindset. *Environmental Impact Assessment Review* **62**, 183–194. https://doi.org/10.1016/j.eiar.2016.04.007.
Stelzenmüller V, **Coll M**, **Cormier R**, **Mazaris AD**, **Pascual M**, **Loiseau C**, **Claudet J**, **Katsanevakis S**, **Gissi E**, **Evagelopoulos A**, **Rumes B**, **Degraer S**, **Ojaveer H**, **Moller T**, **Giménez J**, **Piroddi C**, **Markantonatou V and Dimitriadis C** (2020) Operationalizing risk-based cumulative effect assessments in the marine environment. *Science of the Total Environment* **724**, 138118. https://doi.org/10.1016/j.scitotenv.2020.138118.
Stelzenmüller V, **Coll M**, **Mazaris AD**, **Giakoumi S**, **Katsanevakis S**, **Portman ME**, **Degen R**, **Mackelworth P**, **Gimpel A**, **Albano PG**, **Almpanidou V**, **Claudet J**, **Essl F**, **Evagelopoulos T**, **Heymans JJ**, **Genov T**, **Kark S**, **Micheli F**, **Grazia M**, … **Rumes B** (2018) A risk-based approach to cumulative effect assessments for marine management. *Science of the Total Environment* **612**, 1132–1140. https://doi.org/10.1016/j.scitotenv.2017.08.289.
Stockbridge J, **Jones AR**, **Gaylard SG**, **Nelson MJ and Gillanders BM** (2021) Evaluation of a popular spatial cumulative impact assessment method for marine systems: A seagrass case study. *Science of the Total Environment* **780**, 146401. https://doi.org/10.1016/j.scitotenv.2021.146401.
Stockbridge J, **Jones AR and Gillanders BM** (2020) A meta-analysis of multiple stressors on seagrasses in the context of marine spatial cumulative impacts assessment. *Scientific Reports* **10**(1), 11934. https://doi.org/10.1038/s41598-020-68801-w.
Sutherland GD, **Waterhouse FL**, **Smith J**, **Saunders SC**, **Paige K and Malt J** (2016) Developing a systematic simulation-based approach for selecting indicators in strategic cumulative effects assessments with multiple

environmental valued components. *Ecological Indicators* **61**, 512–525. https://doi.org/10.1016/j.ecolind.2015.10.004.

Tamis JE, **de Vries P**, **Jongbloed RH**, **Lagerveld S**, **Jak RG**, **Karman CC**, **van der Wal JT**, **Slijkerman DME and Klok C** (2015) Towards a harmonised approach for environmental assessment of human activities in the marine environment. *Integrated Environmental Assessment and Management* **12**(4), 632–642. https://doi.org/10.1002/ieam.1736.

Tamis JE, **Jongbloed RH**, **Piet GJ and Jak RG** (2021) Developing an environmental impact assessment for floating island applications. *Frontiers in Marine Science* **8**, 664055. https://doi.org/10.3389/fmars.2021.664055.

Tulloch VJD, **Adams MS**, **Martin TG**, **Tulloch AIT**, **Martone R**, **Avery-Gomm S and Murray CC** (2022) Accounting for direct and indirect cumulative effects of anthropogenic pressures on salmon- and herring-linked land and ocean ecosystems. *Philosophical Transactions of the Royal Society B: Biological Sciences* **377**(1854). 20210130. https://doi.org/10.1098/rstb.2021.0130.

Van Roon MR, **Rigold TP and Dixon J** (2016) SEA planning responses to estuarine cumulative effects of watershed urbanisation. *Journal of Environmental Assessment Policy and Management* **18**(3), 1–30. https://doi.org/10.2307/enviassepolimana.18.3.06.

Willsteed EA, **Birchenough SNR**, **Gill AB and Jude S** (2018a) Structuring cumulative effects assessments to support regional and local marine management and planning obligations. *Marine Policy* **98**, 23–32. https://doi.org/10.1016/j.marpol.2018.09.006.

Willsteed EA, **Jude S**, **Gill AB and Birchenough SNR** (2018b) Obligations and aspirations: A critical evaluation of offshore wind farm cumulative impact assessments. *Renewable and Sustainable Energy Reviews* **82**, 2332–2345. https://doi.org/10.1016/j.rser.2017.08.079.

Willsteed EA, **Gill AB**, **Birchenough SNR and Jude S** (2017) Assessing the cumulative environmental effects of marine renewable energy developments: Establishing common ground. *Science of the Total Environment* **577**, 19–32. https://doi.org/10.1016/j.scitotenv.2016.10.152.