Science of the Total Environment 577 (2017) 19–32

Contents lists available at ScienceDirect

Science of the Total Environment

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

Review

Assessing the cumulative environmental effects of marine renewable energy developments: Establishing common ground

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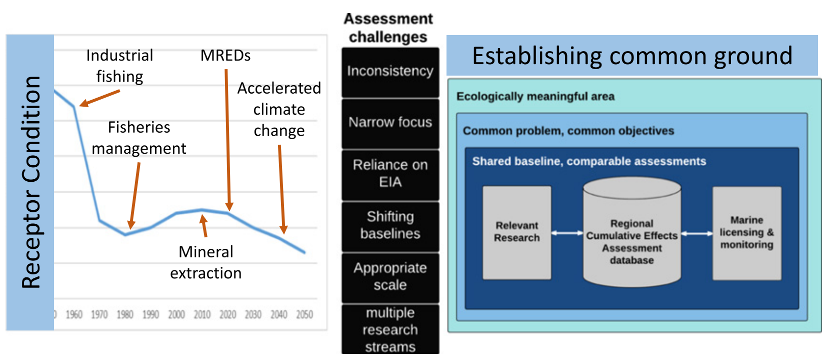
HIGHLIGHTS

- Cumulative environmental effects in the marine realm are reviewed.
- Cumulative environmental assessment approaches are shown to be currently inadequate.
- CEA should be fed data from EIAs, not vice versa.
- A coordinated and multidisciplinary framework of CEA is proposed.
- Coordinated CEA offers robust analysis that frames the wider environmental debate.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 September 2016
Received in revised form 18 October 2016
Accepted 19 October 2016
Available online 3 November 2016

Editor: D. Barcelo

Keywords:
Cumulative effects assessment
Cumulative effects
Marine renewable energy
Environmental impact assessment
Ecosystem approach
Marine management

ABSTRACT

Assessing and managing the cumulative impacts of human activities on the environment remains a major challenge to sustainable development. This challenge is highlighted by the worldwide expansion of marine renewable energy developments (MREDs) in areas already subject to multiple activities and climate change. Cumulative effects assessments in theory provide decision makers with adequate information about how the environment will respond to the incremental effects of licensed activities and are a legal requirement in many nations. In practise, however, such assessments are beset by uncertainties resulting in substantial delays during the licensing process that reduce MRED investor confidence and limit progress towards meeting climate change targets. In light of these targets and ambitions to manage the marine environment sustainably, reducing the uncertainty surrounding MRED effects and cumulative effects assessment are timely and vital. This review investigates the origins and evolution of cumulative effects assessment to identify why the multitude of approaches and pertinent research have emerged, and discusses key considerations and challenges relevant to assessing the cumulative effects of MREDs and other activities on ecosystems. The review recommends a shift away from the current reliance on disparate environmental impact assessments and limited strategic environmental assessments, and a move towards establishing a common system of coordinated data and research relative to ecologically meaningful areas, focussed on the needs of decision makers tasked with protecting and conserving marine ecosystems and services.

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http://dx.doi.org/10.1016/j.scitotenv.2016.10.152
0048-9697/© 2016 Published by Elsevier B.V.

Contents

1. Introduction

The cumulative environmental effects (hereafter cumulative effects) of marine renewable energy developments (MREDs) remain highly uncertain (Bailey et al., 2014; Masden et al., 2015; MMO, 2013) and are problematic in light of ambitious renewable energy targets and aspirations to use the seas sustainably (Bergström et al., 2014; Copping et al., 2014). MREDs, defined here as infrastructure developments that generate electricity from wind, wave, tidal and current resources, add to current pressures or introduce novel stressors that may positively or negatively impact marine ecosystems (Gill, 2005; Linley et al., 2009), thus appropriate assessments of the consequences of development are warranted (Gill, 2005). Efforts to reduce uncertainties to acceptable levels are complicated first and foremost by the numerous knowledge gaps about cause-effect relationships between effects and ecosystem components (MMO, 2013; Lindeboom et al., 2015) but also by the many interpretations of what cumulative effects and cumulative effects assessment (CEA) are (Duinker et al., 2012). Revisiting the origins and evolution of CEA provides insight into the wide application of the term observed today and the plurality of approaches applied.

The origins of CEA as a process are closely linked to the formation and rise of environmental impact assessment (EIA). EIA was formalised following the enactment of the National Environmental Policy Act of 1969 (NEPA) in the USA, established in the wake of popular concern and political action linked to environmental degradation caused by rapid industrial and agricultural progress in the 20th century (Glasson et al., 2012; Du Pisani, 2006). EIA is premised on sustainable development, sensu WCED (1987), being desirable, hence the consequences of activities should be accounted for in decision-making before they happen (International Association of Impact Assessment (IAIA), 2009; Glasson et al., 2012). In the late 1970s, it was realised that for EIA to fulfil its potential, approvals for activities needed to consider other activities in close spatial and temporal proximity (Canter and Ross, 2010). NEPA was thus revised in 1978 to explicitly require the assessment of cumulative effects and, over time (1995 in Canada and 1997 in the European Union, for example), environmental legislation in numerous regions of the world has followed suit (Canter and Ross, 2010; Connelly, 2011).

The practise of CEAs received greater attention in the 1980s and 1990s, as litigation was successfully brought against environmental agencies in the USA deemed not to be meeting their responsibility to assess and manage cumulative effects (Canter and Ross, 2010; Schultz, 2012). Scientists working in different fields increasingly realised the fundamental importance of managing cumulative environmental change, leading to transboundary research initiatives resulting in important conceptual and methodological advances (Cocklin et al., 1992; Beanlands and Duinker, 1984; Preston and Bedford, 1988). Ecological principles began to play a role in EIA, for example the focus on a limited set of valued ecosystem components, or receptors (Beanlands and Duinker, 1984). While interpretation of the principle remains problematic (see Ball et al., 2012), the focus on receptors that experience the effects of development over temporal and spatial scales greater than those typically considered by EIAs for individual projects inevitably led to a spotlight on cumulative effects (Duinker et al., 2012; Therivel and Ross, 2007).

Increasing recognition by policy-makers of the role cumulative effects play in shaping marine and terrestrial ecosystems can be observed in the proliferation of legislation requiring regulators to consider cumulative effects (Judd et al., 2015). While the language stipulating CEA and the impetus behind the legislative drivers varies, the intent of the drivers is consistent; to enable effective protection and management of the environment (Judd et al., 2015). Similarly, growing awareness of how an increasing range and intensity of anthropogenic stressors influences the condition and resilience of ecosystems has led to numerous CEAs of one form or another driven by scientific inquiry. However, while the range of drivers has increased, the bulk of information about the cumulative effects of anthropogenic activities applied in environmental planning and management continues to stem from one source, EIAs completed for individual developments (Duinker et al., 2012; OSPAR Commission, 2008). This is problematic, as EIA-led CEA has historically been (e.g. Cooper and Canter, 1997; Cooper and Sheate, 2002) and continues to be highlighted as a weak link within the EIA process (Canter and Ross, 2010; Wärnbäck and Hilding-Rydevik, 2009; Pope et al., 2013), in large part due to the shortcomings of EIAs at identifying the significance of minor activities accumulating to impact valued receptors and the wider environment (Therivel and Ross, 2007; Squires and Dubé, 2013; Duinker and Greig, 2006). Cumulative effects, defined as effects of an additive, interactive, synergistic or irregular nature that are caused by individually minor but collectively significant activities, accumulate over broad temporal and spatial scales (Harriman and Noble, 2008).

The term CEA (including cumulative impact assessments) has thus become an umbrella term that today encompasses a plurality of interpretations and approaches that seek to address a broadly similar problem, that of cumulative environmental change, sensu Spaling and Smit (1993). In the marine environment, where the crux of management is the protection of natural ecological characteristics while delivering services and benefits to society (Elliott, 2011), CEA, as a source of information about the effects of multiple activities on the environment, could provide strategic support to marine managers and planners (Stelzenmüller et al., 2013). However, the present variability between CEAs, whether conceptual or methodological, is problematic, as outputs are frequently incomparable, preventing assessments of the cumulative effects of, for example, MREDs, at scales appropriate to the identification, mitigation and management of cumulative effects (Judd et al., 2015).

The review was thus completed with the aims of establishing why the variance of CEA approaches exist today, how this is problematic for MRED development today, and how this is problematic in terms of the broader global ambition to implement ecosystem approach management of marine waters. The review includes examination of the key considerations of CEA and why these continue to pose a challenge for marine managers and decision-makers given the current lack of consistency between CEA methods. Finally, recommendations are put forward, which seek to provide tangible considerations to enable improved CEA, supported by the presentation of a conceptual structure to coordinate CEA and pertinent research in a given area.

2. Cumulative environmental change and MREDs

Marine renewable energy developments have shone a spotlight on CEA, as the number of applications for development licenses increase while uncertainty about MRED cumulative effects remains (Masden et al., 2015). In nations that subscribe to sustainable development principles, the environmental effects of MREDs should be a decisive consideration during the planning, licensing and decommissioning processes. However the scale and pace of development and installation has outpaced knowledge of MRED effects, particularly of cumulative effects (MMO, 2013). In many jurisdictions, an expanding MRED industry also overlaps in time with marine management ambitions that hinge on managing cumulative effects to maintain ecosystem services and benefits (Elliott, 2011; McLeod et al., 2005). Thus the impetus to reduce greenhouse gas emissions from the energy generation sector using renewable energy resources (Gibon and Hertwich, 2014) is constrained by the imperative to use coastal and marine waters sustainably. In countries where legally-binding targets for greenhouse gas emission reductions exist and overlap with viable energy resources, proponents of MREDs are calling for accelerated development (e.g. in EU waters; European Commission, 2014). However, the absence of consensus about the nature of cumulative effects and the consequent uncertainty about how to conduct CEA (see Duinker et al., 2012; Judd et al., 2015) prevents thorough strategic planning and causes delays. In the UK, for example, MRED development commenced prior to the government's strategic environmental assessment (Glasson et al., 2012) and delays during the consenting process of up to 42 months for individual MREDs are reported (RenewableUK, 2013). As a result, project costs increase, development timelines extend and investor confidence is impacted (DECC, 2012).

In European waters, where MRED implementation is well advanced, research has focussed on identifying and quantifying effects of construction and operation on particular receptors (notably seabirds, marine mammals and some fish species). Lindeboom et al. (2011) reported on the short-term effects of an individual offshore wind farm noting no significant direct impacts were identified relative to the studied receptors. Similarly for wave and tidal devices, no clear evidence for significant impacts on fish and shellfish arising from individual devices have been observed (Freeman et al., 2013). Studies from monitoring offshore wind farms in Belgian (Degraer et al., 2013) and German (Federal Maritime and Hydrographic Agency (BSH) and Federal Ministry for the Environment, 2014) waters do not point to clear long-term significant impacts to studied receptors, but as noted by Degraer et al. (2013), assigning positive (e.g. fish aggregation) or negative values (e.g. collisions with turbine blades) to observed effects requires local observations to be put in context of receptor populations and the ecosystem more broadly. Thus significant cumulative effects and significant environmental change cannot be ruled out. There are clear gaps in the current understanding of how effects from multiple, large-scale developments will propagate over time and space through an ecosystem. The ecological effects of MREDs, as opposed to the effects of individual stressors on individual receptors, remain largely unexplored (Bailey et al., 2014; MMO, 2013; OSPAR Commission, 2008; van der Molen et al., 2014) and uncertainties remain high (Masden et al., 2015) . In the EU EIA legislation requires developers to undertake CEA and for marine managers to make decisions cognisant of likely cumulative effects. As with marine planning and licensing more broadly, Environmental Statements coming from EIAs that accompany individual developments are the principle sources of information about MRED cumulative effects for regulators (OSPAR, 2008). However, confidence in the CEAs therein is limited (Maclean, 2014), which in large part stems from the "EIA-plus" (Therivel and Ross, 2007) approach applied, which are not well suited to determining if effects arising from individual developments are cumulatively significant (Harriman and Noble, 2008).

The challenge of assessing MRED cumulative effects is increased by MREDs being constructed and operated within an evolving environment that hosts a dynamic range of users and activities. As a result of decades or centuries of use, many marine ecosystems where MREDs are or are planned to be installed already show signs of degradation (Lotze and Milewski, 2008; Halpern et al., 2008a, 2008b; Andersen et al., 2013). In such areas, ecosystems are less resilient and more susceptible to incremental increases in pressures (Crowder and Norse, 2008; Thrush and Dayton, 2010; Thrush et al., 2008a, 2008b). Thus reducing the uncertainty surrounding MRED cumulative effects also requires knowledge gaps that relate to the effects of other marine activities to be addressed. Knowledge gaps abound in relation to numerous maritime activities (see Table 1), exacerbating the uncertainties surrounding MRED effects, as effects from multiple activities overlap and interact in time and space to have a greater net effect on the environment or ecological components (Duinker and Greig, 2006).

The introduction of additional and novel stressors into the environment by MREDs therefore presents a risk that significant environmental change may occur that conflicts with objectives to protect and sustainably manage the marine environment. Deciding how significant the change is likely to be and thus whether the risk is acceptable requires CEA to advance to enable the ecological effects of MREDs to be identified, quantified, and placed in context of other activities and the condition of the receiving environment. Recognising that MREDs present a significant opportunity to deliver climate change mitigation plans (Gibon and Hertwich, 2014), enhance national and regional energy security, and are touted as a source of economic growth (European Commission, 2014), reducing the uncertainty surrounding MRED

Table 1
example maritime activities with effects that may temporally and spatially coincide with MRED effects, and which are also subject to uncertainties about the resultant environmental effects. Effect interactions between effects created by each activity may compound or otherwise interact to result in cumulative effects.

Maritime activity	Example uncertainties	Example references
Oil & gas exploration and extraction	Effects of: seismic noise; habitat change; oil pollution	(Barker and Jones, 2013; Hauge et al., 2014)
Aggregate extraction	Effects of: habitat loss; increased sediment concentrations	(Foden et al., 2010; Cooper et al., 2007)
Navigational dredging	Effects of: habitat loss; increased sediment concentrations	(Tecchio et al., 2016)
Commercial fishing	Effects of: direct mortality; trophic changes; habitat change	(Shannon et al., 2014; Rice, 2008)
Artisanal and recreational activities	Effects of: direct mortality; trophic changes; habitat change	(Hoover et al., 2013; Riera et al., 2016)
Shipping	Effects of: noise and vibration	(Hawkins et al., 2014)

cumulative effects is timely and vital for climate change mitigation and marine management ambitions.

3. Key considerations in cumulative effects assessment

The concept of cumulative environmental change addresses the need to identify, mitigate and manage the effects of the continuum of human activities on the health of the environment. Effects of these activities accumulate over broad temporal and spatial scales to change the environment (Cocklin et al., 1992; Contant and Wiggins, 1991; Spaling and Smit, 1993). In context of MREDs, this requires decision-makers to be aware of the effects of existing MREDs and the likely effects of planned MREDs, and to be aware of how those effects are likely to interact with existing effects of other human activities happening in the same environment, such as aggregate extraction, commercial and recreational fishing, disposal at sea.

Cumulative effects assessments thus need to account for effects that arise over time, over broad spatial scales, which originate from multiple sources and which interact. These attributes of cumulative environmental change are interrelated and collectively result in the cumulative change observed in the environment (Spaling and Smit, 1993). Each of these attributes or considerations are discussed further, as well as two additional considerations (the focal point of a CEA and the context within which a CEA is undertaken) to provide a frame of reference from which to consider CEA as a tool to manage cumulative environmental change.

3.1. Temporal accumulation

Time is one of the less examined attributes of cumulative environmental change and is less considered in CEA in large part due to the shortfall of historical data that can be correlated with spatial data (Halpern and Fujita, 2013). Temporal accumulation refers to change brought about by disturbances or perturbations accumulating as the period between perturbations is shorter than the period of ecological recovery (Spaling and Smit, 1993). Typologies of cumulative effects have been developed, including different means of temporal accumulation, or time crowding and time lags (Cooper, 2004; Glasson et al., 2012), however cumulative effect typologies are debated (see Cocklin et al., 1992). Duinker and Greig (2006), who initially developed a classification of cumulative effect types, subsequently argued that classifications can distract from the critical point, which is to assess the net effect of stressors on valued receptors. A key consideration is thus recognising that effects can accumulate over time in a continuous, periodic, or irregular manner and occur over long or short time scales (Spaling and Smit, 1993).

The temporal accumulation of effects typically manifest as functional effects, where processes (such as the flow of energy) or controlling properties (for example, environmental carrying capacity) are altered (Smit and Spaling, 1995). From a management perspective, CEAs should thus be designed to inform an iterative process, which includes the flexibility to account for incremental changes over time (Cooper, 2004), as well as considering the relevant historical evidence to take account of the relevant changes to support assessments (Bull et al., 2014; Squires and Dubé, 2013). This latter point is crucial to avoid assessments failing to account for “shifting baselines”(Elliott et al., 2015; Pauly, 1995), where assessments of change are measured against a baseline which is significantly different from the original state of the receptor (Hobday, 2011). Where predictions about future effects due to development are required, as with MREDs, scenarios should incorporate a sufficient time horizon to account for forecast development and changes, including climate change (Duinker and Greig, 2007; Cornwall and Eddy, 2015). Efforts to address the potential cumulative effects of MREDs in a given area should thus consider a sufficient historical perspective to determine trends in key receptors and stressors (e.g. Andrews et al., 2014) and be forward looking to consider how predicted effects will interact with forecast trends in environmental conditions and stressors.

3.2. Spatial accumulation

Spatial accumulation, where the effects of perturbations overlap in space (Spaling and Smit, 1993), can result in cumulative change, as the space between perturbations is less than that required to disperse the disturbance (Cooper, 2004; Spaling and Smit, 1993). Spatial accumulation, as with temporal accumulation, can occur over variable scales, from local to regional to global (Spaling and Smit, 1993). Consideration of spatial accumulation is more developed than temporal accumulation enabled by information technology developments such as geographic information systems (GIS) that can analyse and visualise georeferenced datasets (Halpern and Fujita, 2013). Spatial effects typically manifest as structural effects, such as fragmentation of habitats and population shifts (Smit and Spaling, 1995). CEA methodologies thus need to identify the appropriate scale to analyse and assess the spatial accumulation of effects that may affect an ecosystem, which in this case may be also influenced by the characteristics of the area, the resilience of the resident fauna and the intensity of activities undertaken in a given area (Smit and Spaling, 1995). Hence addressing the potential cumulative effects of MREDs requires consideration of the extent of pressures arising from MREDs, existing and planned, cognisant of how the effects of individual developments may accumulate to effect receptors within an ecologically connected area.

3.3. Endogenic and exogenic sources of pressure

Sources of effects contributing to cumulative environmental change can be singular or multiple in origin (Cocklin et al., 1992), but in environments where multiple activities occur, the state of the environment reflects the effects of multiple pressures arising from multiple sources (Duinker and Greig, 2006). CEAs variably assess similar or dissimilar pressure types often chosen for inclusion depending on the driver of a CEA, whether legal or scientific (Judd et al., 2015). CEA addressing cumulative environmental change requires consideration of the effects of multiple sources of perturbations, as the ambition is to understand how environmental condition has been and is likely to be affected by human activities (Cocklin et al., 1992; Squires and Dubé, 2013).

There are two categories of pressures that contribute to change in the system being studied: endogenic and exogenic (Elliott, 2011). Endogenic pressures are those that are created within the system that can be managed; exogenic pressures, such as climate change, are those that emanate from outside the system or operate at scales beyond the system (Elliott, 2011). The effects of climate change are already being felt in coastal environments and changes to date are a fraction of the change predicted, as the seas and oceans respond to physically-driven and chemically-driven changes (Cox et al., 2000; Harley et al., 2006). Climate change adds complexity to the understanding of anthropogenic cumulative effects by introducing stressors that interact with endogenic pressures (Harley et al., 2006) and which challenges CEA, as it operates at a global scale and is subject to uncertainty (EEA, 2015). However, CEAs of MREDs would be incomplete without consideration of potential climate change effects given the time scale of MRED lifecycles (MMO, 2013).

Assessing how MREDs, as individual and/or multiple developments, will affect the environment therefore requires an assessment of MRED stressors both existing and forecast, placed into context of an analysis of the condition of the environment receiving the stressors (the baseline) and analyses of how the environment responds to effects (Dubé, 2003; Duinker et al., 2012; Judd et al., 2015; Marcotte et al., 2015). This is challenging as clear knowledge gaps remain for MREDs in their own right and for MREDs together with other activities.

3.4. Ecological connectivity

The connectivity between elements of the biophysical world (and of society to ecosystems) introduces further interdependencies that influence cumulative environmental change (Spaling and Smit, 1993). Thus while the concept of CEA is intuitive, the practicalities of assessment are complicated by a complex reality of interactions between causations, processes and organism populations, and of human activities, past and present, combining to simultaneously affect numerous areas within an area of study (Bedford and Preston, 1988). Thus assessments of the significance to the environment of changes that result from current or proposed activities, which typically consider unlinked components in the environment, should be viewed as pieces of an incomplete puzzle.

The connectivity between ecosystem components leads to the potential for indirect effects of stressors to arise, such as food web effects caused by changes in prey abundance (e.g. Perrow et al., 2011). CEA therefore requires a broader perspective to be applied that takes into account the connections and effects on biodiversity and ecological functions in a given area (Thrush and Dayton, 2010; Strong et al., 2015). As marine management objectives expand to a more holistic perspective, assessing how activities and stressors influence ecosystem functions, rather than individual species, may provide a more efficient means of monitoring ecosystem health (Strong et al., 2015). For example, in seafloor systems, marine benthic organisms perform essential functions, helping those particular systems to deliver many goods and services. Ecological functions can be manifold, some examples are habitat provision, secondary production, sediment reworking via bioturbation. Recently, at the EU level under the Marine Strategy Framework Directive there is a pressing need to ascertain seabed and ecosystem functions (Birchenough et al., 2012; Birchenough et al., 2013) to support sustainable use and management of marine resources. The effects of individual functions combined with the rate of functioning governed by relationships between abiotic and biotic factors are key parameters to understand the way seafloor systems operate (Reiss et al., 2009).

3.5. Placing receptors at the centre of assessments

A key criticism of EIA-led CEA is the stressor-led approach, which assesses how single stressors arising from a proposed development together with the same stressor arising from proximal developments or activities impact a valued receptor (Squires and Dubé, 2013; Dubé et al., 2013; Duinker et al., 2012). Recognising that receptors experience multiple stressors and accumulate effects over broad temporal and spatial scales, EIAs thus struggle to assess how receptors respond to cumulative effects (Therivel and Ross, 2007; Duinker et al., 2012). To appraise how additional or novel stressors from one or many activities will impact a receptor requires sufficiently broad horizons that include consideration of the array of stresses that human activities impose on the receptor (Duinker and Greig, 2006; Duinker et al., 2012). Receptors, rather than stressors, therefore, should be the focal point of CEA and guide the identification of the various stressors to include in an assessment of how an activity or activities will impact receptors. The use of the term “impact” also brings into play the distinction between “effects” and “impacts” of stressors. To determine whether a stressor effect is of sufficient magnitude and intensity to have a meaningful impact on a receptor, for example a significant decline in population, typically requires additional information or research, however many studies use the term impact based on findings that suggest an effect (Boehlert and Gill, 2010). MRED CEA studies typically assess receptor responses to individual stressors, such as habitat loss, generated by a limited number of activities, such as offshore wind farm construction and aggregate dredging (e.g. Smart Wind, 2015). The results contained in such CEAs are presented as determinations of impact significance, however to determine the cumulative effect of a stressor on a receptor requires consideration of the range of stressors acting on the receptor (Duinker and Greig, 2006), i.e. effects, not impacts, sensu Boehlert and Gill (2010) have been assessed.

CEA methodologies that consider the traits and sensitivities of receptors to guide the design of an assessment are better able to identify and predict multiple stressor effects (Segner et al., 2014; Teichert et al., 2016). Receptor-led approaches also support improved consistency between CEAs by enabling unifying metrics to be identified that can be applied to a receptor or function (Segner et al., 2014). Assessments that have placed receptors at the centre of MRED CEA have been instructive in identifying the potential risks of widespread MRED deployments relative to wide-ranging mobile receptors (e.g. underwater noise effects on marine mammals; Heinis and de Jong, 2015; collision risks for seabirds and bats; Leopold et al., 2014). Such CEAs also enable investigation into one of the longstanding uncertainties surrounding CEA, that of appropriate temporal and spatial boundaries. CEAs that centre on the receptor imply boundaries being applied based on temporal and spatial characteristics of receptors (Therivel and Ross, 2007; Segner et al., 2014).

3.6. Purpose and context

The final consideration discussed here is the purpose of a CEA and the context that shapes the design of a CEA. Why a CEA is undertaken influences the approach taken, the receptors included and thus the output, poorly-defined and overly generic assessments lead to variability and uncertainty that is problematic for marine managers. While drivers behind marine CEA are varied (see Judd et al., 2015), the movement away from sectoral management to ecosystem approach management suggests that variability in a planning and management context could decrease if CEAs converge on a common position about the aim and output of CEAs regardless of activity.

The ecosystem approach to management has emerged as a tenet around which marine management is centred (Elliott, 2011; Long et al., 2015; McLeod et al., 2005), recognising that the combined sources of pressures, rather than isolated sectors, require management if sustainable use of the seas is to be achieved (Curtin et al., 2015; Borja et al., 2013; Elliott, 2011). In Europe, the obligation of EU Member States to achieve Good Environmental Status (see Borja et al., 2013) for marine waters by 2020 has led to regional assessments of the state of the environment (e.g. HM Government, 2014) and the mapping and assessment of the effects of multiple human pressures on environmental status (e.g. Andersen et al., 2013). Regional studies provide context for CEAs relating to discrete activities, and could form the basis for a common baseline to support future CEAs. Many of the uncertainties that apply to CEA broadly also apply to regional CEA, for example cause-effect knowledge gaps, data paucity and a lack of assessment tools (Foden et al., 2011a, 2011b). Further, the conceptual issues about what cumulative effects are and how to assess them remain pertinent for regional CEA also. A critical point is while policy-makers, marine managers and researchers have converged on cumulative effects as a key issue to resolve, the varied aims, contexts and expectations of CEAs leads to outputs that are not necessarily fit for purpose for marine management ambitions (Judd et al., 2015).

4. Key challenges to improving cumulative effects assessment

For CEA to evolve into a consistent, appropriate decision-making tool, a series of challenges remain that require resolution. Key to advancing CEA are: coordinating the multitude of approaches to CEA to enable currently disparate methodologies to contribute to improving regional understandings of cumulative environmental change; overcoming the dominance of EIA-led CEA in the planning and licensing systems; enabling CEA to provide ecosystem-relevant information; and applying CEA within the context of an appropriate baseline. To meet these challenges requires common ground to be established within a defined area by provision of an overarching frame of reference. These challenges are expanded on in the following sections.

4.1. Convergent thinking, divergent approaches

From predictive, EIA-based origins, CEA today includes retrospective, pressure-based approaches (e.g. Halpern et al., 2008a, 2008b), predictive, stressor-based approaches (e.g. standard EIAs), and frameworks seeking to integrate both predictive and retrospective approaches (Dubé et al., 2013). The focus of CEAs ranges from individual species (e.g. caribou, Johnson et al., 2015; harbour porpoises, Heinis and de Jong, 2015), to habitats (e.g. seagrass, Grech et al., 2011; fish habitat in estuaries, Teichert et al., 2016), to ecosystem functions and services (e.g. biodiversity; Andersen et al., 2015). The scale of CEAs varies correspondingly, from boundaries defined by the extent of stressors arising from a single development, by species distribution (e.g. seabirds and bats, Leopold et al., 2014), to ecologically meaningful areas (e.g. watersheds, Squires and Dubé, 2013; the Baltic, Korpinen et al., 2012), increasing to global marine areas (e.g. Halpern et al., 2008a, 2008b).

The emergence of regional CEAs owes much to the conceptual and practical advances associated with improving the management of wetlands (e.g. Preston and Bedford, 1988) and watersheds (e.g. Dubé, 2003). Recognising that EIA and project-driven CEA could not match the spatio-temporal dynamics of valued receptors or the broader environment (Preston and Bedford, 1988; Squires and Dubé, 2013), CEA researchers assessed increased spatial scales to consider the effects of multiple stressors acting within ecologically meaningful areas. In the marine environment, a clear example of expanded boundaries stems from the North Sea, where improved CEA tools were developed in response to ongoing and expanding industrial activities. Regional boundaries have been applied in response to legislative drivers to assess human pressures in the marine environment (e.g. Andersen et al., 2013). The expansion of MREDs in the North Sea has driven CEA forward, with cumulative effects of MREDs stressors coming under scrutiny (e.g. Bailey et al., 2014; MMO, 2013; Pine et al., 2014; Wright and Kyhn, 2015). CEAs for MREDs that apply broader spatial scales include those completed under FAECE (Framework for Assessing Ecological and Cumulative Effects of offshore wind farms), a structured methodology developed for the Netherlands government, that distinguishes between a legal and ecological approach, recognising that legally compliant CEA may not be ecologically relevant (Ministry of Economic Affairs, 2015). The framework has been applied regionally, investigating cumulative disturbance to marine mammals caused by impulsive underwater noise (Heinis and de Jong, 2015) and the cumulative effect of collision and habitat loss on seabirds and bats (Leopold et al., 2014). As with many marine CEAs, the paucity of data and uncertainties about cause-effect relationships require assumptions to be made that limit the confidence in the outputs (Heinis and de Jong, 2015; Leopold et al., 2014). However, the application of novel methodologies that define the spatial boundaries based on the receptor, and which determine significance in context of the receptor population are important advances for marine CEA.

While data paucity is problematic, regional CEAs are developing rapidly building on advances in understanding stressor-receptor relationships (e.g. stressors affecting fish in estuarine waters; Teichert et al., 2016), receptor traits (e.g. spatial behaviours of seabirds relative to offshore wind farms; Bradbury et al., 2014); mapping (e.g. iterating a CEA using novel temporal data; Clarke Murray et al., 2015a, 2015b), and applying novel conceptual frameworks (e.g. Vries et al., 2012). Literature points to the development of CEAs, particularly CEAs completed for MREDs, advancing via progress grounded in academic research, rather than advances driven by the EIA process. For example, elucidating the cumulative effect of collisions of seabirds with offshore turbine blades has progressed by applying advances in distribution modelling (e.g. Miller et al., 2013) and species sensitivity modelling (e.g. Bradbury et al., 2014). Such advances have in turn enabled CEAs at scales appropriate to receptors.

A similar process of iterative CEA development can be observed with the application and refinement of the spatial analysis methodology published by Halpern et al. (2008a, 2008b). The mapping approach developed by Halpern et al. (2008a, 2008b) has been instrumental in progressing marine CEA by building on advances in geospatial analysis techniques to match broad-scale habitats with anthropogenic activities and using expert judgement to estimate the sensitivity of, and thus impact to, the habitats. Adaptations of the approach have been applied to regional waters (e.g. Canada's Pacific coast; Ban et al., 2010; Mediterranean Sea and Black Sea; Micheli et al., 2013), to include indirect pressures as well as direct anthropogenic pressures (e.g. climate change and industrial development; Clarke Murray et al., 2015a, 2015b), and to enable effects of anthropogenic activities on specific ecosystem components to be assessed (e.g. on marine predators; Maxwell et al., 2013). Further refinement is required to adapt advanced spatial analyses to meet the needs of marine managers, by providing information at a scale appropriate for management interventions, validating predicted stressor intensities and by combining spatial analyses with suitable temporal information to provide indications of environmental change (Halpern and Fujita, 2013; Judd et al., 2015).

Conceptual frameworks, such as the driver-pressure-state-impact-response (DPSIR) framework (e.g. (Elliott, 2002), have been influential in bringing systems thinking to understanding relationships between drivers and effects (Atkins et al., 2011) and the DPSIR approach has been recommended for marine CEA (MMO, 2013; Kelly et al., 2014). DPSIR continues to develop with the integration of human welfare as a link in the framework (DSPWR; Cooper, 2013) and to identify activities resulting in pressures (Driver-Activities-Pressures-State-Impact-(Welfare)-Response; DAPSI(W)R; Elliott, 2014). Reflecting the connectivity between natural systems, effects and responses, the DPSIR approach has further developed to account for interactions between linkages, a networked approach, to support prioritisation of marine management interventions (Knights et al., 2013). A variation on the driver-effect framework, CUMULEO (Cumulative Effects of Offshore activities) has been developed and proposed as a “conceptual umbrella” (Tamis et al., 2015) to bring direction to the various forms of environmental assessment, working from the strategic level down to project level (Tamis et al., 2015). Network thinking is applied to map the relationships between multiple activities developed by Knights et al. (2013) to address the assumed independence between linkages that limits standard DPSIR approaches (Gregory et al., 2013; Knights et al., 2013). A variation of CUMULEO, CUMULEO-RAM, has been tested in Dutch coastal waters, translating spatial information about activities and stressors into indicators of ecological significance (Vries et al., 2012). As well as considering relationships between activities, the model output includes estimates of the contribution of each activity to effects on receptor survival and reproduction, an important step forward for CEA in context of marine management.

4.2. A call for multidisciplinary action

The ubiquity of cumulative effects in the environment and the impact cumulative effects have on the quality and health of the environment (Duinker and Greig, 2006) result in many lines of research being relevant to CEA. For CEA to advance beyond isolated perspectives towards the broader perspective required to identify, assess and manage cumulative environmental change requires multidisciplinary thinking. Multiple stressor analyses and ecological modelling, which seek to elucidate cause and effect relationships in complex networks are increasingly relevant to CEA. Multiple stressor analyses seeking to identify and rank stressors to enable targeted management interventions (e.g. conservation of seagrasses, Giakoumi et al., 2015; quality of fish habitat within estuaries, Teichert et al., 2016) hold promise to enable more effective CEAs by providing structured methodologies around which key stressors can be identified relative to the resource in question.

Marine ecosystem models assist with analysing and testing the dynamics of foodwebs within marine ecosystems and provide a means of estimating how ecosystems respond to stressors (Steenbeek et al., 2013). As such, the models hold promise to support CEA by enabling stressor effects to be modelled at ecologically meaningful scales and by supporting the establishment of a baseline by assessing ecosystem status (Piroddi et al., 2015). Ecopath with Ecosim (Christensen et al., 2005) is a widely used modelling approach that is evolving to enable the integration of spatial and temporal dynamics within ecosystem models (Coll et al., 2015; Steenbeek et al., 2013). Physical models have also been applied to test the effects of physical disturbance due to MREDs on ecosystems (van der Molen et al., 2014). Modelling effects is an attractive option, as empirical studies at sea tend to be prohibitively expensive (Alexander et al., 2016), but despite the mathematical complexity, models are simplified simulations of the real world and are based on assumptions, thus validation of models is critical to test, refine and improve modelling tools (Forrest et al., 2015). Again, as with CEA more broadly, the paucity of data, issues of scale and data resolution, and the knowledge gaps about cause-effect relationships pose challenges for model development and validation (Alexander et al., 2016).

In the context of identifying and managing sources of cumulative environmental change, the different approaches vary in terms of the receptors considered, methodologies applied and stressors assessed. Additionally significance, specifically the likelihood of an effect occurring that has a significant impact on a valued receptor (see Boehlert and Gill, 2010) is variably interpreted (Ehrlich and Ross, 2015). The outputs of the approaches also differ, from spatial outputs, to diagrammatic outputs highlighting key stressors, to networks of linked drivers and ecosystem components. Thus while many research streams are relevant to managing cumulative environmental change and to CEA, a key challenge is to enable the outputs of relevant research streams to converge on resolving a commonly understood problem, and to encourage interdisciplinary and cross-border research.

4.3. The dominance of EIA constrained cumulative effects assessments

EIA-constrained CEA continues to dominate decision-making support in practise (Duinker et al., 2012) despite EIA approaches struggling to deliver meaningful CEA (Gunn and Noble, 2011; Squires and Dubé, 2013; Therivel and Ross, 2007). While EIA grapples with meeting expanded expectations around CEA, EIAs have become increasingly resource-heavy and burdensome (Smart et al., 2014; Wright, 2014) while failing to meet the evolving information needs of regulators and decision-makers tasked with protecting and maintaining the overall condition of the environment (Hegmann and Yarranton, 2011; Judd et al., 2015). The continued focus of EIAs on regulatory compliance (Ball et al., 2012) rather than CEA advancement suggests that EIA-led CEA alone, unless fundamentally changed, is unlikely to resolve the "conundrum of cumulative effects assessment" (Judd et al., 2015). Whether individual developments can reasonably be expected to assess effects at the spatio-temporal scales that apply to receptors, which may include migratory species, watersheds or ecosystems, is moot (Freeman et al., 2013), and it has been argued that responsibility for CEA should be borne by governments (e.g. Duinker and Greig, 2006). A counterpoint to this argument is the strength of decision-making processes associated with EIA and the widespread acceptance of EIA as a process to support sustainable development (Glasson et al., 2012). Noting that the arguments against standard EIA approaches (Glasson et al., 2012) as a means of addressing cumulative environmental change are well established and have been tested (e.g. EIAs not identifying incremental declines in habitat connectivity for woodland caribou, Johnson et al., 2015; EIAs not identifying the incremental loss of habitat for burrowing birds, Heneberg, 2013), calls for a rethink of the relationship between EIA and CEA (Greig and Duinker, 2014) remain pertinent.

Numerous authors have pointed to the need for cross-border regional or strategic approaches to CEA (e.g. Duinker et al., 2012; Duinker and Greig, 2006; MacDonald, 2000; Gunn and Noble, 2011) and generic frameworks to coordinate tiered environment assessments have recently been proposed (e.g. CUMULEO; Tamis et al., 2015). While the rationale for strategic approaches to proceed project-level assessments is intuitive and well founded (Lobos and Partidario, 2014; Tetlow and Hanusch, 2012), the reality in many areas, for example United Kingdom waters of the North Sea, is that project-level assessments precede strategic assessment (Glasson et al., 2012). Further limitations of relying on strategic environmental assessments to resolve the EIA-cumulative effect conundrum are that strategic environmental assessments tend to apply standard EIA approaches to impact assessment (Lobos and Partidario, 2014) and decision-making structures are less robust than EIA processes (Gunn and Noble, 2011). Arguably, in the context of CEA and cumulative environmental change, the conceptual questions (e.g. what stressors and receptors should be included, what time and spatial scales for assessment are appropriate, how to consider exogenic pressures) and practical questions (e.g. how do receptors respond to multiple stressors; how do changes propagate through the ecosystem) pose greater obstacles to strategic environmental assessments overcoming the CEA conundrum. Enabling the regional approaches to CEA will thus require cross-border, multidisciplinary approaches that combine to reduce uncertainty and illuminate where priority effects are impacting the status of the environment.

An alternative to stressor-based assessments are the effects-based assessments that put the environment as the focal point of the assessment, and seek to measure changes in indicators relative to a reference condition (Dubé et al., 2013). The priority of effects-based assessment is the monitoring and measurement of ecological change (Dubé et al., 2013), which has implications for managers and planners who also require knowledge about the causes, as well as consequences of effects, and support to manage and mitigate future effects (Judd et al., 2015). Thus while there are limitations to stressor-based, predictive methods, such approaches in combination with effects-based, retrospective CEA hold greater promise of enabling sustainable development than one approach in isolation (Dubé, 2003; Dubé et al., 2013). Coordination of project and regional CEA also offers the potential to combine strengths of each approach (Fig. 1). In countries where development and activities are required to submit EIAs in support of a development application, the frequency of assessments offers inputs of data obtained during characterisation and monitoring studies that could improve the resolution of regional baselines. Furthermore, regional CEAs that apply meaningful spatial boundaries relative to cumulative environmental change could inform the determination of appropriate spatial boundaries for project CEAs.

4.4. Adapting CEA to support ecosystem assessments

Realising the potential of CEA to support holistic marine management requires CEA to provide information about the effects, current and forecast, of human activities on an ecosystem. This is challenging due to the natural variability of ecosystems and the many knowledge gaps that exist about ecosystem structure and functioning (Thrush and Dayton, 2010). The potential for interactions between effects, which may result in non-linear responses (Crain et al., 2008; Piggott et al., 2015) and between nested ecosystem components (Malone et al., 2014) have led CEA to be labelled an intractable problem (Stakhiv, 1988). The nature of the marine environment exacerbates the CEA challenge as the three-dimensional scale from seabed to surface, the connectivity between areas linked by vast dispersal distances of eggs and larvae (Crowder and Norse, 2008; Carr et al., 2003) combined with the difficulties of visual observation make marine research expensive and logistically challenging (Parsons et al., 2014).

The difficulties observing marine processes and responses to stressors mean that empirical observations, particularly sustained observations of the dynamics of marine systems, are often lacking (Malone et al., 2014). In the context of CEA, while advances in spatial analyses improve predictions about where cumulative effects concentrate (e.g. Halpern et al., 2008a, 2008b) and progresses in

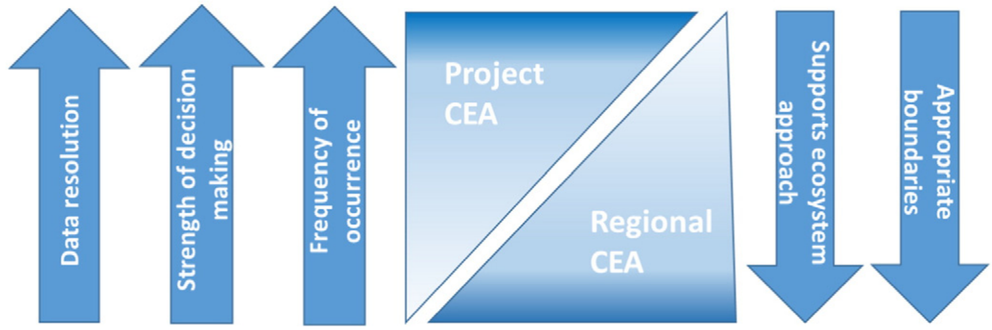

Fig. 1. comparison between characteristics of typical project-driven CEA and regional CEA. The direction of the arrow indicates increasing strength of the characteristic relative to the need to identify and manage cumulative environmental change. Benefits of project CEA relative to regional CEA include the higher resolution of data, the strength of decision-making associated with project assessments, and the frequency of assessments completed. Regional CEA, by contrast, tends to apply more appropriate boundaries (notably spatial) to assess cumulative effects and the results of which support ecosystem approach management. Coordinating these scales of assessment to resolve a common problem would lead to more efficient progress towards developing a CEA system capable of supporting marine management ambitions.

environmental modelling to predict the significance of cumulative effects (e.g. van der Molen et al., 2014), verification remains difficult due to the paucity of appropriate data (Halpern and Fujita, 2013). To this end, the diverse research streams investigating, for example, cause-effect relationships and multiple stressor interactions, aid improved CEA by providing data and insights into how cumulative effects arise and interact. Equally, published results of monitoring programmes that observe the environmental effects of, for example MREDs (e.g. Degraer et al., 2013; Federal Maritime and Hydrographic Agency (BSH) and Federal Ministry for the Environment, 2014) provide important data that could verify predicted effects and which could enable local observations to be scaled to predict ecosystem-level effects. Critical to advancing CEA will be integrating scientific advances from research into multiple stressor interactions (e.g. Teichert et al., 2016; Tran et al., 2009; Jackson et al., 2015), systematic approaches to mapping cause-effect relationships (e.g. Gregory et al., 2013; Knights et al., 2013) and ecological studies illuminating the sensitivities of species and ecosystems (e.g. Nimmo et al., 2015; Thrush et al., 2008a). Providing CEA practitioners with access to fit for purpose information and appropriate CEA tools that enable disparate datasets to be combined will be a key development to advance CEA in a given region.

4.5. Establishing a baseline

For CEA to support environmental management in an area with ongoing and forecast activities, it is necessary to establish a fixed baseline against which to evaluate predicted effects (Bull et al., 2014). Establishing a baseline for CEAs is contentious, as approaches alternatively recommend a baseline developed from historical conditions (e.g. Squires and Dubé, 2013) or working from the present condition (e.g. Vries et al., 2012). EIAs for MREDs veer towards the latter by including existing pressures within the baseline, i.e. assuming that the current condition of VECs or the environment is normal. However this shifting baseline approach risks accommodating and masking environmental change (Pauly, 1995) potentially presenting marine managers with a Sisyphean task as reference points continually change (Gatti et al., 2015).

Marine systems tend to experience a wide range of perturbations, which can result in a series of succession patterns. Depending on the level of the perturbation, some systems may often return to a pre-impacted state or in some cases experience further levels of disturbances (Birchenough and Frid, 2009). The perturbed nature of most marine ecosystems suggests that an “original” state is unlikely to be recovered, particularly in light of climate change (Hobday, 2011). Thus determining an appropriate baseline is difficult, particularly as the concept of an equilibrium state is entrenched in ecological thinking (Hobday, 2011). The challenge of defining a baseline also hinders the establishment of thresholds, which are widely considered to be essential if the significance of effects are to be quantified relative to a receptor (Duinker et al., 2012; Seitz et al., 2011; Westbrook and Noble, 2013). The requirement to refer to thresholds is presently problematic, as more often than not, thresholds are unknown and determining defensible thresholds based on empirical evidence is scientifically and socially challenging (Duinker and Greig, 2006; Foley et al., 2015; Groffman et al., 2006). As with CEA, the application of the concept of thresholds is open to interpretation, which, exacerbated by questions about scale, natural variability and nonlinear system responses, can reduce confidence in defined thresholds (Groffman et al., 2006). Finally thresholds can vary between jurisdictions, hindering regional assessments for receptors that range beyond national boundaries, for example sound exposure thresholds for marine mammals in European waters (Luedeke, 2012). Thus as maritime activities continue to expand, pragmatic alternatives are necessary to support management where thresholds are absent. Where thresholds are absent, the determination of trends based on the integration of historical data, where available, provides an opportunity to guide management decisions (Mcclenachan et al., 2012). The use of trends can identify the extent to which a population has changed over time and thus provides insights into whether or not a receptor is likely to be resilient to or particularly sensitive to additional stress (Mcclenachan et al., 2012), which may provide much needed insight into the significance of effects.

The use of different baselines between assessments brings into focus determinations of significance. EIA is concerned with identifying significant environmental impacts (Beanlands and Duinker, 1984; Glasson et al., 2012), but significance is a difficult term to pin down, as it is relativistic and can relate to statistical, ecological, social or project significance (Beanlands and Duinker, 1984). Without shared temporal and spatial points of reference between assessments, the context within which determinations of significance are made may vary, including temporal and spatial scales, interpretations of value, ecological sensitivity and so on (Wood, 2008). For CEA, which requires that the effects of different activities and stressors on receptors can be compared, such variation is problematic.

As with temporal scale, the spatial scale applied to assessments can influence the determination of significance. The spatial scale applied and how variability within time and space is dealt with have fundamental bearings on how likely it is that an effect will be detected (Hewitt et al., 2001). What appears significant at a local level may appear insignificant in a regional context, for example. Spatial scale, in comparison with the temporal component of CEA, is easier to conceptualise and integrate into an assessment, in large part due to advances in geographic information systems (GIS). Temporal scale is difficult to integrate into assessments (Halpern and Fujita, 2013), although recent evaluative CEAs have investigated temporal change in pressures in an area compared with previous iterations (Halpern et al., 2015; Clarke Murray et al., 2015a, 2015b).

A challenge for CEA in a given area is thus to put an appropriate frame of reference in place, including a temporal line in the sand from which future CEAs can use to determine the significance of changes to valued receptors, and which can be used to measure changes caused by permitted but not yet constructed developments. A challenge is identifying suitable receptors relative to CEA for which historical data exists that enables trends to be determined and against which counterfactual scenarios (without development) could be modelled (Bull et al., 2015).

4.6. Establishing common ground

A universal definition for cumulative effects and of CEA seems unlikely given the variety of drivers behind CEA research and the lack of consensus about the nature of cumulative effects (Duinker et al., 2012). While the lack of consensus leads to variability that impedes resolution of one interpretation of the problem, arguably the flexibility is positive as different CEAs seek to address discrete and perhaps more tractable parts of the problem, and provide insights into interactions between elements of the ecosystem. Thus the range and breadth of CEAs may lead to a more rapid resolution of the CEA problem. Every CEA, however, should be accompanied by a clear statement of the objective, scope and boundaries of the assessment (Duinker et al., 2012; Cooper, 2004; Judd et al., 2015), and each assessment should be guided by a specified definition of cumulative effects appropriate for the task in hand (Duinker et al., 2012; Judd et al., 2015), hence the importance of CEA principles being elaborated relative to marine management (see Judd et al., 2015).

From a marine management perspective, variability between CEAs is problematic (Ball et al., 2012; Judd et al., 2015). Thus while the breadth of CEAs undertaken in an area could present an advantage, it is appropriate that common ground is established from which to guide CEAs relative to the licensing and management of marine activities. This would require a common position to be agreed about the objective and outputs of CEAs completed for proposed activities, such as MREDs, in a given area. This common ground would need to apply to all activities within a given area. Ultimately improvements in environmental condition will require integrated management of the variety of effects generated by the multitude of users (Elliott, 2013), thus marine managers require compatible information from CEAs regardless of the activity or pressures considered.

For regional management to benefit from CEA requires managers to have access to information from assessments designed to identify and assess effects accumulating or otherwise interacting over different temporal and spatial scales, and generated by multiple activities. As suggested in this paper, the plurality of methodologies and different assessment scales could be interpreted as a strength. We suggest that CEA is thus coordinated within a meaningful area in terms of purpose and outputs. Coordinating CEA by defining what CEA is for relative to a region that is meaningful, ideally in an ecological rather than jurisdictional way, provides an opportunity to harness the multitude of assessments and pertinent research (Fig. 2).

Fig. 2 illustrates a representation of a nested system to provide a structure from which to coordinate CEAs conducted within an ecologically meaningful area by enabling the flow of information to and from decision-makers, EIA practitioners and CEA researchers regardless of the scale at which individual CEAs are conducted. The regional CEA database informs marine management, including licensing marine activities, which is nested within the regional management system. EIA-led CEA becomes CEA-led EIA and significance determinations are informed with reference to the regional CEA database. The information flow between research and databases is an iterative process that can allow CEA to improve over time by directing research to address priority knowledge gaps and by taking into account new knowledge, helping to improve the regional database. Existing activities would then be integrated into the baseline, but effects and trends accounted for to avoid shifting baselines. When an application for a license permitting a development or activity is entered into the marine licensing system (the process stream on the left hand side of Fig. 2), the CEA process, from stressor generation study through to the determination of significance, is guided by the regional CEA database to enable comparable CEAs that contribute to the regional picture.

The representation in Fig. 2 is designed to coordinate CEAs at regional and project level to reduce the incongruity between CEAs completed at different scales and for different activities. The nested system also redefines the roles of CEA and EIA, becoming CEA-led EIA that feed into the regional system designed to support the marine management ambitions to manage cumulative effects.

EIAs remain important, not only to maintain the polluter pays principle, but, from a practical perspective, because EIAs provide higher resolution information, thus coordinated CEA-led EIAs offer the opportunity to improve the resolution of the baseline. The development of, for example, distribution modelling techniques (e.g. Reiss et al., 2015) suggests that project-level data could become valuable to regional assessments (if made available), by increasing the resolution of temporal and spatial datasets for habitats, species abundances and distributions. Such a system would in theory be cost efficient for marine industries as well as marine regulators and managers, by enabling a more streamlined system to develop over time that builds on incremental advances in receptor understanding, appropriate boundaries and fit for purpose monitoring that can respond to changes in environmental conditions and system understanding.

The suggestion to systematically nest the information within an ecologically meaningful area draws attention to the need for a transboundary approach. In areas where multiple coastal states contribute to and need to manage cumulative effects, the need to share information and CEA tools, compatibility of outputs and coordination of governance mechanisms to manage cumulative effects increases in importance. MREDs, as a relatively novel and rapidly expanding marine industry, are a pressing issue in numerous regions, are potentially associated with beneficial as well as short-term adverse environmental effects (Boehlert and Gill, 2010; Linley et al., 2009), and hold strong potential to reduce the greenhouse gas emissions associated with generating energy (Gibon and Hertwich, 2014). CEAs have been completed for individual MRED developments during the planning and licensing process, and considerable monitoring data has been generated by individual developments and via formal studies (e.g. Degraer et al., 2013). Numerous CEAs also exist for stressors or pressures generated by other marine industries (Korpinen et al., 2013; Wright and Kyhn, 2015; Foden et al., 2011a, 2011b). Further, CEAs exist for formal spatial and ecosystem approach planning (e.g. UK regional marine plans), for formal guidance (e.g. Heinis and de Jong, 2015), and much more commonly for academic research.

While much of the information from these sources may not be immediately comparable, by defining common ground for CEA in a given region, past CEAs could be revisited in light of unifying receptor-centric metrics, and the outputs of future CEAs could be coordinated. Establishing and using a regional baseline and regional CEA database that incorporates habitat maps, cause-effect analyses, effect-receptor analyses sensitivity analyses (for habitats and species, including mobile species), would enable the use of shared or compatible metrics in the assessment of effects and activities from different sectors, placed in context of the environment (i.e. receptor-led CEA). From a planning perspective, the efficiency and accuracy of the database and its utility during planning should improve through iterative development and improved connectivity between scientific advances and CEAs/EIAs.

The concept of nested approaches to support effective CEA is not novel (e.g. MacDonald, 2000; Tamis et al., 2015). The system represented in Fig. 2 differs by making explicit the need to first define the meaningful area, secondly agreeing the management and strategic planning objectives for that area, and thirdly establishing a location-specific

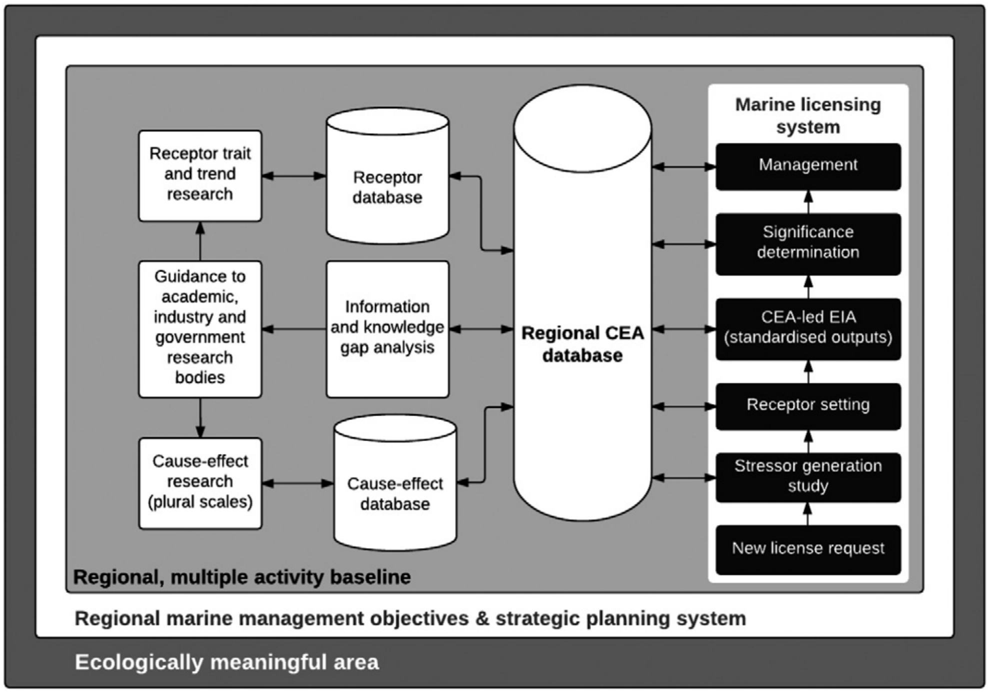

Fig. 2. Summary schematic representing a nested system to coordinate CEAs within an ecologically meaningful area. The conceptual diagram encompasses a series of licensing activities over a regional management system. The direction of arrows indicates the flow of information; double headed arrows indicate a flow of information in both directions to enable iterative improvements in the regional CEA knowledge base.

baseline that applies to all CEAs (or EIAs) completed for activities and developments in the area. This systematic nested approach would clarify the broader temporal and spatial boundaries relative to the meaningful area and enable the development of a dynamic database where CEAs completed for individual developments or activities benefit from and feed into a regional CEA database that is available to regulators, marine managers and researchers.

The system posited seeks to contribute to realising the potential of CEA by clarifying the relationships between CEAs completed at different scales and providing a common position from which the complex, multifaceted problem of CEA, covering a multitude of activities, cause-effect relationships and receptors can be broken into tractable chunks while enabling the pieces of the puzzle to feed into a larger, regional picture. The system seeks to evolve EIAs into fit for purpose assessments that place clear expectations on developers and EIA practitioners relative to the information needs of marine managers and planners concerned with effects accumulating at scales beyond those that could be reasonably assessed by individual developments. Coordinated CEA, building on a shared foundation, technically rigorous, collaborative and focussed on a common problem, would provide decision-makers and the public with a shared narrative to debate what trade-offs society at large is willing to accept in the pursuit of economic growth and social wellbeing.

5. Conclusions

Cumulative effects assessment is an umbrella term for a broad range of methodologies, driven by numerous drivers, that seek to assess how past, current and future activities lead to changes in the environment that impact the goods and services society derives. The multitude of approaches, while problematic in one regard, holds greater promise to reduce the many uncertainties by enabling tractable chunks of the problem to be addressed, providing the outputs are comparable and can inform a regional picture. Within a meaningful area, whether defined by jurisdictional or, preferably, ecological boundaries, the pressing need is for CEA to evolve to provide comprehensive cumulative environmental change assessments and it is of particular concern that CEA advances to become the much needed tool decision-makers require to sustainably manage the marine environment. For CEA to evolve to fulfil this role requires existing knowledge, tools and future advances from multiple streams of research to be brought together within a modular or iterative system that results in improvement characterisations of ecosystems and the receptors therein, and the responses to variable and interacting stressors. There is, therefore, a clear need to support coordinated and multidisciplinary development of CEA to advance our knowledge of how cumulative effects from multiple activities (e.g. MREDs) incrementally change the environment, and how effects can be managed and mitigated to enable sustainable use of the seas. In Box 1 we offer some tangible aspects for consideration, which will have to be added into this process.

Reducing uncertainty regarding MRED cumulative effects is given impetus by the pressing nature of climate change mitigation targets, the need to meet energy security quotas, the demand for blue growth and the drive to ensure the sustainable use of the marine environment for this and future generations. Considering these varied demands raise questions well beyond the remit of this paper, for example the inevitable value-driven trade-offs, as multiple interests compete for access to resources that are resilient up to a point. Coordinated CEA offers the potential for transparent, robust information that can frame the wider debate required about the consequences of historical, current and future anthropogenic activities in the seas.

Acknowledgments

This work was funded by a National Environment Research Council-(NERC) Industrial CASE Studentship (NE/L009668/1) and the UK Department for the Environment, Food and Rural Affairs funded Maritime Industries - Environmental Risk and Vulnerability Assessment – MINERVA Project (ME5213). SJ was also part funded through the EPSRC/ESRC International Centre for Infrastructure Futures (ICIF) grant (EP/K012347/1). We are grateful to the 4 anonymous reviewers for their constructive suggestions, which greatly enhanced the manuscript.

Box 1
Ten key considerations to advance CEA in defined ecological areas subject to integrated marine management.

- Define a meaningful area and the ecological receptors that provide insight into the health and functions of the ecosystem therein
- Establish a baseline, level of variability and the 'most' important receptors that require assessment and monitoring (a targeted approach may be a necessary starting point if there are many such receptors)
- Define appropriate spatial and temporal scales, depending on the ecological patterns, the level/magnitude of activities and developments, cognisant of financial constraints (e.g. monitoring will need to reflect what is financially feasible recognising that frequency may change depending on how the system responds and confidence in effect significance determinations)
- Integration at all levels: cross sectoral, cross border and multidisciplinary approaches are a must, whilst attempting to understand cumulative effects. This is perhaps one of the primary weaknesses of current approaches which apply a narrow perspective to what is a complex and multidisciplinary problem
- Validation of predicted effects as well as critical assessment of the significance of changes following, for example construction and operation of individual and multiple developments in a given area
- Define the significance of changes in ecological and management terms. This will help to define and target an appropriate level of effort for individual development assessments and define the expected benefits of such efforts
- Explore and integrate indirect effects into CEAs, for example using ecological modelling. Future research could compare whether assessments focussed on ecological functions or indicators thereof are more informative in support of marine management ambitions than the current approach of assessing isolated species protected by punitive legislation
- Accept and acknowledge the level of 'uncertainty of these changes', as there will be areas that require further data collection, dedicated specific tools and distinct approaches (e.g. cross-border collaboration for migratory species, different methodologies for sessile and mobile receptors). Directed research targeted at priority cause-effect relationships at scales relevant to key receptors would enable CEA to advance specific to an activity to advance (e.g. Electromagnetic field (EMF) effects on sensitive species migrating across multiple cables)
- Recognise the temporal component of changes (e.g. short-term construction effects, long-term operational effects, unknown decommissioning effects) and integration of variable effects into the licensing and management processes. Developing guidance for legislators, regulators and CEA/EIA practitioners to adhere to support ecologically meaningful CEA will be an important next step
- Consider implications of environmental change due to development on social receptors and welfare, including the potential for short-term effects as well as long-term changes to have significant impacts on, for example, individual vessel earning capacity

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