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Journal:	*ICES Journal of Marine Science*
Manuscript ID:	ICESJMS-2014-393.R2
Manuscript Types:	Original Article
Date Submitted by the Author:	10-Apr-2015
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Keyword:	Pressure, human activities, Management, Combined effects, maritime spatial planning

A spatially-resolved pressure-based approach to evaluate combined effects of human activities and management in marine ecosystems

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Abstract

Our oceans are heavily utilised by a wide variety of human activities that exert pressures which negatively impact marine ecosystems, occasionally leading to unsustainable rates of exploitation. A linkage framework approach can be used to make independent associations between sectors, activities and the pressures they introduce. However in reality, many different sectors and their associated activities overlap in time and space, potentially changing the severity of their impact as pressures combine, and undermine the efforts of environmental managers to mitigate the harmful effects of those activities. Here we present a spatially resolved approach to assess the potential for combined effects using a linkage framework assessment. Using illustrative examples from the North East Atlantic, we show the likelihood of changes in pressure severity as a result of multiple overlapping activities. Management options to limit pressure introduction are explored and their benefit - measured as a reduction in area of seafloor impacted - assessed. In its simplest form, the approach can be used to develop potential precautionary management options in areas where data availability is poor and more comprehensive management measures where data is more widely available.

Key words: pressure; human activities; management; combined effects; maritime spatial planning

Introduction

The exploitation of marine resources is causing widespread changes to the structure and state of marine ecosystems, and at the broad scale, there are few areas of the ocean that are devoid of any human activity (Halpern *et al*., 2008). Managing the complex interactions of overlapping multiple activities that compete for space remains a challenging task, but one which has been recognised as essential if the sustainable provision of ecosystem goods and services from our oceans is to be achieved (McLeod *et al*., 2005).

In 2007, the European Union (EU) proposed an Integrated Maritime Policy (IMP) (EC, 2007) as the mechanism for providing a long-term (sustainable) improvement in quality of life. A key instrument of the IMP is Maritime Spatial Planning (MSP), which provides a framework for arbitrating between competing sectors and managing their impact on the marine environment and progression towards sustainably exploited ecosystems (Reid *et al*., 2005; Halpern *et al*., 2009). The success of MSP is challenged by the need to manage numerous human activities that vary in spatial and temporal footprint (Eastwood *et al*., 2007), the pressures from which impact the marine environment (Crain, 2008; Knights *et al*., 2013 and 2015) and overlap in many areas (Figure 1). As marine activities continue to expand in spatial and temporal footprint, competition for maritime space will undoubtedly increase such that there is greater conflict between sectors. MSP has the potential to play an important management role by resolving many of these spatial conflicts (Reid *et al*., 2005; Halpern *et al*., 2009), however management success is dependent on realistic assessments of impacts that could be undermined if the overlap of activities (combined effects) is not taken into consideration.

Comparing the impact of human activities on the marine ecosystem requires both a method of linking human activities to specific pressures, (NB pressures are also referred to as stressors in the literature, e.g. Halpern *et al.,* 2008, Brown *et al.,* 2014), and a measure of sensitivity of the ecosystem and its components to those pressures (Stelzenmuller *et al*., 2010a; Foden *et al*., 2011). Rogers (2005) defined a pressure as an anthropogenic factor that induces environmental change and which is generally viewed negatively i.e. a detrimental effect (Gabrielsen and Bosch 2003). The types (e.g. Knights *et al*., 2013) and distribution of pressures (e.g. abrasion, substrate loss, contamination) have been described individually for a number of major sectors and their activities that operate in marine habitats, such as fishing, artificial structures, dredging, shipping (e.g. Eastwood *et al*., 2007; Foden *et al*., 2011). Linkages between sectors, their activities and ecological components of the ecosystem through pressures have also been described using linkage frameworks (e.g. Driver-Pressure-State-Impact-Response (DPSIR); White *et al*., 2013), however linkages have tended to be viewed independently of one another, such that the full range of pressures affecting a characteristic may not be identified or managed effectively (Knights *et al*., 2013).

Management measures to limit the harmful effects of activities have thus far generally attempted to protect a specific habitat, species or other feature of interest through management of a single sector/activity and consideration of their pressures (Commission of the European Communities (EC) 2009; Khalilian *et al*., 2010). Implementation of management measures on a sector-by-sector basis has the potential to miss impacts that only occur when pressures from multiple sectors and their activities act in combination. In such cases, individual sectors would continue to contribute to negative effects on the ecosystem.

Several studies have shown how the severity of a pressure type can change amongst activities depending on the frequency and intensity of introduction i.e. when activities overlap (Eastwood *et al.,* 2007; Evans and Klinger, 2008; Halpern *et al.,* 2008). However, assessing severity is not straightforward. It is often assumed that pressures act in an additive way i.e. the impact of two of the same or different pressure types are simply added together (e.g. Halpern *et al.,* 2007, 2008; Ban and Alder, 2008; Stelzenmuller *et al.,* 2010b). However, pressures may also interact in non-linear, synergistic (Folt *et al.,* 1999; Folke *et al.,* 2004; Christensen *et al.,* 2006; Crain *et al.,* 2009) or antagonistic ways (Folt *et al.,* 1999) depending on the pressure type and ecological component impacted such that the outcome of interactions of multiple pressures is hard to predict (see Brown *et al.,* 2014 for an overview of considerations).

Here, for simplicity, we consider only additive interactions, which we define as when the same pressure type occurs in the same place. We refer to this as a *combined* effect. However, it should be noted that this term (as well as *cumulative impact*; e.g. Crain *et al.,* 2009) has been used to describe situations when pressures of different type interact additively (Folt *et al.,* 1999; Breitburg & Riedel, 2005; Darling *et al.,* 2010). We do not consider other relationships (e.g. synergistic or antagonistic) on the basis that it is often unclear, in part due to a paucity of direct manipulative evidence of multiple stressor effects, how the severity of interacting pressures can change beyond a simple additive process of the same pressure type.

Combined effects present a considerable challenge to resource managers such that the implementation of a management measure, which was perhaps designed to mitigate the impacts of a single activity, may be undermined by a failure to account for pressures arising from a non-target sector or activity which continue to impact on the ecosystem (Crain *et al*., 2009) and lead to further or continued departure away from the environmental objective (Breen *et al*., 2012).

The consequences of combined impacts on ecosystems as a result of multiple pressures are discussed in a number of theoretical and empirical studies (Folt *et al*., 1999; Folke *et al*., 2004; Vinebrooke *et al*., 2004; Christensen *et al*., 2006; Halpern *et al*., 2008) but quantifying their impact remains a challenge (see Darling and Côté 2008 and references therein). Recent advances have used spatial information to describe the occurrence and intensity of human activities coupled with the sensitivity of the ecosystem to that activity and its pressures (Halpern *et al*., 2007, 2008; Robinson *et al.,* 2013). These studies have been valuable in identifying features of the ecosystem at greatest risk from on-going human activities (e.g. Halpern *et al*., 2007, 2008), however, the activities contributing to that risk are rarely specified, nor is the potential for management measures to mitigate that risk fully explored (but see Stelzenmüller *et al*., 2010b and Knights *et al.,* 2015).

Identifying threats to marine ecosystems, the areas at greatest risk of damage or loss from those threats, and strategies to mitigate those risks is at the forefront of recent environmental policy (e.g. the Marine Strategy Framework Directive (MSFD) (EC, 2008). With this in mind and building on previous work, we have developed a geospatial assessment approach with three main objectives. First, the mapping of major marine activities and associated pressures to identify overlap, so that areas with the potential for combined effects can be identified. Second, the outputs may be used in the development of an approach that enables different spatial management options to be assessed and prioritised in terms of reductions in risk. And third, to develop an approach without the need for costly and quantitative spatial monitoring to be undertaken. Here, we demonstrate how our spatially-resolved combined effects framework, when applied in its simplest form, can be used in the determination of management measures, and explore the practical applications of how composite sector-pressure data layers could be used to support the development and evaluation of those measures.

Methods

A spatially-resolved approach was developed to assess the combined impact of multiple activities. Building on a linkage framework describing the interactions between sector activities and the ecosystem (White *et al.,* 2013) and an independent assessment of threat to the ecosystem from each of those linkages (a ‘pressure assessment’, *sensu* Robinson *et al.,* 2013), we consider the potential for combined effects to occur and the potential for their management.

Linking Sectors, Activities, Pressures and Ecological components: Creating a Linkage Matrix

Links between sectors, activities, pressures and the ecosystem were identified and compiled to create three linkage matrices, each describing a series of links i.e. (1) sector → activity; (2) activity → pressure; and (3) pressure → ecological component. Each cell in a matrix describes the potential interaction between the two components, for example, indicating which pressures impact which ecological components (White *et al.,* 2013). All 3 matrices can be combined into a single matrix to describing the pathways through which sectors impact the environment. We refer to each pathway i.e. sector → activity → pressure → ecological component combination as an "impact chain" herein (Knights *et al.,* 2013). Impact chains were defined following an extensive review of the peer-reviewed scientific literature and published reports resulting in a combined matrix of 5,515 potential impact chains. In total, we considered 18 sectors, 98 activities, 24 pressure types and 11 ecological components in the development of our linkage matrices.

Assessing the severity of impact chains using a pressure assessment approach

We used a pressure assessment approach to qualitatively assess each impact chain using a categorical assessment of exposure and sensitivity criteria (see Robinson *et al.,* 2013 for details). Impact chains were assessed by expert judgment using five criteria: Exposure of the ecological component to a sector-pressure combination (1) spatial and (2) temporal overlap; (3) Severity of the interaction (i.e. *degree of impact, DoI* herein) which incorporates weighting on high versus low severity impacts and *chronic* versus *acute* effects); and Recovery from impact composed of (4) component resilience, and (5) pressure persistence. Each impact chain was evaluated considering prevailing conditions and applied here at a European regional sea scale. The expert group was comprised of >40 academics and researchers who were part of the ODEMM project (www.liv.ac.uk/odemm) and originating from 17 partner institutions from 13 different countries. Experts undertook an extensive review of both primary and grey literature prior to their evaluations (e.g. Knights *et al.,* 2011) to ensure most up-to-date understanding and knowledge was used in making their judgement.

Spatial Analysis

To illustrate the application of our combined effects assessment methodology, we truncated the outcomes of the pressure assessment (Robinson *et al*., 2013) to a sub-set of sectors namely: aggregates, fishing, oil and gas, renewable energy (specifically offshore wind farms) and telecommunications, and considered the impact of these sectors on sublittoral sediment habitats (EUNIS Level 2, Class A5.5, Connor *et al*., 2004) of the North Sea region of the North East Atlantic (Figure 1). These sectors were chosen because of their current prevalence throughout much of the region, the fact that they all introduce multiple types of pressure that can impact on sublittoral habitats and species, and the public availability of spatial (georeferenced) datasets that describe the distribution of those sectors throughout the region (geo-data sources are given in full in Table S1).

The spatial data we used was unmodified from its raw form with the exception of the fishing layer. In this case, data were derived from the Vessel Monitoring System (VMS) describing the speed and location of any individual vessels >15 m long operating in the North Sea. These data were filtered to include only information of vessels “at sea” i.e. in operation (after Lee *et al*., 2010) and included all gear types (mobile e.g. benthic and demersal trawls and static e.g. pots and nets). We further truncated the data to include only those vessels at sea for 24 h or more. We did not use VMS data grouped by annum, as the resolution is too coarse to enable spatial and temporal overlap with other sectors to be resolved. Similarly, data for vessels at sea for < 24 h were excluded on the basis that it can include erroneous or 'non-fishing' data points and lead to over-estimates of fishing pressure in some instances. By excluding these vessels, our analysis may alternatively under-estimate fishing pressure in some areas, but in the majority of cases, vessels classified as "< 24 h" tend to occur in the same areas as those vessels operating for > 24 h, such that underestimates of seafloor area impacted by fishing are unlikely. For all other sectors, the licensed area was used to describe the sector distribution (see Table S1 for full details). Habitat maps were available as georeferenced data layers from EUSeaMap (EMODnet). All shapefiles (georeferenced polygons describing the spatial distribution of sectors and habitat) were compiled within a Geographic Information System (GIS) (ArcInfo 9.3, ESRI).

Mapping the spatial distribution of sector-pressures

Each sector generates several different pressure types: the fewest were generated by the telecommunication sector and the most by the fishing sector (Figure 2). The distribution of pressures can be described in one of two ways: (1) dispersive; or (2) non-dispersive. A dispersive pressure (e.g. marine litter) can spread beyond the operational spatial footprint of the sector, whereas a non-dispersive pressure can only occur where the sector is in operation (e.g. abrasion). Dispersive pressures therefore have the potential to result in combined or cumulative effects at locations different to their source of introduction. Predicting where those locations are, could be achieved using approaches such as hydrodynamic modelling (e.g. Mead and Rodger, 1991; Mead, 2004) but this extends beyond the proof-of-concept objective of this study. As such, here we only consider non-dispersive pressures to illustrate our framework, as the spatial footprint of the sector can simply be used as a proxy for pressure distribution. We recognise that in areas where dispersive pressures occur, we may underestimate combined or cumulative effects as a result of their exclusion from the analysis.

Pressure criterion: Degree of Impact (DoI)

The DoI criterion (see Robinson *et al.,* 2013), which describes the likely severity of the impact, was chosen as a primary mechanism to assess the combined impact of sector-pressures. The DoI of each pressure type can differ in classification between either a **low severity** impact pressure, a **chronic** severe impact pressure, or an **acute** severe impact pressure (see definitions in Table 1 and distributions amongst sectors in Figure 2). Low severity pressures were removed from the analysis based on the definition that, irrespective of the frequency or magnitude of introduction (or overlap) of that pressure, no significant adverse effects on the ecosystem would occur (Robinson *et al.*, 2013). Here, a significant adverse effect is seen when a pressure causes changes in characteristic structure or functioning of a habitat. Furthermore, at this stage we only considered additions of the same pressure type (e.g. abrasion from fishing combining with abrasion from aggregate dredging) rather than combinations of different pressure types (e.g. abrasion from fishing with changes in siltation from aggregates), although we recognise the potential for such interactions to occur (see introduction above for references).

The distribution of each pressure was mapped in GIS (ArcInfo 9.3, ESRI) based on the spatial distribution of the sector and the number of pressure polygons determined from the linkage tables (after White *et al.*, 2013). Attributes of each polygon included the DoI which was assigned to the pressure type from the Robinson *et al.,* (2013) pressure assessment database (Figure 2).

The extent of each sector and its overlap with the seafloor was calculated using join and union tools from the analysis toolbox (ArcInfo 9.3, ESRI) and the number of overlapping pressures was calculated using merge (data management) and intersect (analysis) tools, allowing the area of pressure overlap(s) with the seafloor (km^2) to be estimated.

An independent assessment of acute pressure distribution

Based on the spatial distribution of pressures and following an independent assessment of degree of impact for those pressures, the distribution and number of acute pressures per unit area of seafloor was determined. The number of acute pressures was calculated by overlaying all pressure shapefiles and the number of acute pressures present summed with no assumption of combined effects or pressure interaction, e.g. the potential for chronic severity pressures to become acute in severity was ignored (Figure 5a).

A combined assessment of acute pressure distribution

Where pressures overlap in space or time, there is potential for combined effects to occur which may alter the severity of the impact on sublittoral habitats. A set of rules was developed to determine if and when the severity of a pressure could change (e.g. from chronic to acute severity) following overlap of the same pressure type from different sectors.

Spatial overlap is a relatively straightforward concept, although the resolution of data describing the spatial extent of sector pressures is generally coarse such that methods are used (e.g. buffering, Lee *et al.,* 2010) when plotting spatial extents to allow for uncertainty. Here, we adopted a precautionary approach whereby we consider the spatial extent of pressures as the scale of the licenced area of the sector rather than considering smaller spatial scales (e.g. the foundation of a single wind turbine).

Temporal overlap is perhaps a more challenging concept. Here, ‘time’ refers to not only the persistence of the pressure (see Robinson *et al.,* 2013 for definitions) but also its intensity. This interaction determines how frequently a pressure type needs to be introduced to cause a combined effect. However, the persistence and intensity thresholds required for combined effects to occur are unknown and remain un-quantified.

On that basis, we assumed that when two or more chronic pressures of the same type (but from different sectors) overlapped, all contributing impact chains in that area would become acute in severity (Figure 3). For example, fishing and aggregate dredging both introduce a chronic pressure (e.g. sedimentation) and where the footprint of these sectors overlaps in space, the pressure combines and becomes acute i.e. causing instantaneous mortality due to the volume of sediment introduced to an area (Figure 3). We recognise that both the spatial and temporal overlap assumptions made may lead to overestimates of combined effects in some cases and therefore the outcomes are precautionary.

In areas where an acute pressure is present, the area of seafloor underlying that pressure was assumed to be immediately impacted (i.e. organisms are instantly killed). Given that “acute” was the most severe degree of impact category, this severity category cannot become more severe irrespective of whether or not there is overlap. As such, DoI assessment of each impact chain had one of three possible states: (1) DoI (stays) chronic, (2) DoI (stays) acute, or (3) DoI changes state from chronic to acute. For each linkage, all possible DoI states were calculated should pressure overlap occur (i.e. DoI stays the same or changes from the initial assessment). All possible DoI states were determined using a chain of conditions and functions in *R* (*R* Development Core Team, 2011) (Figure 4). The resulting DoI state data table was then joined to data describing the spatial extent of the targeted sectors in ArcGIS and a Python script used to determine which of the DoI states was appropriate in a given unit area km^2. The spatial extent of sector-pressures (km^2) of combined pressures was estimated in the same way as the independent assessment above. Difference plots (e.g. Figure 5c) were generated by subtracting the number of pressures km^{-2} in the combined assessment from the number of pressures km^{-2} in the independent assessment. For brevity, only the spatial extent of acute pressures (km^{-2}) is shown although similar figures can be produced for areas of chronic DoI where the intensity of pressure introduction may be an issue.

Assessing the performance of management measures in light of overlapping sector activities

To assess the potential for single-sector management to alleviate pressure and reduce impact on the seafloor, we identified a case study area of 67,500 km^2 (Figure 1 inset) and evaluated the change in spatial extent of the seafloor (km^2) impacted by sector-pressures if a single sector was excluded entirely. However we recognise that it may not be feasible to remove some sectors entirely (e.g. permanent structures such as oil and gas and renewables). Changes in impacted seafloor area (km^2) were calculated for five scenarios with management targeted at one of five sectors in each scenario. Given that each sector introduces at least one acute pressure (Figure 2), the spatial extent of the sector footprints could be used without the need to differentiate between pressure types.

Results

When considering all five sectors in combination, there was no change in the total spatial extent of acute pressure between the independent assessment and the combined assessment (Figures 5a and b). This was because all sectors included in the assessment introduce at least one pressure type that is acute in its severity (Figure 2). When considering each sector and its pressures separately (e.g. fishing-abrasion or aggregate extraction-abrasion as a separate un-combined footprint), a large area of the seafloor was impacted by at least one acute sector-pressure, and in worst cases, up to 30 acute sector-pressures per km^2 (Figure 5b) where there was considerable overlap between multiple sectors (Figure 1).

The change in the number of acute sector-pressures occurring per km^2 of seafloor between the independent and combined assessment increased indicating the presence of overlap between two or more chronic pressures of the same type (Figure 5c). However, the area of overlap and a change in pressure severity (i.e. chronic to acute) was limited to relatively small areas of the North East Atlantic and there was no change in the total number of acute sector-pressures km^2 across large areas of the region, irrespective of whether an independent or combined assessment methodology was used (Figure 6). Both methodologies estimated ~89 % of the North East Atlantic seafloor area was impacted by fewer than five acute sector pressures per km^2, indicating that, of the sectors included in this assessment, large areas of the seafloor are impacted by a single sector operating in isolation (Figure 6).

In areas where sector-pressure overlap did occur, the combined assessment revealed relatively small (~140 km^2) areas of seafloor where the number of acute sector-pressures km^2 increased beyond levels predicted by the independent assessment (Figure 6). In the independent assessment, a maximum of 18 acute pressures (km^{-2}) were identified, but this increased to a maximum of 30 acute sector-pressures (km^{-2}) in some areas in the combined assessment (Figures 5a, 5b and 6). The increase in pressure density was primarily due to the overlap of fishing with the non-renewable energy (oil and gas) and offshore renewable energy sectors. There was an especially large increase in the areas with 16-20 pressures per km^2 (equivalent to 4,153km^2) attributed to the overlap between offshore renewable energy, aggregate extraction and fishing in the southern North Sea area (Figure 1 inset area).

Single Sector Management

Overall 63% of the seafloor (42,839km^2) within the management area explored was impacted by one or more sectors (Figure 7 and Table 2). The spatial distribution of each sector varied between sectors, ranging from 20 km^2 in the case of telecommunications to in excess of 30,000 km^2 for fishing (Table 2). Estimates of the overlap of a single sector with any other sector ranged from as little as 45% of the total sector extent in the case of telecommunications, up to a maximum of 90% for offshore wind farms (Table 2). The potential for single-sector management to reduce combined effects on the seafloor was evaluated by determining the extent to which sector-pressures occurs in isolation or overlap with one another. Reductions would only be seen if sector-pressures occur in isolation. The greatest reduction in impacted seafloor area under this scenario/ approach would be achieved following the exclusion of fishing (37 %) (not least due to the greater spatial extent in comparison to other sectors), followed by oil & gas (22 %), offshore wind (2.4 %), aggregates (1.5 %) and telecommunications (< 0.1 %) respectively (Figure 7, Table 2).

Discussion

We developed a methodology to assess the potential for combined effects from multi-sector use of marine ecosystems in the North East Atlantic, which if unaccounted for, can lead to underestimates of threat to marine ecosystems and undermine management objectives and measures. We applied a simple set of rules to available spatial datasets describing the distribution of marine sectors coupled to an expert judgement assessment of threats to marine ecosystems from sector activities. Similar data have previously been used to indicate where sectors can be in competition for maritime space (Ban and Alder, 2008; Stelzenmüller *et al.*, 2010b). Where overlap occurs, pressures have the potential to become more severe in their impact. Our approach evaluates how and where overlapping pressures might occur and represent a greater risk to the marine environment. This approach will assist resource managers to identify areas that are not only potentially more difficult to manage but also areas where improvements could be achieved more simply, either by way of cross-sectoral or pressure management (e.g. Knights *et al.*, 2013; Piet *et al., in press*), or by maritime spatial planning to reduce overlap between sectors in space and time. Coupling these outcomes with more detailed maps of sensitive ecosystem characteristics or protected features should further support managers in achieving environmental objectives. The approach was designed to make use of existing data and expert knowledge, making it a cost-effective mechanism for prioritising and streamlining management activities. Minimising costs is desirable for policy makers in the current austere economic climate, especially where there is a desire to meet environment targets towards sustainable use of marine space.

Comparison of the independent and combined effects assessment outputs demonstrated the potential for independent assessments to underestimate threats to the ecosystem by failing to consider potential changes in pressure severity where sectors overlap. This was demonstrated considering a simple additive interaction between the same pressure type and non-dispersive pressures. If cumulative impacts are as pervasive in the environment as proposed (e.g. Darling & Côté, 2008; Crain *et al.,* 2009), it can be hypothesised that our combined estimate is in fact a 'best-worse' case scenario rather than a worst-case scenario. Inclusion of other interactions e.g. between different pressure types as well as synergistic and antagonistic relationships (see Brown *et al.,* 2014 and references therein), can be expected to lead to further increases in the threat to ecosystem habitats and ideally should be included in the future, although it remains to be seen the extent and change in severity that will occur as a result of such interactions.

Considering only non-dispersive pressures is also likely to underestimate the spatial extent of pressure overlap and thus combined and cumulative effects, as numerous pressures are dispersive and may well move beyond the physical footprint of a sector. Modelling approaches (e.g. hydrodynamic modelling, Mead and Rodger, 1991) or the use of buffers around known pressure distributions (e.g. Eastwood *et al.,* 2007; Halpern *et al.,* 2008) could shed further light on areas that may be more susceptible to combined effects from dispersive pressures, although in the latter case, such an approach should be driven by some underlying understanding of possible dispersal distance as otherwise, applying a fixed buffer distance (i.e. assuming symmetrical dispersal) could misrepresent locations of combined effects as dispersal distances (kernel) are often asymmetrical (e.g. Nickols *et al.,* 2015).

While the total spatial extent of sector activities were the same in both the independent and combined assessments, the independent assessment did not identify areas where multiple sectors overlap (sectoral conflict and management complexity) or areas that may be under greater threat from pressures as a result of combined effects. Current policy drivers such as the Marine Strategy Framework Directive (EC, 2008) promote the use of an ecosystem-based approach to management to improve ecosystem health and (any) improvement will be reliant upon appropriate interventions to reduce or remove pressures that are causing negative effects on the functioning of the ecosystem. An independent assessment could mislead managers into developing management strategies that are unable to reduce the magnitude of threat (Breen *et al*., 2012) and/or lack the complexity to manage all relevant combining pressures, resulting in some activities or pressures being unregulated (Smith *et al*., 2007).

It is common that the same pressure type is introduced by different activities, which overlap in time and/or space (Stelzenmuller *et al*., 2010b; Knights *et al*., 2013). Here, using relatively simple scenarios that excluded a single sector from an area where considerable sector conflicts occur, we have shown the limited environmental benefits that might be achieved (i.e. a reduction in impacted seafloor area) versus the cost (a ‘cost’ being a reduction in the operational area of a sector) of doing so. When the cost of management exceeds the perceived benefits and assuming decisions are economically biased, it is considered unlikely that a management measure will be considered viable (Baral *et al*., 2004). Here, we have not considered the value of an area of seafloor to a particular industry in terms of its 'quality' (Klein *et al.,* 2013) and used a broad habitat classification (i.e. EUNIS Level 2, sublittoral sediment) in our analysis rather than adopting more specific habitat classifications. Clearly spatial management decisions are likely to be driven by the value of the resource to society versus the cost of management and value to the environment (Klein, 2013; Auerbach *et al.,* 2014; Knights *et al.,* 2014) and an analysis using more highly resolved habitat classifications could easily be undertaken to determine if certain habitats that are identified as being particularly valuable to the region from an environmental, societal or economic perspective are impacted by combined effects.

We considered only five of the many sectors that operate in the North East Atlantic (Halpern *et al*., 2008; Knights *et al*., 2013), yet large areas of seafloor were impacted by multiple overlapping acute pressures. The inclusion of additional sectors is likely to further compound the scale of effects from multiple pressures on seafloor integrity. Managing sectors in isolation is therefore only likely to partially address problems of environmental degradation and in the worst cases, management objectives may have no net benefit due to other acute pressures remaining unmanaged. This emphasises the need for a multi-sectoral approach to management of combined pressures if improvements in seafloor state are to be achieved.

Overlap between sector activities presents several challenges to managers implementing an ecosystem approach. Firstly, it is unlikely that any one management measure will control all drivers that influence a policy objective/target such as good environmental status (GES). Rather, it is more likely that a suite of measures (i.e. a strategy) will be required to control the threats from pressures arising from multiple sectors and activities (Knights *et al*., 2013) such that ecosystem state improves. This alternative approach to management has been shown to be successful in several cases where it has been applied (e.g. the Nitrates Directive) (see OSPAR, 2010 for further details). The implementation of pressure-targeted management programmes, does however, have its own challenges. These include the considerable time and resource commitments required for participating and building capacity among stakeholders (often arising from the limited trust and sectoral protectionism between sectors) as well as the capacity and/or willingness to participate in long-term integrated management programmes (Rutherford *et al.,* 2005; Knights *et al*., 2014). However, these challenges can be overcome, for example, by developing measures in conjunction with stakeholders that are easily associated with a specific policy objective and display tangible targets and benefits (Watson, 2005; Carwardine *et al.,* 2009).

Improvements to future assessments

We have presented an approach that can be used to assess and identify areas of habitat that are greatest risk from human activities, providing a mechanism for targeted decision-making by resource managers that best supports current environmental objectives. Here, our objective was to demonstrate proof-of-concept, doing so using broad-scale distribution maps of sector activities and non-dispersive 'static' pressures to illustrate key considerations. However, the approach can be applied to address impacts at other, more refined, spatial scales. For example, the incorporation of high-resolution GIS data layers describing the location of wind turbines or oil well heads could be used to address small-scale impacts at a site level, rather than the broad scale approach we have implemented here which adopted licenced areas as its basis. In this instance, we may well overestimate combined impacts.

In developing the underlying rules of the methodology, we made some general assumptions. First, we assumed that the recovery of the habitat to a pre-impacted condition would be instantaneous once the pressure was removed, but in reality, sublittoral habitats can take days, weeks or years to recover from an impacted to a pre-impacted state (Thrush and Dayton, 2002) depending on local conditions. This limitation could be addressed by the inclusion of habitat resilience data to improve estimates of the relationship between impact and recovery (see Eno *et al.,* 2013).

Second, we assumed that when a chronic pressure of the same type (e.g. sedimentation) was introduced by two or more sectors (e.g. fishing and aggregate dredging) that co-occurred, then both pressure impact chains changed from chronic to acute in their severity (see Table 1). We used this simplified assumption for demonstration purposes only, but recognise that the intensity of pressure introduction may vary both within and among sectors depending on the specific activity being undertaken, such that the number of overlaps that are required to impart a change in degree of impact from chronic to an acute severity may vary. In many cases, the intensity of introduction of a specific pressure type by a specific sector activity is unknown, as is the critical intensity threshold that is required to impart a detrimental impact on the ecosystem or any of its components.

Third, we assumed that where acute interactions occur, and irrespective of the number of overlapping acute pressures, the severity of interaction would not increase. This assumption was based on our definition that an acute pressure would lead to instantaneous mortality, which we view as the worst-case scenario, and further additions could not lead to further reductions in ecosystem state (Table 1). An improved understanding of interaction of pressures where they overlap will shed light on whether this is an appropriate assumption moving forward.

Ecosystem-based management is continually challenged by the complexity of interactions between on-going sector activities and the environment. It is clear that combined effects are prevalent in many areas of the ocean as a result of competition for resources such that the pressures generated by those activities overlap, which can lead to more severe impacts than if those sectors occurred in isolation, presenting complex spatial management issues if conservation is to be achieved. Our approach utilises broad-scale geographic data coupled with an expert judgement assessment of threat that does not require exhaustive and prohibitively expensive studies to underpin it. As such, we suggest that the approach can be applied to assess and identify areas of habitat that are at greatest risk from human activities and provide a mechanism for targeted decision-making by resource managers that best support current environmental objectives.

Acknowledgements

This work is funded by and is part of the ongoing research within the EU FP7 programme "Options for Delivering Ecosystem Based Marine Management" (ODEMM; grant number: 244273; www.liv.ac.uk/odemm). We would like to thank Stuart Rogers for helpful comments on our draft manuscript.

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EU sea map disclaimer

Information contained here has been derived from EUSeaMap Consortium webGIS data (www.jncc.gov.uk/page-5040) which is made available under the pilot project for the European Marine Observation Data Network (EMODnet), funded by the European Commission's Directorate-General for Maritime Affairs and Fisheries (DG MARE).

Fishing VMS data

VMS data were provided by the UK's Department for Environment, Food and Rural Affairs (Defra) in raw, uninterpreted form. The Secretary of State for the Environment, Food and Rural

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Table 1. (a) Degree of Impact definitions used to classify a sector-pressure combination in the pressure assessment, and (b) the rules to determine possible Degree of Impact changes should pressure overlap occur. **NB** Degree of Impact classification can vary between pressure types but not within pressure types (i.e. among sectors) (after Robinson *et al.* 2013)

a). Degree of Impact classification definitions		
A **Low severity (L) DoI** is an interaction that, irrespective of the frequency and magnitude of the events, never causes a noticeable effect for the ecological component of interest in the area of interaction. There are never high levels of mortality, sustained and noticeable reductions in breeding/recruitment success, or loss of habitat or change in its typical species or functioning, at the spatial scale of the interaction, i.e. proximate ecological responses (*sensu* Harley *et al.,* 2006). **NB** These sector-pressure combinations were removed from the analysis.	A **Severe-Chronic (C)** interaction is described as an impact that will eventually have severe consequences at the spatial scale of the interaction, if it occurs often enough and/or at sufficiently high levels e.g. where disease levels might build up over time, eventually leading to levels where a high number of individuals would be killed or habitat features would change. No inference is made as to when the pressure impact becomes severe; simply that at some frequency and intensity, a pressure can lead to severe impacts on that ecological component.	A **Severe-Acute (A)** interaction is described as a severe impact over a short duration e.g. for species, a high proportion of individuals are killed immediately where there is an interaction of the pressure and the component. In the case of habitats, such interactions cause an immediate change in habitat type, i.e. change or loss of characteristic features and/or species in the area of interaction. An Acute (A) interaction can occur after just one event.
b). Rules for changes in DoI classification		
DoI remains Chronic	**DoI becomes Acute**	**DoI remains Acute**
• There is no overlap between a pressure of the same type (e.g. abrasion) arising from different sectors. • Pressure of the same type (e.g. abrasion) from two or more sectors overlap in space but not time.	Pressure of the same type (e.g. abrasion) from two or more sectors overlap in space and time.	The pressure DoI is already acute.

Table 2. The extent of sublittoral seafloor impacted by acute sector-pressures when a sector is managed in isolation using a hypothetical management box (Figure. 1 inset and Figure. 7).

Sectors and Management Scenarios (a-e)	**Sector spatial extent (km^2)**	**Area not overlapping with another sector (km^2)**	**Area overlapping with one or more sectors (km^2)**	**Remaining area of seafloor impacted after sector removal (km^2)**
(a) Aggregates	4,243	660	3,583	42,179
(b) Fishing	30,185	16,050	14,135	26,789
(c) Oil & Gas	17,152	9,383	7,769	33,456
(d) Renewables	10,463	1,017	9,446	41,822
(e) Telecoms	20	8	12	42,831

Figure 1. The location and overlap of sectoral activities (top) and the number of sector-pressures impacting the seafloor (bottom) for a discrete area of the North East Atlantic. Inset: a hypothetical management area (67,500 km^2) for evaluating the performance of management areas in light of combined pressure effects.

Figure 2. The number of different pressure types introduced by five different sectors and classified by their degree of impact (low; chronic; acute) that operate in a discrete area of the North East Atlantic. The Degree of Impact categories Low, Chronic, Acute are defined in Table 2.

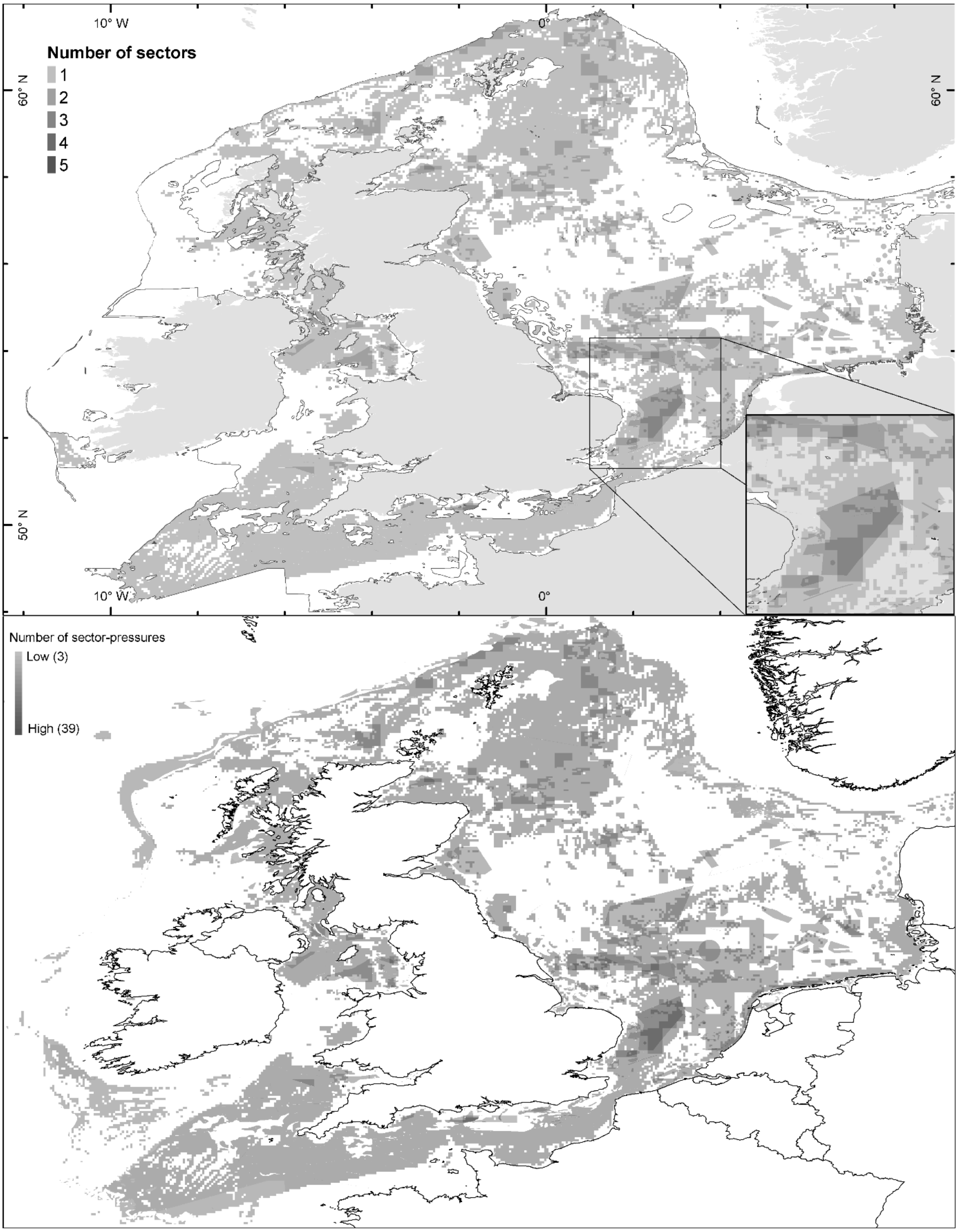
Figure 3. Illustration of combined effects where sector-pressures overlap in the same geographic space. Each cell represents a unit area of seafloor. Chronic pressures from sectors A and B overlap in space/time resulting in combined effects and an increase in severity (e.g. cell 1a). Where an acute sector-pressure occurs, there is not further increase in pressure severity (e.g. cells 1b and 3c). Where there is no pressure overlap, the pressure severity does not change (e.g. cells 1c, 2b and c, and 3b).

Figure 4. A schematic of the combined effects framework. Spatial data were compiled within ArcGIS 9.3. Changes in pressure DoI were predicted if overlap were to occur between a sector-pressure type using the conditions described in Table 2 resulting in multiple outcomes for a given sector-pressure combination being generated. A Python script in ArcGIS was used to select the appropriate DoI combination per unit area of space (km^2) i.e. if overlap occurred given the spatial extent of sector-pressures.

Figure 5. The spatial extent of acute sector-pressures derived from (a) independent assessment, (b) Combined assessment and (c) difference plot indicating an increase in the number of acute sector-pressures per unit area following the combined assessment.

Figure 6. The number of acute-sector pressures per km^2 identified by the independent (white bars) and combined (grey bars) assessments. The independent assessment identified no areas where acute sector-pressure density exceeded 21 km^{-2}.

Figure 7. Change in the spatial extent of sublittoral seafloor that is impacted when a sector is removed from the area. Estimated changes in the impacted extent (km^2) are given in Table 2. Scenarios tested were the removal of: a) Aggregates; b) Demersal fishing; c) Oil and gas infrastructure; d) Renewable energy installations; and e) Telecommunications. Box area = 67,500km^2.



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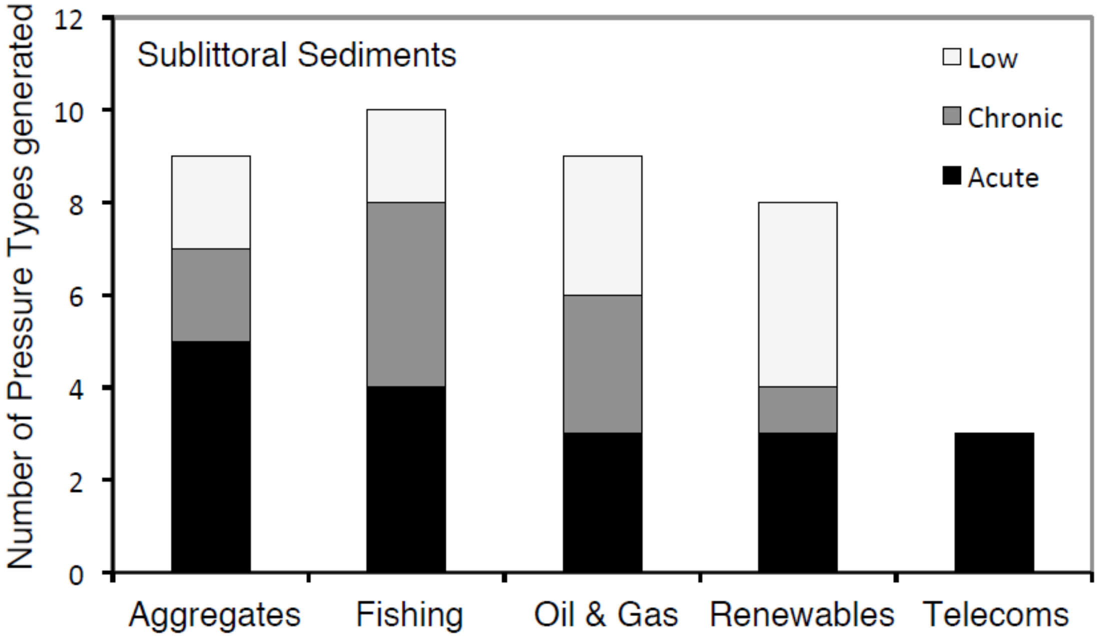

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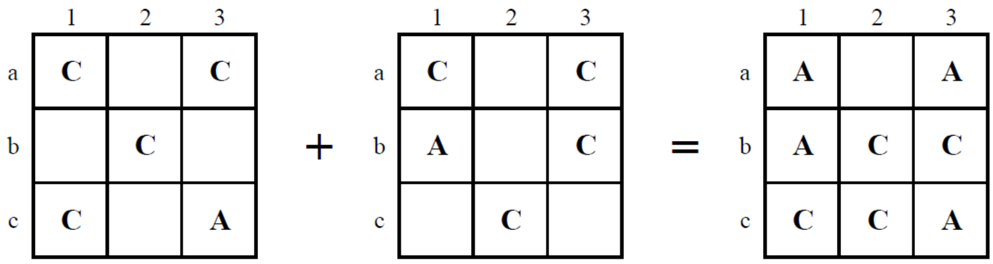


	1	2	3
a	C		C
b		C	
c	C		A

\+

	1	2	3
a	C		C
b	A		C
c		C	

=

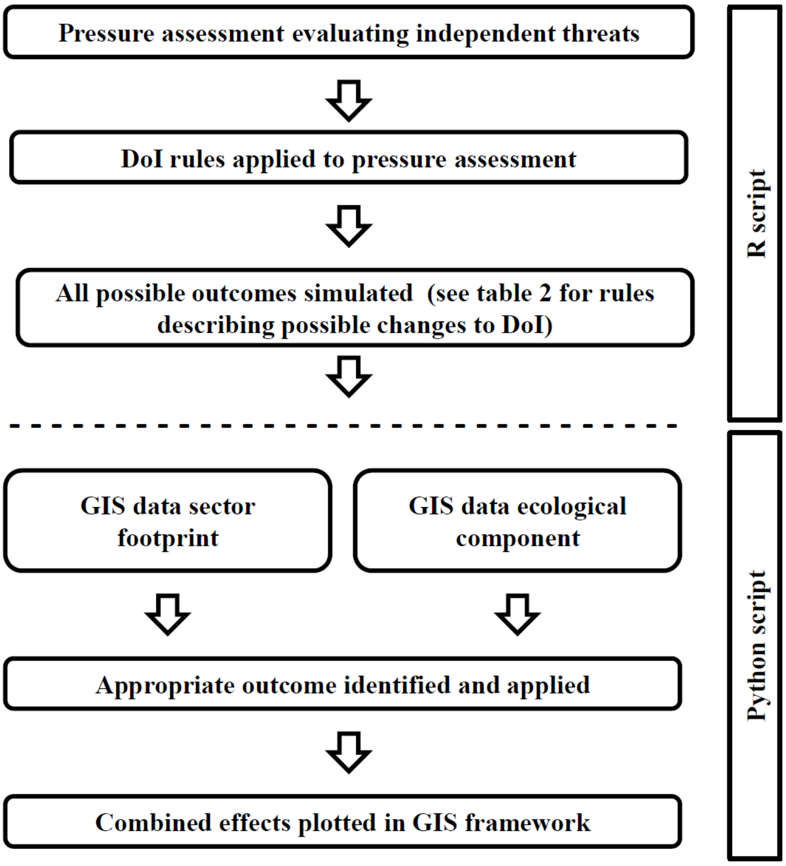
	1	2	3
a	A		A
b	A	C	C
c	C	C	A

Sector A: 5 of 9 cells impacted. Acute (A) = 1, Chronic (C) = 4.

Sector B: 5 of 9 cells impacted. Acute (A) = 1, Chronic (C) = 4.

Combined Effect: 8 of 9 cells impacted. Acute (A) = 4, Chronic (C) = 4.

Figure 3. Illustration of combined effects where sector-pressures overlap in the same geographic space. Each cell represents a unit area of seafloor. Chronic pressures from sectors A and B overlap in space/time resulting in combined effects and an increase in severity (e.g. cell 1a). Where an acute sector-pressure occurs, there is not further increase in pressure severity (e.g. cells 1b and 3c). Where there is no pressure overlap, the pressure severity does not change (e.g. cells 1c, 2b and c, and 3b).



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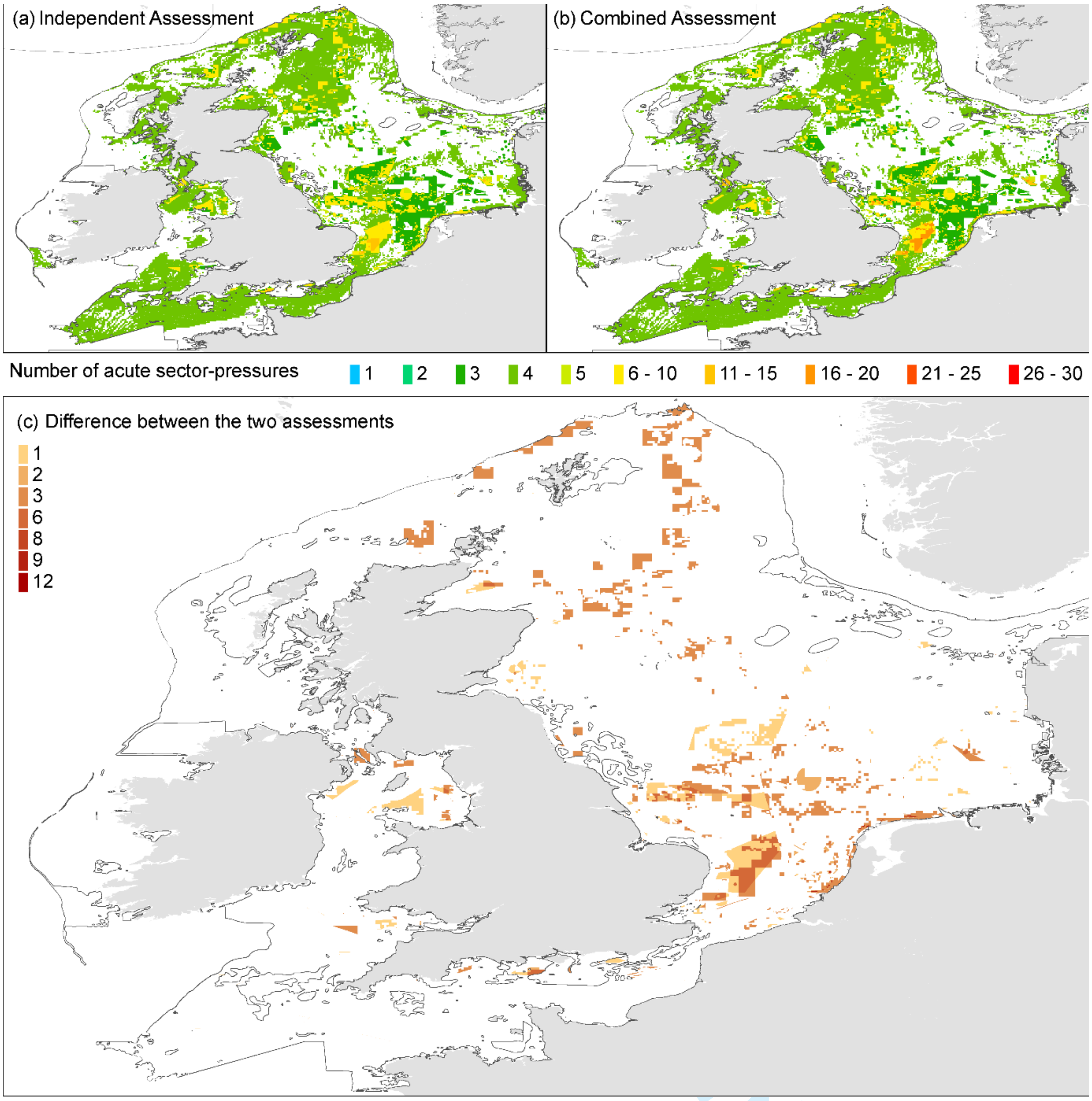

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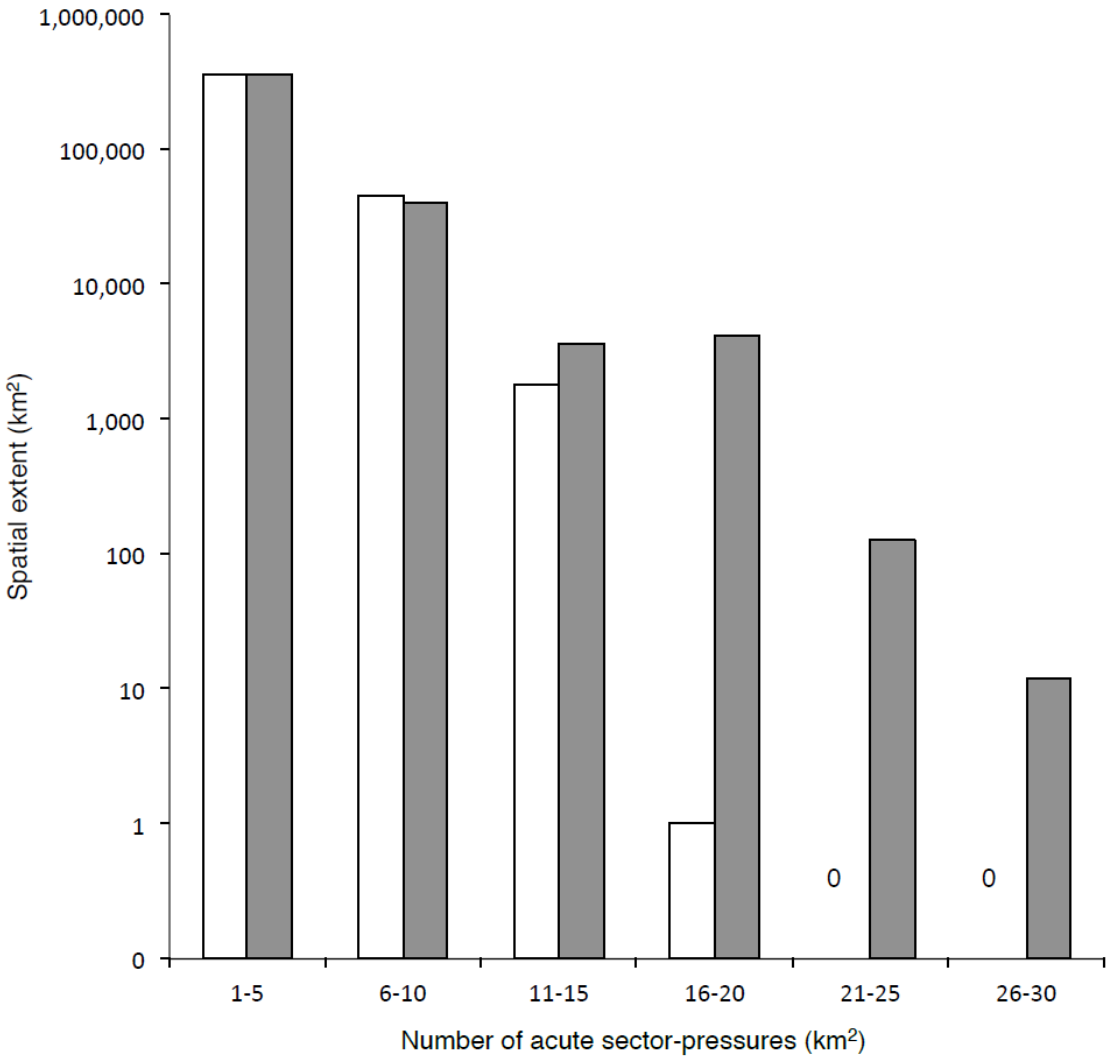

Figure 6. The number of acute-sector pressures per km^2 identified by the independent (white bars) and combined (grey bars) assessments. The independent assessment identified no areas where acute sector-pressure density exceeded 21 km^{-2}.

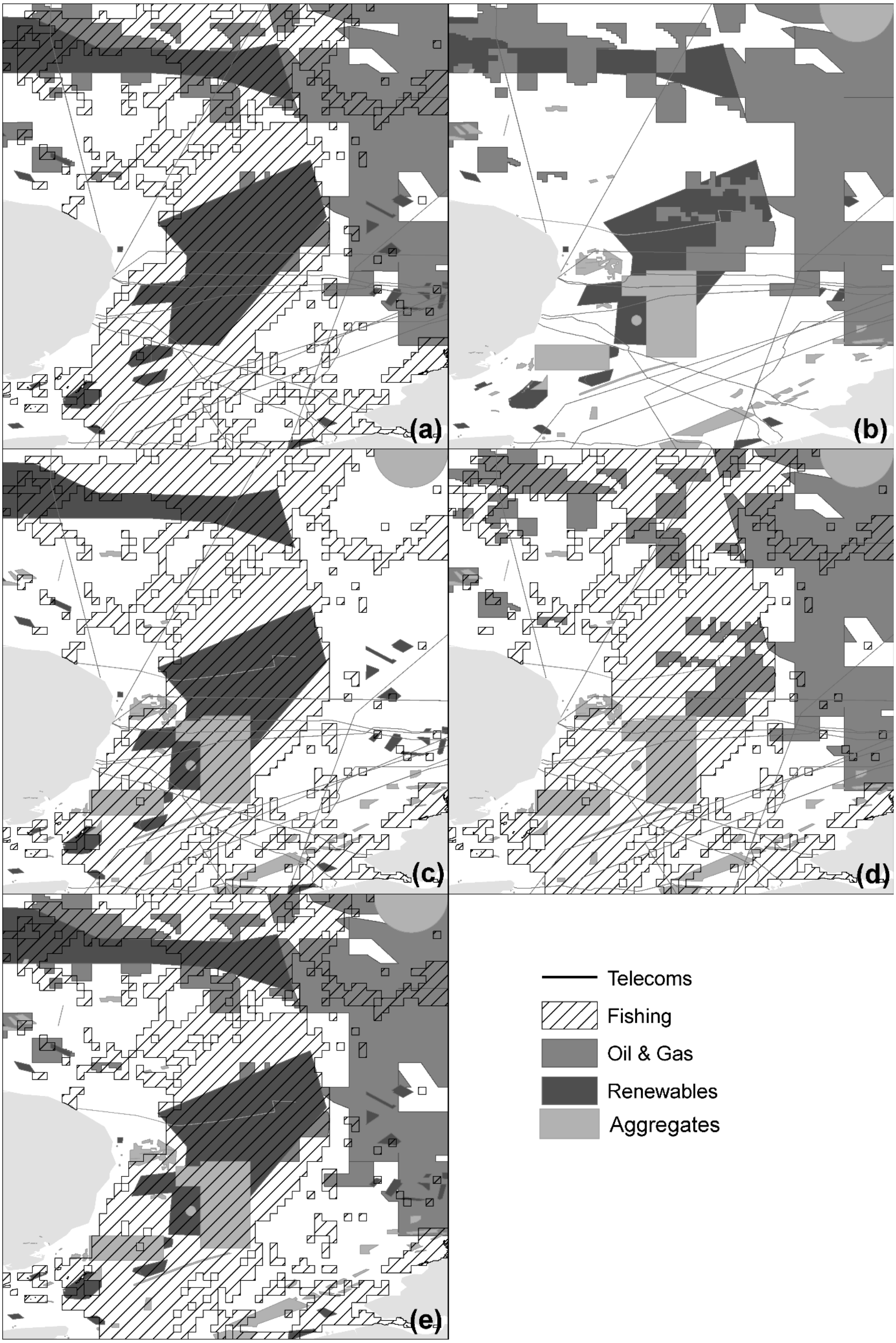
(a)
(b)
(c)
(d)
(e)
Telecoms
Fishing
Oil & Gas
Renewables
Aggregates

Figure 7. Change in the spatial extent of sublittoral seafloor that is impacted when a sector is removed from the area. Estimated changes in the impacted extent (km^2) are given in Table 2. Scenarios tested were the removal of: a) Aggregates; b) Demersal fishing; c) Oil and gas infrastructure; d) Renewable energy installations; and e) Telecommunications. Box area = 67,500km^2.