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Review

A review of support tools to assess multi-sector interactions in the emerging offshore Blue Economy

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ABSTRACT

Multiple ocean sectors compete for space and resources, creating conflicts but also opportunities to plan for synergistic outcomes that benefit multiple sectors. Planning and management are increasingly informed by qualitative and quantitative methods for assessing multi-sector interactions to identify trade-offs and synergies among sectors and with the environment, but there is a need to critically review the alignment of these tools with the requirements of Blue Economy stakeholders. Through a systematic literature review, an operational maturity analysis, and a survey of Blue Economy stakeholders, we found that the most well-developed tools for assessing interactions between multiple Blue Economy industries, and with the environment, are spatial prioritization tools, such as Marxan and multi-criteria decision support tools; and spatial static tools, such as cumulative effect mapping. More complex process/dynamic tools such as ecosystem and oceanographic models are well developed for single sectors, particularly water quality assessments and commercial fisheries, but have been less commonly applied in multi-sector contexts. Our review and stakeholder survey highlighted that assessing the environmental and operational suitability of sites for Blue Economy infrastructure in conjunction with operational impacts, trade-offs and decommissioning considerations requires: 1) a toolbox of approaches that covers a range of spatial, temporal and ecological scales; 2) tools that capture interactions and feedbacks among sectors, and with the environment, without being unnecessarily complicated (i.e., tractable to use and allow for effective communication of findings); and 3) continued synthesis of approaches and tools used across sectors such as commercial fishing, aquaculture, offshore renewable energy, and offshore engineering.

1. Introduction

The term 'Blue Economy' refers to "*the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystem*" (The World Bank, 2017). Competition for ocean space and access to its resources is rapidly increasing (Hodgson et al., 2019; Jouffray et al., 2020), especially within the coastal zone. This is driving Blue Economy sectors to expand further offshore into more high energy environments. Across the globe, these sectors include seafood and marine products (fishing and aquaculture), tourism and

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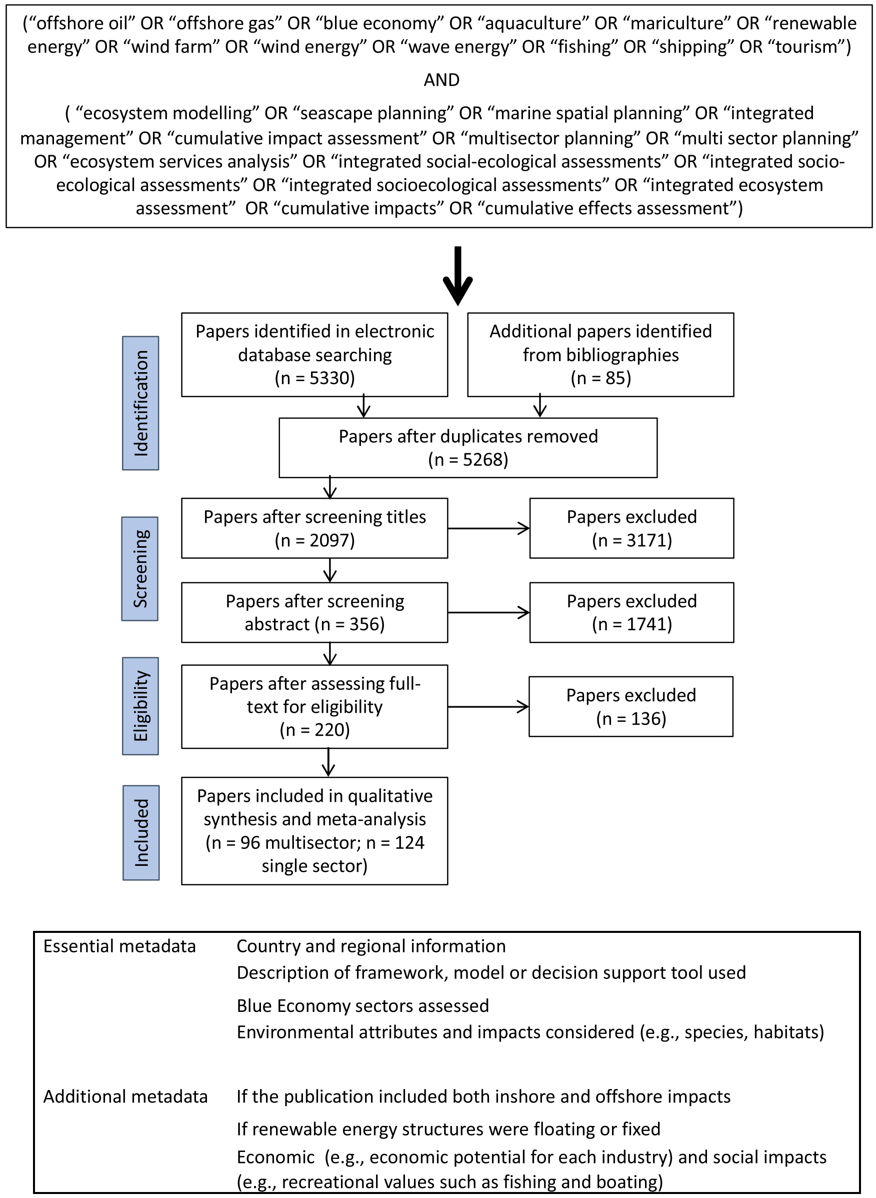

Fig. 1. Keyword search terms, PRIMSA reporting guide and literature review filtering.

recreation, energy capture (oil and gas, as well as renewables such as wind and wave farms), and shipping (maritime traffic). The relative importance of the more newly developed industries that have the potential to grow rapidly in coming decades, such as offshore renewable energy and aquaculture, is increasing (Stelzenmüller et al., 2022). Developing industries face novel challenges when moving offshore as they must consider uncertain tenure (Skladany et al., 2007), environments that are physically demanding on infrastructure, and potential impacts on ecosystems that have largely existed under low human threat compared to coastal ecosystems (Halpern et al., 2019). Further, large- and small-scale operators often co-exist and integrating all proponents in assessments of interactions is necessary to equitable blue growth (Cisneros-Montemayor et al., 2019). To ensure sustainable ocean use, it is important to understand what knowledge (tools, practices and datasets) can be transferred from existing coastal and offshore sectors to emerging offshore sectors, and what operational and environmental issues might arise as a consequence of novel combinations of offshore human activities and related ocean use.

To address increasing competition for ocean resources across multiple activities, regulators and industry need support tools that can assess trade-offs and synergies across the triple-bottom-line of social, environmental and economic outcomes (Stelzenmüller et al., 2013). For example, offshore wind farms may have negative impacts on some fisheries by removing areas around wind farms from fishing grounds, but may also provide benefits by creating artificial habitat, and protecting fish breeding stocks and critical habitats (Bergström et al., 2013; Halouani et al., 2020). In addition to single-sector interactions with the environment, the cumulative environmental effects of offshore infrastructure development are complex (Willsteed et al., 2017). Expanding and developing industries offshore is a means to disperse their spatial footprint and so reduce existing conflicts in the coastal zone. It also offers an opportunity for governments to introduce additional decision support mechanisms such as multi-use zoning ways and at scales that optimizes triple-bottom-line outcomes. However, the connectivity of the marine environment can disperse the footprint of an activity well beyond its local geographic bounds (Condie et al., 2018). Some offshore marine environments (i.e., seamounts) are particularly sensitive to such disturbance due to biota having strong dependence on specific habitats or long recovery and regrowth times (Rijnsdorp et al., 2018; Todd et al., 2015). Complexities within the human dimension can also arise, as

Table 1
Descriptive classification of the different tools used to assess multi-sector interactions.

Category	Definition	Examples	Applications in decision making
Conceptual and semi-quantitative tools	Conceptual and semi-quantitative models are generally based on expert opinion and conceptual models of the system under investigation. Conceptual models may have directional links between nodes, which assume causal relationships	Qualitative network models, or signed digraphs (*sensu* Dambacher et al., 2015), and Bayesian Belief Networks built using expert elicitation.	Strategic decision making, informing cumulative effects assessment, and providing an evidence base to inform a more detailed risk assessment process (e.g., via press perturbation where the flow-on effects of an increase/decrease in one component is seen in other system components). These approaches are a key communication tool for capturing different perspectives from stakeholders and also are useful for narrowing the set of plausible system representations.
Spatial static tools	Spatial static tools generally involve using a GIS to overlay industry assets, environmental attributes (e.g., fishery areas, species or habitat distributions), management zoning (e.g., marine protected areas - MPAs), pressures, threats or conflicts to inform marine spatial planning. The general aim is to identify sites for industries that minimise conflict and potential interactions based on static GIS layers.	The most common example of this is cumulative effect mapping (*sensu* Halpern et al., 2008), and vulnerability assessment (*sensu* Ruckelshaus et al., 2016).	Broad range of applications from strategic planning, and cumulative effects assessment to inform marine spatial planning and restricted use zones.
Spatial prioritization tools	Prioritization tools are more sophisticated than static tools in that they generally include an explicit inclusion of priorities to support spatial planning (e.g., cost functions, costs/benefits approach or trade-offs assessment). Approaches may be purely economic or may be based on assets or values defined at stakeholder workshops.	Examples include Multi-Criteria Evaluation, the spatial planning tool Marxan, trade-off analysis, and more bespoke examples that include the integration of bio-economic models (Lester et al., 2018; White et al., 2012). Marxan is referred to here as it is both a tool explicitly used in many publications, but also because it is representative of a wider array of similar spatial optimization tools, such as Zonation, which can be used in the same way.	Used by government, industry proponents, conservation non-governmental organisations and research organisations. Applications include strategic planning and marine spatial planning to inform site selection for industries such as finfish aquaculture.
Process/ dynamic tools	Process and dynamic models are complex and data intensive tools to assess trade-offs and interactions, while incorporating feedbacks (reviewed in Geary et al., 2020). The models are based on conceptual and theoretical frameworks that represent a synthesized understanding of processes and parts of the system being assessed (including hydrodynamics and nutrient cycling to ecosystem dynamics and even economic or sociocultural responses and networks).	A complex model example is the ecosystem model 'Atlantis', which incorporates biophysical, economic and social components across multiple marine industries (e.g., Fulton et al., 2017). However, simpler, more targeted model frameworks also exist (e.g., Models of Intermediate Complexity of Ecosystems; Plagányi et al., 2014). Other dynamic tools include connectivity models (Bravo et al., 2020), and atmospheric and oceanographic models derived from equations of motion, sometimes incorporating empirical observations (i.e., data assimilation).	Applications include strategic planning (e.g., assessing trade-offs directly or providing information that forms part of the decision for new industry) and tactical state and national fisheries management (e.g., managing fish catch quotas), and other sectors. These tools are commonly employed as part of environmental regulatory requirements for industry such as finfish aquaculture – for example to evaluate the effects of water quality and nutrient loads from proposed aquaculture production.

Table 2
Categories used to delineate the operational maturity of tools.

Classification	Description	Number of published studies
Absent	The technique has not been used or documented.	0
Developing	The technique has some research evidence and has been implemented in peer-reviewed studies or reports.	≥ 1 but < 5
Maturing	The technique has sufficient evidence and has been implemented in ≥ 5 but < 20 peer-reviewed studies or reports.	≥ 5 but < 20
Mature	The technique has well-proven evidence and has been implemented in ≥ 20 peer-reviewed studies or reports.	≥ 20

different sectors and interest groups can have diverse (and potentially conflicting) objectives for an area (Depellegrin et al., 2017; Smith et al., 2017). There may be significant opportunities to plan for synergistic outcomes that enhance socio-economic benefits and minimise environmental impacts by co-locating and co-managing Blue Economy industries, therefore optimizing ocean use and minimizing the potential for widespread impacts.

Identifying synergistic triple-bottom-line outcomes requires tools that can identify, quantify, and predict interactions among different sectors throughout the lifetime of an activity, from initial planning prior to commissioning through to project decommissioning (Klinger et al., 2018). However, the assessment of within and between sector interactions can be challenging if data to support stakeholder engagement and planning are not readily accessible, guidance on the data that needs to be synthesized is unclear, and appropriate tools to assess multi-sector interactions are unavailable. While a number of support tools have been developed that assess the significant issue of multi-sector impacts (e.g., White et al., 2012; Fulton et al., 2014; Lester et al., 2018), they vary in their complexity, data needs and application. Examples of these tools range from a spatially explicit, coupled biological–economic model to evaluate trade-offs between renewable energy, commercial fishing and the tourism sector (White et al., 2012), to fully comprehensive assessment models considering the entire ecosystem (including human components) (Fulton, 2010; Fulton et al., 2014). Government policy, industry strategic plans, marine spatial plans and regulations on blue economy industries are increasingly informed by tools that assess cross-sector interactions. Biogeochemical models of water quality, for example, are utilised under environmental regulatory requirements for finfish aquaculture in Tasmania, Australia. Additionally, coupled hydrodynamic-biogeochemical modelling is used for reporting on the Great Barrier Reef, Australia (Steven et al., 2019a, 2019b). Despite growth in the use of decision support and regulator tools, there remains a need to critically review the alignment of these tools with the needs of an ever-increasing range of ocean industries and stakeholders. This is especially true in the context of emerging industries where a broad horizon scan of available tools is warranted to support either subsequent more detailed applications of these tools for proposed offshore developments, or the creation of new tools if substantial gaps in capability exist.

In this paper, we built on previous syntheses (Pınarbaşı et al., 2017; Stelzenmüller et al., 2013) and reviewed the tools specifically used to assess ocean multi sectoral interactions. We focussed our analysis on studies that assess interactions between multiple Blue Economy industries due to the growing interest in the co-location of industries (Griffin et al., 2015), and with the environment. First, we conducted a systematic literature review of the existing tools used to assess cross-sector interactions between multiple Blue Economy industries and the environment. Second, we conducted an Operational Maturity Analysis (OMA) to identify the maturity of tools that have previously been used to assess multi sector interactions, and compared these to the maturity of single sector studies identified using the same literature review search terms. Third, we surveyed stakeholders in industry, government and research to identify their perceptions and challenges for infrastructure development, and associated tool development needs for the emerging offshore Blue Economy. Finally, we synthesised and identified knowledge gaps, particularly regarding the tools needed to assess the industries, and their multi-sector interactions, and identified additional tools that might help to fill these gaps and challenges.

2. Methods

2.1. Literature review

We conducted literature searches using Google Scholar and Web of Science on 7 May 2020. Our search criteria consisted of 27 keyword terms (Fig. 1). Our Web of Science search span encompassed all years, and we used the following search indices; SCI-EXPANDED, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC. The Google Scholar search included up to the first 1000 journal publications in peer-reviewed primary literature for each of the search terms. The Web of Science and Google Scholar searches resulted in 5330 potential publications (Fig. 1). Following the preferred reporting items for systematic review and meta-analysis protocols (PRISMA - Shamseer et al., 2015), we screened potential publications by removing duplicates and omitting papers by title, where the publication was clearly not relevant to our search, and then further screened by assessing the publication abstracts, including keyword lists. Publications were then assessed for eligibility by full-text assessment. We only included publications that used frameworks and tools for assessing cumulative effects, interactions, and trade-offs between Blue Economy infrastructure development and the environment. Following this, we included publications that were identified in the reference sections from the included publications (an additional 85 publications). While our search terms were targeted towards multi-sectoral studies, we also reviewed all single sector publications that were identified based on search criteria.

Excluding duplicates, out of 5268 potential publications systematically screened for inclusion in our meta-analysis, 96 addressed multi-sector interactions. Even though the focus of the review was on multi-sector publications, we kept 124 publications which addressed single-sector interactions (within-sector interactions or interactions with the environment), resulting in a final 220 publications included in our synthesis and meta-analysis (Fig. 1). The single-sector publications were generally implied to have an integrative approach that might have potential to be applied to multi-sector issues in the future. We acknowledge that our review is biased to searchable research papers in English. To try and reduce the language bias (*sensu* Nuñez and Amano, 2021), we repeated the search terms in Spanish on 31 August 2020, which yielded an additional three multi-sectoral publications which were included in our analysis. We only included publications that reported the essential metadata in Fig. 1. Further, technical reports and grey literature from government agencies and non-government organisations were under-represented in the literature, especially from non-English publications.

2.2. Tool types

Based on the results of the systematic review, we categorised tools into four different categories: conceptual and semi-quantitative, spatial static, spatial prioritization, and process/dynamic (Table 1). The development of these categories was based on the way each tool was used in each individual study; not on the potential applications of that tool. For example, multi-criteria evaluation can be based on conceptual models, be spatially static, and be used in spatial prioritization and optimisation frameworks. See SI 1 for a more comprehensive breakdown of tools.

2.3. Operational maturity analysis

Operational Maturity Analysis (OMA) is a standardized method for assessing the level of maturity of technological innovations (Becker et al., 2009). We used OMA as a screening technique to identify and compare the maturity of a categorical suite of tools that have previously been used (or have the potential for use) to assess both multi- and single sector interactions, with the aim of determining which tools may be transferable offshore in their current form, or need to be adapted/modified. We classify tools that could be used (e.g., are 'mature' and ready for immediate application – Table 2), as well as developing tools that have utility but may be currently under-utilised in the marine sector. We assume that mature tools have been successfully implemented to such a degree that they represent a solid starting point for uptake in the offshore context, warranting further detailed evaluation.

We also categorised industry sectors to evaluate the number of sectors considered in assessments. Sectors included: commercial fishing, aquaculture, offshore renewable energy, offshore engineering (including oil and gas), other offshore (e.g., shipping, military, tourism, and logistics related industries), and land and coastal based activities (e.g., dredging, coastal built infrastructure, land-based pollution).

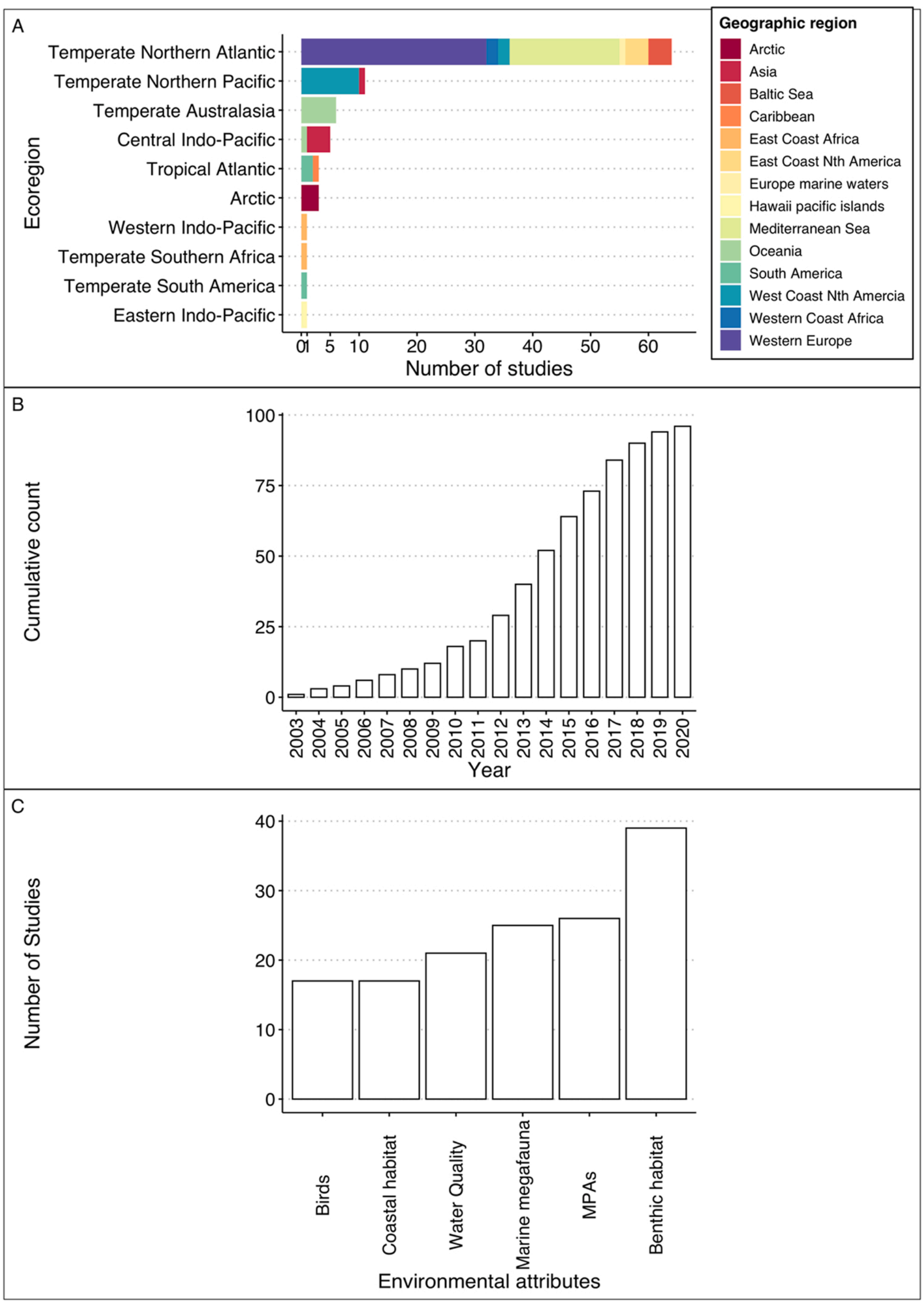

Fig. 2. A) spatial distribution of studies identified in the review that assess multi-sector interactions. The number of studies is grouped by general geographic regions within marine ecoregions.; B) the cumulative number of studies published each year since 2003; and C) the top six environmental attributes considered in assessments.

2.4. Industry survey and thematic analysis

We designed an online survey and asked respondents to describe the main challenges they perceive their industry to face in regard to: site selection; environmental impact assessment; interactions with other industries that share the same resource; social licence and perceptions; and site closure and decommissioning. We also asked which decision support or marine spatial planning tools their industry uses and whether these tools are used to assess trade-offs or interactions between multiple sectors. Finally, we asked for the ideal components of a tool to serve their needs. We used snowball sampling (where respondents are asked to recruit other relevant participants) to disseminate the survey across industry stakeholders, including regulators, industry representatives and researchers. Survey responses were anonymous, and key themes in responses were identified using thematic analysis (following Braun and Clarke, 2006). Thematic analysis is a six-step process involving: "*1) data familiarisation, 2) generating initial codes to categorise data, 3) searching for themes, 4) reviewing themes, 5) defining and naming the themes, and finally 6) reporting themes*" (Braun and Clarke, 2006). Coding and theme identification were conducted independently by two of this study's authors, and then themes were reviewed, defined and named. The survey was conducted in accordance with the human ethics guidelines of Griffith University (GU reference number 2020/155). We received 24 responses to the survey from individuals and a group. The majority of respondents were associated with Australian sectors, though there was representation from Europe (United Kingdom, Belgium) and South America (Chile).

3. Results

3.1. Literature review

A total of 96 multi-sector publications were included in the review based on our inclusion criteria and were predominantly from Western Europe and the Mediterranean (51% of studies - Fig. 2A). Efforts to assess multi-sector interactions have rapidly accelerated since 2011 with almost 80% of publications published since then (Fig. 2B). Studies simultaneously assessed between 2 and 11 sectors. The predominant Blue Economy sectors assessed included commercial fishing (74 publications), offshore engineering (including oil and gas) (53), aquaculture (52), renewable energy (48), and 'other' offshore actives which included shipping, military, tourism, and logistics related sectors (61). Land and coastal activities (including dredging, mining, physical structures etc) were also commonly assessed (31), Around 70% of publications (66/96) included both inshore and offshore sites, while six publications solely assessed inshore activities, and another six solely focussed on offshore assessments. The remaining studies did not specify whether activities were inshore or offshore.

Only five studies covered the triple bottom line and simultaneously assessed environmental, economic, and social attributes. Of these studies, four used spatial prioritisation tools (Lester et al., 2018; Pınarbaşı et al., 2019; White et al., 2012; Zanuttigh et al., 2016), while the fifth used process/dynamic tools (Fulton et al., 2017). Almost 25% of multi-sector studies (23/96) explicitly included social values in their assessments. Activities such as recreational fishing, boating, as well as tourism were the primary recreational and tourism activities considered. Only 14% (13/96) of multi-sectoral studies explicitly considered an economic component such as the financial benefits of co-location or the economic potential for each industry. The primary attributes relating to the environment included overlap with Marine Protected Areas (including sensitive and ecologically significant areas, rare and endangered species, nursery areas, etc), and effects on water quality, benthic habitats and their associated communities, coastal habitats (mangroves, saltmarsh), marine megafauna, birds, marine biodiversity in general, and numerous fish related indices including populations, communities, and species richness (Fig. 2C).

3.2. Operational maturity analysis

We found that studies generally approach the assessment of multi-sector interactions with tools that fall within the spatial static and spatial prioritization categories. The most mature modelling tools for

Table 3
Operational maturity assessment highlighting the number of studies that assess single- and multi-sector interactions (between two or more industry sectors) using different categories of tools (assessed maturity, based on level of use indicated by the colour gradient). Industry sectors are: commercial fishing, aquaculture, offshore renewable energy, offshore engineering (including oil and gas), other offshore, and land and coastal based activities. Other offshore industries assessed include shipping, military, tourism, and logistics related industries. Single-sector studies are shown for comparison, but the Information may not be comprehensive as the search was targeted towards multi-sector studies.

	Tool			
Blue-economy sector combinations	Conceptual/ Semi-quantitative	Spatial static	Spatial prioritization	Process/ Dynamic
Single sector	24	52	32	52
Two sectors	11	18	16	2
Three sectors	6	13	8	0
Four sectors	15	25	10	1
Five sectors	7	8	1	2
Six or more sectors	4	1	0	0

Mature: The technique has sufficient evidence and has been implemented successfully in ≥20 peer-reviewed studies or reports	Maturing: The technique has sufficient evidence and has been implemented successfully in ≥5 but <20 peer-reviewed studies or reports	Developing: The technique has some research evidence and has been impl emented successfully in ≥1 but <5 peer -reviewed studies or reports	Absent: The technique has not been used or documented

Table 4
Operational maturity assessment highlighting the maturity of tools used in single sector studies (assessed maturity, based on level of use, indicated by the colour gradient). Other offshore industries assessed include shipping, military, tourism, and logistics related industries. The data within this OMA table only includes studies collected as part of the multi-sector literature search, using the same search terms.

	Tool			
Blue economy sectors	Conceptual / Semi-quantitative	Spatial static	Spatial prioritization	Process/ Dynamic
Offshore engineering (including oil and gas)	15	5	1	1
Offshore renewable energy	1	11	10	5
Commercial fishing	4	16	9	39
Aquaculture	3	15	10	6
Other offshore	1	4	2	1
Land and coastal activities	0	1	0	0

Mature: The technique has sufficient evidence and has been implemented successfully in ≥20 peer-reviewed studies or reports	Maturing: The technique has sufficient evidence and has been implemented successfully in ≥5 but <20 peer-reviewed studies or reports	Developing: The technique has some research evidence and has been implemented successfully in ≥1 but <5 peer -reviewed studies or reports	Absent: The technique has not been used or documented

assessing multiple Blue Economy sectors are spatial prioritization tools such as Marxan and multi-criteria decision support tools, and spatial static tools such as cumulative effect mapping using GIS (Table 3). In contrast, process/dynamic tools are most often applied for single sectors, particularly commercial fisheries (Table 4), but less in multi-sector studies (Table 3). Within single-sector approaches, tools addressing seafood and marine products were more mature relative to other industries, and studies on commercial fishing generally utilised more complex tools compared to those on aquaculture, which has traditionally relied on spatial static approaches (Table 4). We found that multi-sector studies in offshore engineering generally used conceptual and semi-quantitative tools such as expert elicitation, qualitative network models and Bayesian Belief Networks (Table 3). Multi-sector assessment tools have typically been used to assess 2–4 Blue industries. While only a relatively small number of process and dynamic tools were identified, they included examples that simultaneously assessed up to five sectors.

Table 5
Summary of themes, challenges identified through the stakeholder survey, and assessment tools that may be able to address these challenges.

Theme	Challenges	Assessment tools
Multi-sector interactions	Assessing cumulative impacts, trade-offs, and synergies Need to address feedbacks Need for governance and management frameworks (e.g., marine spatial planning) Site selection	Process/dynamic tools and spatial prioritization tools
Integrated tools and assessment methods	Novel approaches to support multi-sectors operating in offshore environments Efficient and effective reporting	Process/dynamic tools and spatial prioritization tools
Stakeholder concerns	Transparency in decision-making Effective engagement Securing social license Integrated planning frameworks for site decommissioning	All of the tool types considered can be used to service this need in some form.
Limitations in baseline data	Site selection Environmental impact assessments (EIAs)	Process/dynamic tools, especially tools that synthesize data to produce comprehensive data products (e.g., oceanographic modelling)

3.3. Industry survey and thematic analysis

Responses (n = 24) were spread evenly across industry (25%), research organisations (25%), government (21%), and universities (25%), with one response from a non-for-profit organisation. Over half of the responses were either directly or indirectly associated with seafood and marine products (e.g., offshore engineering to support aquaculture). Approximately 60% (15/24) of respondents had used more than one type of tool to assess trade-offs and these were primarily spatial static and spatial prioritization tools (SI 1). We identified four themes that survey respondents consistently said were key to the success of offshore developments (Table 5). First, the assessment of multi-sector interactions was identified as being particularly challenging and important for site selection, although having advice on interactions was also seen as crucial for the success of Blue Economy industries. Second, there was demand for integrated assessment tools, such as tools that consider both ecological and economic outcomes. Third, local stakeholder engagement and community support were identified as key for project success. Assessment tools were seen as supporting this engagement through facilitating access to information and improving transparency of decision making. Finally, a lack of baseline data was commonly cited as a general challenge for developing tools that can support site selection for new activities and environmental impact assessments.

4. Discussion

The offshore Blue Economy is rapidly expanding in an effort to sustain a growing human population. A sustainable, equitable, ecosystem-based approach to 'blue development' demands the consideration of the potential for cumulative effects arising from multi-sector operations, as well as interactions between multiple sectors in environmental assessments (Lombard et al., 2019; Winther et al., 2020). We used a multi-faceted approach, combining a systematic literature review, operational maturity analysis and stakeholder survey to assess the current support tools used to assess multi-sectoral interactions between Blue Industries and the environment and identified where support tools can contribute to solving current industry challenges. Our analysis showed that the most well-developed tools for assessing interactions are spatial prioritization tools, such as Marxan and multi-criteria decision support tools; and spatial static tools, such as cumulative effect mapping using GIS. More complex process/dynamic tools such as ecosystem and oceanographic models are well developed for single sectors, but have been less commonly applied in multi-sector studies. Below we consider key needs and opportunities that emerge from our analysis.

4.1. Insights from the literature review and OMA

The majority of multi-sector studies identified in the literature review focussed on industries operating in Western Europe, the Mediterranean and the west coast of the United States. While these geographic regions have seen some of the longest history of explicit consideration of multisector interactions – and so dominates cumulative publication libraries as a result – we also acknowledge that the review is exposed to biases (e.g., in the form of language or grey vs published literature). There is also an additional challenge of achieving adequate representation of the diverse Indigenous enterprises and smaller scale participants in the blue economy in developments (e.g., small-island developing states and small-scale fisheries and aquaculture – Cohen et al., 2019), and overcoming this to integrate all proponents in the assessment of interactions is necessary for effectively supporting equitable blue growth (Cisneros-Montemayor et al., 2019).

Amongst the available published literature, we found that multi-sector studies generally approach the assessment of interactions using a range of tools that fall within spatial static and spatial prioritization classifications (a pattern that is anecdotally supported by colleagues in Africa and Asia). Only five studies simultaneously assessed the triple-bottom-line, highlighting the difficulty of conducting comprehensive assessments for multiple sectors (Fulton et al., 2017; Lester et al., 2018; Pınarbaşı et al., 2019; White et al., 2012; Zanuttigh et al., 2016). Limited development and uptake of triple-bottom-line tools is likely limiting the efficiency and effectiveness of planning for multiple Blue Economy industries (Stoddard et al., 2012).

The most well-developed support tools for assessing multiple Blue Economy sectors are spatial prioritization tools such as Marxan and multi-criteria decision analysis, and spatial static tools such as cumulative effect mapping using GIS. In contrast, process/dynamic tools such as ecosystem and oceanographic models are well developed for single sectors, particularly commercial fisheries, but have been less commonly applied in multi-sector studies. The application of existing tools to offshore Blue Economy sectors is nascent but needs further development (e.g., modelling of energy infrastructure-fishery interactions) and continued sharing of tools between different sectors, especially where tools are more developed. The potential use and uptake of approaches to multi-sector assessment generally comes down to data needs, expertise and organisational capacity, development costs, and whether the approach is fit-for-purpose. For example, regarding the spatial placement of industries, tools such as Marxan can likely translate utility from other sectors and inshore experiences to an offshore setting. However, in many instances (at least in the short to medium term) where there are currently fewer conflicts, it may be adequate to use simpler more static tools rather than needing to account for the more dynamic feedbacks between conflicting users. Even before implementing tools such as Marxan, spatial static tools such as spatial data portals and atlases can help the public, stakeholders and decision makers understand the context for and implications of development (Lathrop et al., 2017). Further, different sectors operate on different spatial and temporal scales and representing this in the same modelling framework is challenging. Parallels can be drawn from lessons learned in ecological modelling when representing multiple species and processes that operate across vastly different spatial and temporal scales (Isaac et al., 2020). Additionally, the need to consider mismatch between the scales of management and ecological dynamics remains central. For example, management of the Great Barrier Reef occurs at much larger scales than individual reefs, islands and marine bioregions (Cumming and Dobbs, 2020). Socio-ecological scale mismatches may apply equally to many of the marine sectors operating within Australia's Blue Economy (Cumming et al., 2006).

Below we discuss four case studies that cover each of the tool categories to explore how different types of tools approach the assessment of multi-sector interactions.

4.1.1. Conceptual and semi-quantitative framework

Teck et al. (2010), working within a conceptual and semi-quantitative framework, used expert elicitation to inform a multi-criteria evaluation and quantitatively estimate the relative vulnerability of 19 California Current ecosystems to 53 stressors associated with multiple human activities. Through multi-criteria evaluation, the authors quantitatively estimated each ecosystem's resistance to each stressor and identified the number of species or trophic levels affected by each stressor within each ecosystem. This study illustrates how expert elicitation can be integrated within a multi-criteria evaluation approach to provide a quantitative, transparent and repeatable assessment of relative vulnerability to human activities across individual ecosystems. Expert elicitation in emerging offshore industries can be challenging due to limited real-life experience, rendering the exercise mostly hypothetical (at least in the short-term). However, despite this uncertainty, tallying expert advice on potential hazard and impact pathways could be beneficial to lay a foundational framework underlying decision-making, later supported by monitoring data.

4.1.2. Spatial static framework

Micheli et al. (2013) used a cumulative effects assessment within a spatial static framework to analyse the intensity and distribution of the cumulative impacts of 22 drivers on 17 marine ecosystems of the Mediterranean and Black Seas. Using a cumulative impact model that quantifies the vulnerability of individual ecosystems to human drivers of ecological change (Halpern et al., 2008), the authors were able to quantify cumulative impacts across the whole research area, in addition to identifying areas that were particularly vulnerable to cumulative impacts. This study illustrates how cumulative effects assessments can be used for the synthesis and integration of disparate cross-sector information and represents important opportunities for ongoing monitoring and conservation aimed at preventing future degradation. However, to make such an assessment, there needs to be a robust understanding of both the distribution of ecosystems and their vulnerability to industrial activities. As suggested in the stakeholder survey, this need for baseline data is critical but can be challenging to obtain in offshore environments with emerging industries.

4.1.3. Spatial prioritization framework

Within a spatial prioritization framework, Lester et al. (2018) used a marine spatial planning analytical model to identify candidate locations for aquaculture development within the Southern California Bight, USA, while also considering the impact on existing industries and environmental concerns. Through the application of a bio-economic model, integrated with an analytical trade-off analysis, the authors were able to identify optimal sector wide spatial plans for aquaculture development that simultaneously minimized cross-sectoral impacts on the environment and maximised individual sector values. The embedding of a bio-economic model within a spatial prioritization framework provided the capacity to identify a marine spatial plan that increased overall revenue and had minimal impact (often less than 1%) on existing sectors and the environment.

4.1.4. Process/dynamic framework – borrowing models from other fields

Within a process/dynamic modelling framework, Alexander et al. (2016) developed a spatial ecosystem model to investigate the impact of offshore renewable energy structures on the commercial fishing industry of the Scottish west coast. Using Ecopath with Ecosim and Ecospace modelling software (which had previously been widely used in a fisheries and conservation context), the authors were able to model changes in biomass of species important to commercial fisheries, and to assess the combined effects of artificial reef formation and exclusion zone effects due to the introduction of offshore renewable energy structures. However, this study also raised issues about data availability (a challenge in all modelling frameworks covered in this review), spatial scale and resolution, which limited the accuracy of the model. While this study is a good example of the use of a process/dynamic framework, particularly for setting broad scale strategic directions, it does highlight the infancy and current weakness of this type of modelling approach to multi-sector analysis in terms of tactical operational applications, suggesting that this approach will become more accurate with further development and use in such a role.

4.1.5. Caveats

It is important to note that the single sector OMA results are based on single sector publications that were identified based on search criteria that were targeted to multi-sector studies. Hence, a number of tools that are heavily used to assess single sectors are likely underrepresented in our OMA. For example, the dynamic tool Ecopath with Ecosim has been widely applied in fisheries and conservation, but has a rapidly diversifying set of applications (Colléter et al., 2015), such as integration with 3D gaming technology to explore management scenarios for marine ecosystems (Steenbeek et al., 2021). We acknowledge that the maturity of tools identified in this review does not capture the maturity of tools that may not be used in specific Blue Economy single-sector assessments but might instead come through fields like conservation and be easily adapted (e.g., Marxan and other tools for prioritization).

4.2. Insights from the survey

In addition to the key needs/challenges identified through the survey (Table 5), the survey also identified a number of tools that were not identified during the literature review (See SI 1 for models identified in both literature review and survey, only from the literature review, and only from the survey). The differences in tools used by industry and academic researchers may hinder effective planning for the Blue Economy. This gap between information and practices in industry and academic researchers suggests a more comprehensive review of tools beyond academic publications is needed. The power of knowledge integration to represent ecosystem interactions has been recently demonstrated for a coastal fishery, where information from a diverse array of stakeholders more adequately captured complex ecosystem feedbacks and interactions compared to knowledge from a single group (Aminpour et al., 2021).

4.3. Application of existing tools to address stakeholder needs

The tools used to assess multi-sector interactions vary in their complexity, data needs, and objectives; therefore, no single tool or process can comprehensively satisfy all stakeholder objectives. Instead, a number of different tools are needed at different stages of the planning process to support site selection and environmental management (Addison et al., 2018). The following sections discuss how existing tools can address each of the four primary concerns raised in the survey and identify where tools require further development.

4.3.1. Multi-sector interactions

Survey respondents identified the crucial need to explicitly address multi-sector interactions and feedbacks in the life-cycle of offshore sectors to ensure sustainable ocean use. Existing tools, such as dynamic/process models, could address this need in the future (as shown by the small number of extant inshore applications – e.g., Fulton et al., 2011, Fulton et al., 2017, Steven et al., 2019a, 2019b), but at present are only well developed in single sector assessments. Further targeted development and application of process/dynamic tools, like ecosystem models, which can account for dynamic and non-additive feedbacks among sectors and allow for direct scenario comparisons can benefit multi-sectoral assessments. However, tool development and application must be done with care to ensure tools remain useful rather than being overwhelmed by complexity, especially in dimensions where there is little available data for validation.

4.3.2. Integrated assessment tools

Systems are now being developed to access and better integrate different tools. For example, aquaculture tools are increasing in sophistication with more comprehensive approaches put into use over the past decade, expanding across aspects of production into interactions with other users (Steven et al., 2019a). A primary challenge is that comprehensive integrated assessment tools often require significant data inputs (e.g., Atlantis), as well as substantial technical expertise to use or to develop. While some data layers are easily accessible, offshore ecosystems can pose particular challenges with regards to data availability in a format suitable for planning and assessment. For example, only ~18% of the global ocean's seafloor is mapped at a resolution of 1 km (Mayer et al., 2018).

Key to integrated assessment tools is the ability to incorporate uncertainty and consider feedbacks in the system. Management Strategy Evaluation is one example of an integrated assessment tool that is considered best practice in fisheries decision making (Punt et al., 2016; Smith et al., 1999) and could be applied to assess multiple sectors in an integrated framework. It is a recommended part of Integrated Ecosystem Assessments in the United States (Levin et al., 2014, 2009). Management Strategy Evaluation is a model-based approach where each part of the adaptive management cycle, across production and management systems, is represented (biological, industry operations, monitoring, management decision making, and in some circumstances even the socioeconomic drivers and political lobbying that can influence sector dynamics). Management Strategy Evaluation could address several of the themes identified as critical by industry for improving transparency in stakeholder communication, assessing trade-offs and cross-sectoral impacts. A range of model sub-components can be coupled within the Management Strategy Evaluation framework to evaluate the triple bottom line performance of different management strategies using qualitative and/or quantitative measures to highlight trade-offs (Plagányi et al., 2013). Management Strategy Evaluations are also explicitly participatory, with stakeholders called upon to define model contents and strategies to be tested.

4.3.3. Stakeholder concerns

Survey respondents identified a need to address stakeholder concerns, primarily in regard to obtaining social licence, and addressing negative social perceptions of sectors. The consideration of social dimensions is critical for a successful Blue Economy (Cisneros-Montemayor et al., 2021, 2019). The inclusion of social and cultural dimensions in approximately one quarter of reviewed studies is promising, especially as the factors determining community support for sectors such as fisheries and aquaculture are numerous and complex (Alexander and Abernethy, 2019). The need to address stakeholder concerns can be aided by any of the tools identified in this review, as long as tools are transparent and encourage diverse stakeholder participation (Aminpour et al., 2021). For example, participatory mapping of ecosystem services can inform multi-criteria decision analysis (Klain and Chan, 2012), while visual outputs from spatial static or spatial prioritization tools can contribute towards effective marine spatial planning (Gimpel et al., 2018). Stakeholders should ideally be consulted during tool development, not only to ensure greater buy-in but also so that their knowledge and insights are adequately captured given the complexity of modelling (qualitatively or quantitatively) multiple sectors. We acknowledge that there is a breadth of literature that specifically focusses on modelling social interactions around contested issues (e.g., combining psychological processes and system dynamics - van Putten et al., 2018) that goes much deeper than multi-criteria approaches (Condie and Condie, 2021), however exploring these methods and literature are beyond the scope of this research.

4.3.4. Baseline data limitations

Baseline data was commonly cited as a challenge for developing tools that can support site selection for new activities and environmental impact assessments. Data limitations generally constrain the types of tools able to be applied to assess multi-sector interactions to conceptual and semi-quantitative approaches, and generate much uncertainty. Filling the data gap is therefore critical. Fundamentally this depends on monitoring data, but can be aided through tools with the capacity for data generation. For example, physical oceanographic models – while dynamic by nature – can generate ocean temperature data at high spatial and temporal resolutions for input into other tools. Furthermore, the development of automated monitoring and data collection can help fill this gap (Fer et al., 2021), though will require clear communication between managers, modellers, and designers of autonomous systems with regards to data needs, resolution and reliability (and thus appropriate use). Modelling and monitoring design should be an iterative process, whereby monitoring data can be used to inform models, and models can inform adaptive monitoring and data collection (Addison et al., 2018). Modelling approaches that account for uncertainty can also be useful in characterising system dynamics in the absence of comprehensive data.

5. Conclusions

A diverse array of tools are available to assess interactions and trade-offs, ultimately informing marine spatial planning (Pınarbaşı et al., 2017; Stelzenmüller et al., 2013), and most of which could be transferred to emerging offshore industries as needed. There are geographic gaps in the application of multi-sector assessments, as well as data gaps, limiting the uptake and development of more comprehensive and integrated models. Almost universally, however, gaps remain in accessibility of these tools to different (non-expert) stakeholders and in offshore environments, available data to develop and validate tools is reduced. No single tool can comprehensively satisfy all stakeholder objectives. Rather, a number of different tools (with varying complexity) are useful at different stages of development and decision making to support site selection, evaluate trade-offs, and the management of multi-sector interactions. Our industry survey revealed that many challenges related to multi-sector interactions in particular could be best addressed with process/dynamic and spatial prioritization tools – although other tools may be used as needed, especially for stakeholder engagement. Our study shows there are currently a large range of such tools in various stages of development, but there is also scope for increased development of some approaches that can address uncertainty and integrate across different sectors. Whether new or old there is a strong need for continued sharing of approaches and tools across sectors in offshore environments (e.g., commercial fishing, aquaculture, offshore renewable energy, offshore engineering including oil and gas). Finally, there is a need for better communication between industry, researchers, and stakeholders to inform how best to integrate impacts and concerns from different sectors.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.03.0168.

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