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Sharing the seas: a review and analysis of ocean sector interactions

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Abstract
Ocean activities are rapidly expanding as Blue Economy discussions gain traction, creating new potential synergies and conflicts between sectors. To better manage ocean sectors and their development, we need to understand how they interact and the respective outcomes of these interactions. To provide a first comprehensive picture of the situation, we review 3187 articles to map and analyze interactions between economically important ocean sectors and find 93 unique direct and 61 indirect interactions, often mediated via the ocean ecosystem. Analysis of interaction outcomes reveals that some sectors coexist synergistically (e.g. renewable energy, tourism), but many interactions are antagonistic, and negative effects on other sectors are often incurred via degradation of marine ecosystems. The analysis also shows that ocean ecosystems are fundamental for supporting many ocean sectors, yet 13 out of 14 ocean sectors have interactions resulting in unidirectional negative ecosystem impact. Fishing, drilling, and shipping are hubs in the network of ocean sector interactions, and are involved in many of the antagonistic interactions. Antagonistic interactions signal trade-offs between sectors. Qualitative analysis of the literature shows that these tradeoffs relate to the cumulative nature of many ecosystem impacts incurred by some sectors, and the differential power of ocean sectors to exert their rights or demands in the development of the ocean domain. There are also often time lags in how impacts manifest. The ocean governance landscape is not currently well-equipped to deal with the full range of trade-offs, and opportunities, likely to arise in the pursuit of a Blue Economy in a rapidly changing ocean context. Based on our analysis, we therefore propose a set principles that can begin to guide strategic decision-making, by identifying both tradeoffs and opportunities for sustainable and equitable development of ocean sectors.

1. Introduction

The term Blue Economy has gained immense traction, reflecting the enormous commercial interest in, and efforts devoted to, claiming ocean resources and space in the Anthropocene era [1]. Yet, as a concept it remains ambiguous. When it emerged, in the run-up to the 2012 UN Conference on Sustainable Development process, the expression was invoked to connect the ocean to the 'green economy' [2]. Since then, the concept has been repackaged and conceptualized to match a diversity of discourses anchored in specific geographies and linked to experiences of particular sectors and actors [3], some of which see the ocean as natural capital and a foundation for business development, while others regard it as a means of development for small island states and small-scale livelihoods [2]. The latter indicates a concern for a socially equitable development of the ocean [4], yet this view is far from ubiquitous in contemporary discourses.

While the Blue Economy is generally discussed in an aspirational light with expectations of positive outcomes, it is not unproblematic. The rapid expansion of industrial activities in the ocean continues to outpace global regulatory efforts and generate negative consequences for local communities, small-scale operators and the ocean ecosystem [1, 5, 6]. Already a decade ago Douvere and Ehler [7] noted that the mounting pressure on the marine environment was leading to two types of conflict: *user–environment* conflicts, resulting from cumulative and aggregate environmental impacts; and *user-user* conflicts, resulting from the incompatibility of many ocean sectors, and the foregone opportunity for one sector in the wake of another. While environmental impacts of human activities on the ocean are widely acknowledged and studied [8, 9], to date a systematic assessment of which ocean sectors interact, and how, is lacking. This gap is noted in recent work on multi-sector management [10], and typologies of ocean multi-use [11] as well as conceptualizations of social synergies and tradeoffs for marine conservation [12].

This paper presents a systematic assessment of documented interactions between ocean sectors, based on a review of 3187 articles. Our explicit focus is on interactions between economically important ocean sectors, and how these interactions are mediated by changes in the natural environment. The analysis identifies a multitude of types of ocean sector interactions and thus complements the predominant focus of Marine Spatial Planning scholarship on spatially explicit interactions [13]. It sheds light on both synergies and the potential user conflicts highlighted by Douvere and Ehler [7], which are often overlooked in practice. Disregarding the latter can lead to overly optimistic projections of blue growth potential (e.g. EU Blue Growth Policy [14]) and forecasts that neglect uncomfortable, but possibly inevitable, trade-offs.

We also categorize the documented outcomes of ocean sector interactions and identify three key themes that cut across all of these: (a) the cumulative nature of many sector impacts on ecosystems; (b) observed time-lags in how impacts are manifested; and (c) the differential power of ocean sectors and other relevant and affected actors to exert their rights or demands in the development of the ocean domain. Based on our analysis we conclude by proposing a set of principles that can begin to guide prioritizations, by flagging likely tradeoffs and identifying opportunities for sustainable and equitable governance trajectories. These principles reach beyond purely economic analysis to highlight key social and ecological dimensions of importance for setting the Blue Economy on a just and sustainable course, and for delivering on the 2030 sustainable development agenda.

2. Methodology

2.1. Systematic mapping of the literature

Our assessment of ocean sector interactions is based on a systematic mapping of 3187 abstracts and subsequent analysis of 313 peer-reviewed full-length articles, to identify interactions between economically important ocean sectors documented in academic literature [15, 16] (supplementary materials (from hereon SM) figures S1 and S2 (available online at stacks.iop.org/ERL/16/063005/mmedia)). The review followed a six-step process, outlined in detail in supplementary materials sections 1 and 2, and the review and analysis combines inductive and deductive elements. Interaction is defined as one sector affecting another, either directly or via a mediating activity (elaborated below), in physical space. Interactions among sectors in the policy sphere are not the explicit focus of this paper, but were to some extent captured during qualitative coding (below). Table 1 shows the 14 *ocean sectors* and 5 *mediating activities* used as units of analysis. The inclusion criteria for any sector was that fulfillment of its main objectives comes solely from the ocean. Land-based activities, such as agriculture, and its impacts on the ocean through e.g. runoff, are therefore not included. Table 1 represents the final iteration of an inductive process that started with a broad literature search to capture all sectors of relevance in the ocean domain. This initial search built on a comprehensive review of ocean uses by Jouffray *et al* [1], which helped delineate initial search terms to identify ocean sectors. However, the final list of sectors emerged from the review and coding of all articles. During this process it became clear that certain sectors represented a form of activity that was repeatedly found to mediate effects of one sector on another (SM figure S6). Examples include dredging, or laying of cables and pipelines. These activities are driven largely by the ocean sectors included in our review, and generally do not occur independently. We therefore refer to these as 'mediating activities', to highlight the role they play as mechanisms underpinning ocean sector interactions.

Delineating the ocean sectors and mediating activities allows us to analyze economic sector interactions (or user-user conflicts, *sensu* Douvere and Ehler [7]). However, the biosphere represents the foundation of sustainable blue growth. To also capture user-environment interactions (ibid), we therefore included two proxy units of analysis: 'ecosystem' and 'marine protected areas' (table 1). 'Ecosystem' captures the passive but fundamental role of the biosphere, while 'marine protected areas' (MPAs) represent the most ubiquitous and widespread tool used by human actors to actively promote ocean health [17, 18], which frequently interacts with other ocean sectors and therefore warrants inclusion.

Table 1. List of ocean sectors and mediating activities included as units of analysis. Mediating activities refers to activities that do not generally occur independently but are driven largely by the ocean sectors. 'Ecosystem' and 'marine protected areas' are proxies used to represent the ocean biosphere which forms a foundation of ocean economies and through which many sector-sector interactions are mediated.

Unit of analysis	Description
Ocean sector	
Aggregate mining (agg)	A form of marine mineral mining focused on coarse particulate material such as crushed stone, gravel and sand. Natural aggregates currently represent the most mined mineral in the marine environment.
Aquaculture (aqua)	The farming of plants and animals in coastal and offshore areas. Land-based aquaculture is included if occurring as a result of land reclamation, such as land reclamation for shrimp ponds.
Bioprospecting (bio)	The search for marine organisms from which genetic material is used for development of commercial products (e.g. medicinal drugs), and which frequently also informs efforts focused on conservation and taxonomy.
Desalination (des)	The process of removing salt from seawater, for drinking, sanitation and irrigation purposes.
Fishing (fish)	All fisheries, including large-scale industrial fishing as well as small-scale artisanal or subsistence fishing.
Fossil fuels energy (dril)	Exploration and drilling of offshore oil and gas.
Metal/minerals mining (min)	Mining for metals and minerals (excluding aggregates) on the seabed (e.g. placer deposits of diamonds, tin, titanium and gold in shallow water, as well as the prospect of deep sea mining)
Military activities (mil)	The use of the seas for military purposes, involving the development of airborne, surface, and submarine military power.
Renewable energy (ren)[a]	Other forms of offshore renewable energy, such as currents, tides, salinity gradients, thermal gradients and marine biomass.
Shipping (ship)	The transportation of freight and passengers through the ocean, including cruise ships.
Telecommunications (tel)	The placement of submarine telecommunication cables.
Tourism (tou)	Any ocean-related tourism and leisure activities taking place in coastal and offshore waters, including recreational boating and fishing, swimming, snorkelling or diving. Cruise tourism is considered under the shipping sector.
Wave energy (wave)[a]	Renewable energy using wave power.
Wind energy (wind)[a]	Renewable energy using offshore wind power.
Biosphere	
Ecosystem (eco)	As industrial sectors interact with the ecosystem, this category is included to represent the biosphere, and the general health of marine ecosystems.
Marine Protected Areas (mpa)	Represents the protection of specific areas of the ocean, estuaries and coasts. Generally established to achieve either conservation, touristic value or fisheries management.
Mediating activity	
Dredging (dred)	Dredging of the benthos for the purpose of removing or relocating seabed material, such as sand, mud or gravel.
Land reclamation (rec)	Represents the creation of new land by raising the elevation of the seabed, pumping water out of wetland areas, or filling up coastal deltas.
Underwater cables (cab)	Laying and maintaining underwater cables, including telecommunication cables and power cables.
Underwater pipelines (pipe)	Laying and maintaining underwater pipelines. Includes all types of underwater pipelines, but most commonly refers to transportation of oil and gas.
Waste disposal (disp)	Deliberate disposal of waste in the ocean, including industrial wastes, biomass, chemicals, mine tailings, brine, military munitions, etc. Does not include non-point source pollution, such as nutrient leakage from agricultural land or plastic pollution.

[a] Literature on renewable ocean-based energy can be clearly divided into wind, wave and other renewables, the latter being very recent. Given expected future growth of renewables, mapping of current and plausible future interactions needs to account for them. Wind energy is the most well-established and therefore a larger literature exists around this topic. To avoid the literature sampling being dominated only by wind it was therefore necessary to conduct a search across the three distinct sectors, hence their separate inclusion.

2.2. Analysis

Our analysis involved three steps (SM, figure S1). Methods associated with each are outlined in more detail below and in supplementary materials. Step one assessed ocean sector interactions through systematic coding of the literature (section S1, figure S2). In step two, outcomes of all identified interactions were classified into four categories that relate to: (a) spatial overlap, or effects on (b) the natural capital used by another sector, (c) the operations or (d) the (touristic) value of another sector (table 2). Steps one and two resulted in a database of unique

Table 2. Outcome categories and interaction types. Outcome categories indicate consequences associated with a specific sector-sector interaction, and documented by one or multiple scientific articles reviewed. Interaction type refers to the specific form of interaction between two sectors, and each outcome category is associated with both synergistic and antagonistic ways of interacting (SM, section S3).

Outcome category	Interaction type	Description	Example
Space	*Captures outcomes relates to spatial overlap.*		
	Synergistic	Sectors share space in a way that benefits one or both of the sectors.	Multi-use platforms combining wind farms and aquaculture [19].
	Antagonistic	Conflict occurs due to crowding or competition for ocean space.	The drilling sector causes an increase in oil tankers, which creates crowded shipping lanes [20].
Natural Capital	*Captures outcomes affecting natural capital used by another sector*		
	Synergistic	The interaction results in enhancement of the natural capital of one or both sectors.	Drilling platforms act as artificial reefs, which can enhance the fish populations that the fishing industry inherently relies on [21].
	Antagonistic	The interaction results in diminishment of the natural capital of one or both sectors.	Drilling for oil and gas disturb, kill, or injure marine life through seismic surveys, cause contamination through toxic drilling mud and cuttings [22], and can cause oil spills, which impact the fish populations that the fishing industry inherently relies on [23].
Touristic Value	*Refers to the value of the tourism sector as perceived by users or consumers (i.e. tourists). Does not capture economic value*		
	Synergistic[a]	The interaction results in enhancement of a feature valued by the tourism sector.	In some contexts, a wind farm could enhance the touristic appeal of an area for tourists interested in renewable energy [24].
	Antagonistic	The interaction results in diminishment of a feature valued the tourism sector.	An area heavily populated by aquaculture farms may be less desirable for tourists who value pristine landscapes [10].
Operations	*Captures outcomes affecting the operations of another sector*		
	Synergistic	The sectors interact in such a way that the daily operations in one or both sectors are enhanced.	Cold ironing of ships (provision of electrical power) provided at renewable energy stations [25].
	Antagonistic	The sectors interact in such a way that the daily operations in one sector (or both) are impeded/diminished.	Bottom trawling fisheries damaging wind farm power cables [26].

[a] Note that there is heterogeneity in what is valuable for tourism. For example, in some contexts a wind farm was observed as valuable to tourists interested in renewable energy, while in other cases it was identified as undesirable and aesthetically unappealing. This is accounted for in our results

sector-sector interactions (referred to as interaction types) and associated outcomes [16]. The third step included three distinct analyses. First, we used network analysis to visualize sector interactions and calculate degree centrality scores for each sector (i.e. how connected each node is to other nodes in the network). Second, we visualized patterns of association between outcomes and sectors, and examples were drawn from the interactions database to unpack and exemplify some of the more common mechanisms involved in generating observed outcomes associated with each sector and interaction type. Third, we conducted qualitative analysis of reviewed literature to identify themes of critical relevance for engagement with ocean sector interactions, as they are conceptualized in this review.

During analysis, the directionality of an interaction (i.e. who is affecting who) emerged as a key issue to capture. For example, in a particular context, drilling platforms may enhance fish stocks through their role as artificial reefs, but there is no reverse influence. In another context, drilling and fishing compete for space and crowding generally occurs in both directions. The latter are referred to in our results as bidirectional interactions, and the former as unidirectional.

2.3. Coding and codebook development

Full articles were coded in MAXQDA 2018.2 to identify unique sector-sector interaction types, while simultaneously capturing qualitative information about these interactions. We developed a codebook to capture how different ocean sectors interact with each other (SM section S3). We included all ocean-related ecosystems, including coastal wetlands, estuarine systems, and mangroves. The codebook also intended to capture how sector interactions play out across space and time, and the outcomes of these interactions, as well as any emerging aspects of relevance for how sectors interact. As such, two forms of coding were undertaken (see SM figure S5 for overview of coding schema).

The first form of coding aimed at producing data for quantitative analysis (code 1.1, figure S5), and it is described under 'Interaction type' (SM, section S3.2). This coding focused on specifically identifying interactions between à priori defined sectors. It required a standardized coding procedure to ensure sector interactions were coded based on the same assumptions and that the code category had a strong internal validity. We therefore coded only for the *presence* of a particular interaction. While our intention was originally to also capture the *intensity* of interaction, the codebook testing process revealed that articles were not consistent enough in their description of interactions to deduce intensity. To be included in our analysis interactions needed to be substantiated by empirical evidence, or a well-explained hypothesized mechanism substantiated by multiple publications modelling this interaction. All decisions for inclusion vs. exclusion are documented in the summary sheets (SM section S3.5).

The second form of coding was intended to capture qualitative information about sector interactions and contained both inductive and deductive elements (SM, sections S3.2–3.3). We started with a predefined set of codes based on à priori knowledge of their known importance for our analysis (such as coding for the outcome of any noted interaction), or from a desire to specifically capture issues of clear relevance to achieve not just a *prosperous* but also an *environmentally sustainable* and *equitable* Blue Economy (e.g. codes 'geographic scale' and 'symmetry') (deductive coding). However, we deliberately allowed other codes to be included as relevant issues emerged from the review (inductive coding). These are shown under 'new codes' (figure S5). The codebook was applied and tested by three researchers, and inter-coder reliability assessed (0.875), using Krippendorff's alpha (α) (SM, section S3.4).

2.4. Analyzing qualitative codes

Qualitative coding was done in a first and second round of coding, and included multiple different coding forms (see SM, section 3.3 for more details). We reviewed and classified codes relating to outcomes into four categories, covering both synergistic and antagonistic forms of each outcome category (table 2). An outcome was defined as a result attributable to a specific sector-sector interaction, documented by one or multiple scientific articles reviewed. 'Space' denotes outcomes related to spatial overlap. 'Natural Capital' denotes outcomes affecting natural capital used by another sector. 'Touristic Value' refers to the value of the tourism sector as perceived by users or consumers (i.e. tourists) and captures effects on this value by a sector-sector interaction. It does not aim to capture economic value, as economic depreciation as a result of sector interactions is included under other outcome categories (such as a sector suffering monetary loss from natural capital diminishment like declining stocks, or through interference with operations like entanglement in cables). The specificity of this category to tourism is due to the unique importance of perceived consumer values in this sector. 'Operations' captures outcomes affecting the operations of another sector.

All remaining qualitative codes were reviewed and analyzed to identify core themes of relevance for understanding ocean sector interactions. Cumulative impact and issues of equity emerged from a combined analysis of the codes relating to symmetries of interaction outcomes, areas beyond national jurisdiction (ABNJ), geographic scale of interactions, and cumulative impact. Examination and categorization of outcomes revealed temporal aspects of impact and showed that most sector interaction outcomes have an element of time-lag in them. Even acute events, like oil spills, have delayed effects on biota that linger long after the spill has been addressed [27, 28], and thus contribute to cumulative impact. Past activities and development also have lasting effects today.

The 'symmetry' code allowed us to capture power imbalances between sectors. This code was particularly common among articles discussing interactions with small-scale fishers and highlights a key dimension; namely the differential power of ocean sectors (and actors operating within them) to exert their rights or demands in the development of the ocean domain. Coding for ABNJ allowed us to uncover how ocean sector interactions are discussed beyond countries' exclusive economic zones (table S2). This revealed sector specific trade-offs observed in ABNJ, but also indicates that in the race for finite ocean resources to develop businesses and livelihoods, economic actors have differential power to exert their rights or demands, particularly in ABNJ, as exploitation of this space requires significant human, financial or technical capital.

2.5. Network analysis and visualizations

Network diagrams were created based on sector interactions in the compiled database, using R packages igraph and visNetwork [29, 30]. Degree centrality was calculated for each sector. Patterns of association between outcomes and sectors were visualized using R package, ggplot2 [31].

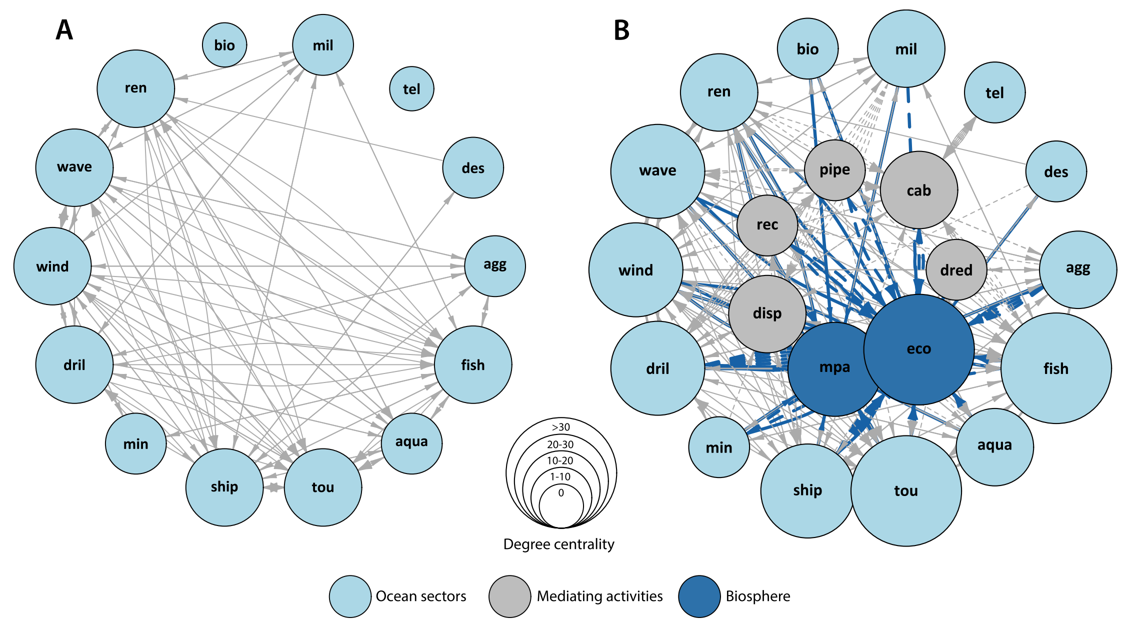

Figure 1. Ocean sector interactions documented by the review. Ocean sectors are shown in light blue, mediating activities in grey, and 'biosphere' proxies in dark blue. Solid lines represent direct interactions, and dashed lines represent interactions occurring via a mediating activity. Node sizes are scaled by degree centrality. Bidirectional interactions are indicated by double-headed arrows. (A) Direct interactions between ocean sectors ($n = 60$ interactions). (B) Direct and indirect interactions between ocean sectors ($n = 154$ (93 direct, 61 indirect) interactions). Mediating activities and biosphere nodes are included to show which activities are involved in indirect sector interactions. Interactions with biosphere nodes are shown in dark blue. An interactive version of this network can be explored at https://gedb.shinyapps.io/OceanInteractions/.

2.6. Limitations

Larger and older sectors, such as shipping and fishing, are associated with a larger body of research than newer, smaller sectors like bioprospecting and renewable energy. Our sampling method accounted for this, but uneven distribution of information across sectors remained, and may have affected the results (SM, section S2). However, plotting the relationship between the number of interactions a sector is associated with and the length of time it has figured in the literature shows no strong correlation (Kendall'a tau-b = 0.4, $p = 0.068$, figure S4). In fact, more recent sectors such as wind, wave, and renewable energies have numbers of documented interactions comparable to aggregates mining and fossil fuels energy, indicating that despite imperfect article sampling, newer sectors are not systematically biased in this regard. Our review encompassed only academic literature. It is plausible that academic articles are biased towards a focus on certain types of interactions, such as on environmental issues. Hence it is important to note that the absence of interactions between ocean sectors could be an indicator of three things: (a) that there is no interaction; or (b) that there are interactions but they have not been studied, identified, and published in the peer-reviewed literature; or (c) our review failed to capture them. Finally, it is important to reiterate that the value placed by tourists on ocean ecosystems is far from the only relevant value dimension, yet cultural or aesthetic services of ocean ecosystems valued by communities are currently not well captured with a framing focused on economic sector interactions.

3. Results and discussion

3.1. Ocean sector interactions

Our systematic mapping of the literature identified a total of 93 unique direct interactions (36 unidirectional and 57 bidirectional). When including interactions occurring via mediating activities and the biosphere, the number of interactions increased by 66% (to 154). The size of sector nodes in figure 1 represents degree centrality and indicates which ocean sectors have a high number of interactions. Degree centrality is akin to measuring the number of unique interactions a sector has, but it has the advantage of also showing which other sectors are involved in these interactions. Fishing stands out as the most highly connected, but tourism, drilling, and shipping also interact with many other sectors, directly or via mediating activities. These patterns may in part reflect historical development of industries. Shipping and fishing have existed a long time and are spatially extensive activities [32] which increases the likelihood of interactions with other ocean sectors. Drilling (oil and gas) is also well-established and currently the largest ocean-based industry, with more than 9000 platforms in service [33], providing ample opportunity for interactions with many sectors, both through spatial crowding and via mediators such as pipelines. Telecommunications and bioprospecting stand out for not currently having any direct interactions with other sectors (figure 1(A)). However, telecommunications are mediated by cables and more than one million kilometers of fiber-optic submarine cables have been installed over the last 20 years [1], leading to interactions with many sectors (figure 1(B)). Marine bioprospecting, on the other hand, increasingly relies on genetic sequence data from databases developed through non-commercial research, rather than physical samples. This suggests the sector's direct interactions with other sectors may remain low [34].

The ocean ecosystem plays a key role in mediating many ocean sector interactions. Figure 1(B) shows all interactions (mediated and direct), but highlights interactions mediated by ecosystems or MPAs. When contrasted with figure 1(A) showing only direct interactions, it underscores the magnitude of sector interactions that occur via impacts on the ocean ecosystem, or efforts to safeguard it.

3.2. Outcomes of sector interactions

Coding of the literature revealed outcomes relating to four dimensions; Space, Natural Capital, Touristic Value, and Operations (table 2). Figure 2 shows the synergistic (both sectors benefit, or one benefits without negative effect on the other) and antagonistic (one or both sectors are negatively affected) associations of these outcome types with each ocean sector. Bidirectional interactions, in which both sectors affect each other, are primarily associated with spatial overlap, with both antagonistic and synergistic outcomes (figure 2(A)). These results are not surprising, as the large literature on marine spatial planning has documented many different forms of spatial conflicts arising within coastal zones and exclusive economic zones (EEZs) [35]. More noteworthy, and not generally emphasized by marine spatial planning, are the documented synergistic spatial outcomes. Most of these synergies are reported for interactions involving various forms of renewable energy, such as single facilities that combine wind and wave energy [25, 36], but also cooperation between the shipping and tourism sectors when sharing port facilities [10]. Wind and wave energy are relatively newer entries to the ocean arena and are thus competing for access to an already crowded space. Finding ways to coexist synergistically is therefore paramount for these sectors, and is reflected in our results [19, 26].

Not all interactions are bidirectional. In many instances, one sector unidirectionally affects another (figure 2(B)). A larger number of these interactions are associated with antagonistic, rather than synergistic effects on other sectors. Touristic value diminishment, and degradation of the natural capital on which another sector depends, are the most widely experienced impacts. Distinct interactions with positive outcomes for other sectors are much less frequent, but when present are commonly associated with natural capital, through provision of habitat or enhancement of biological stocks. The enhancement of other values not linked to the environment, such as touristic appeal of an area, is also a notable positive interaction outcome (figure 2(B)).

Three sectors are particularly prominent among interactions with antagonistic outcomes: military operations, shipping and drilling. Shipping and drilling affect the natural capital base of several other sectors through pollution, but also through the spread of invasive species [37]. They also negatively impact touristic value. Military activities, on the other hand, interfere negatively with the operations of sectors such as fishing, while also diminishing the value of touristic activities. One of the main reasons for this is the interactions of other sectors with formerly dumped barrels of munitions and chemical agents that prevent activities on the seabed and pose long term risk once they begin to degrade and leak [38].

Interestingly, the same sectors associated with antagonistic effects, also tend to have synergistic effects, such as natural capital enhancement through new habitat provision by oil rigs, or port infrastructure. Other examples include synergistic use of space between shipping and multiple other sectors such as tourism, wave energy and drilling [10, 39], and enhancement of operations between renewable energy, desalination, drilling, aquaculture, shipping, and aggregate mining, where one example is renewable energy harnessing the salinity gradient created by desalination [25, 26, 40]. Although military activities do not show positive impacts in our analysis, they have been reported to enhance natural capital by preventing other activities (e.g. by letting fish populations recover from fishing, most famously during WWII) [41]. Worth noting is that the ocean ecosystem is frequently affected by ocean sectors, but unless these environmental impacts were connected (by the reviewed literature) to one or more other sectors, they do not appear in figure 2. However, the outcome categories involving natural capital implicitly highlight that a significant number of impacts from ocean sectors affect the natural environment.

Overall a pattern emerges where some sectors are more involved in synergistic interactions, while others have a bias towards antagonistic interactions and outcomes. While this could be a result of uneven scrutiny, no temporal bias in number of interactions can be discerned (figure S4), suggesting it is unlikely to be the result of more recently emerging sectors having fewer interactions. When contrasting synergistic and antagonistic outcomes, it is worth noting that the scale or magnitude of impact incurred by any one sector cannot be accounted for in this analysis (as noted under methodology). However, by coding for 'geographic scale' in our review it became clear that very few studies of sector interactions examine the aggregate effect

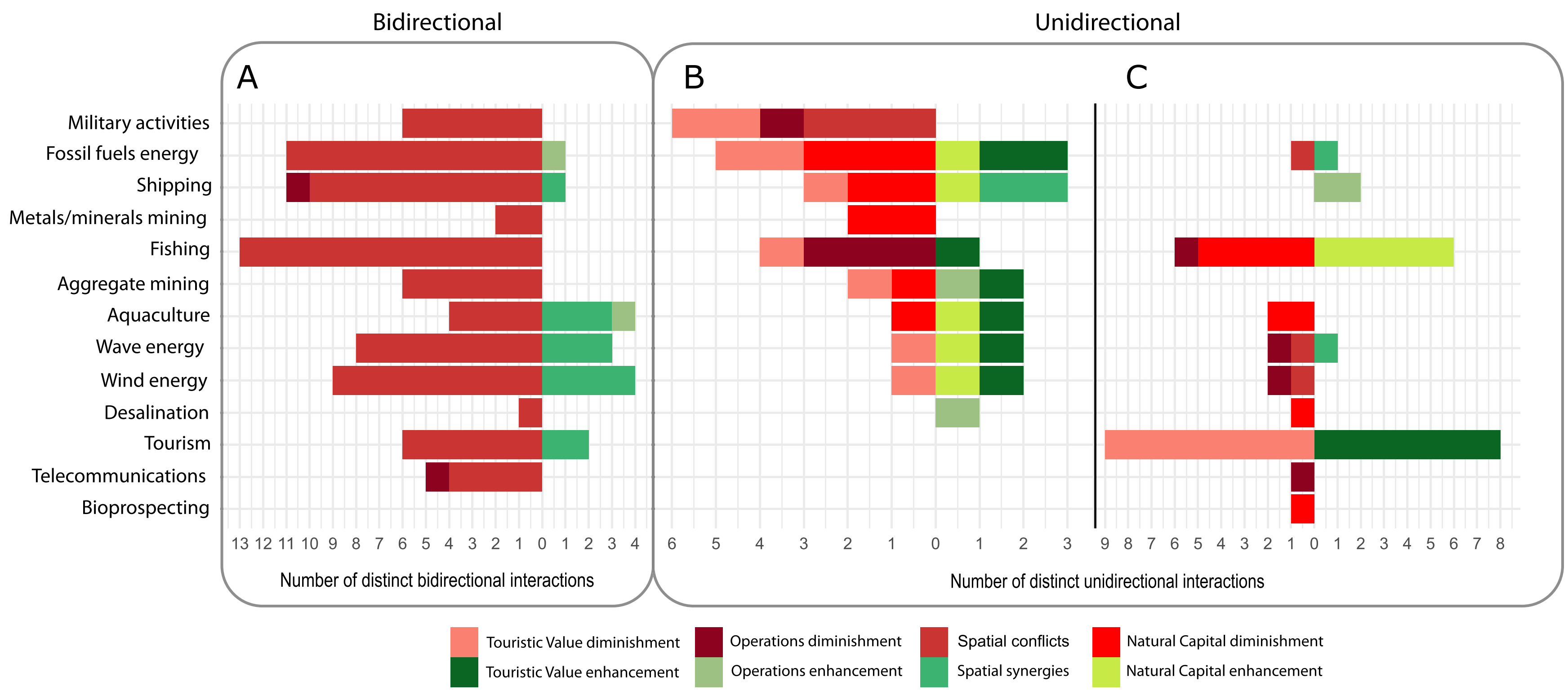

Figure 2. Outcome categories associated with ocean sector interactions. Each panel shows the number of distinct sector-sector interactions identified in the literature, attributable to each sector. Red shades indicate the antagonistic form of each of the four outcome categories, while green shades indicate synergistic ones. Outcomes for both direct and indirect interactions are included, although mediating activities are not displayed. Panel (A) shows bidirectional interactions, i.e. interactions between two sectors where both sectors create the interaction and are both affected by it. Interactions are allocated to both sectors involved and the total number of interactions is therefore inflated, compared with panels (B) and (C). Panels (B) and (C) refer to unidirectional interactions, where (B) shows sectors creating impact for another sector, and (C) shows sectors affected by impact from another sector.

of multiple local impacts (see also [42]). Cumulative ocean impacts have been mapped (see [8]), but without explicitly examining the cross-sectoral interactions involved in creating them. Our analysis complements these efforts by uncovering the multitude of ocean sector interactions underlying such environmental impacts. The value of this lies in highlighting that if merely one sector had environmental impacts, then effective oversight and regulation could be relatively straightforward, but with a rapidly increasing number of ocean sectors involved (figure S7) the situation is more complex and may require new types of stewardship approaches to ensure a prosperous, sustainable and equitable ocean use.

Figure 2(C) shows sectors impacted by others. Tourism and fisheries stand out in this analysis as they depend on healthy environments or biodiversity, and are therefore commonly affected by negative environmental impacts from other sectors. Once again, these antagonistic interactions signal trade-offs between sectors. Tourism is the only sector in which many types of interactions with other sectors appear to result in enhanced value. Examples include diving opportunities on artificial reef structures provided by repurposed drilling platforms and pipelines, and interaction with sectors that are of cultural interest for tourists such as fishing and renewable energy [40, 43]. Fisheries are exceptional because they are both highly affected by negative environmental impact, but also reportedly benefit from stock enhancing effects of new habitat and fish aggregating structures provided by some sectors, mostly as a side effect of their operations or infrastructure [39, 44].

3.3. Mechanisms generating observed outcomes

Using a set of examples drawn from the database of documented ocean sector interactions, we now examine some of the mechanisms reported as generating the synergistic and antagonistic outcomes associated with particular sectors. The sectors in focus in figure 3. Were chosen to illustrate some of the mechanisms behind each of the four outcome categories. Naturally they are only able to represent a small portion of the 154 unique interaction types but aim to provide an illustration and deeper understanding of how each of the four outcome categories can materialize. This helps to understand and anticipate the scale, magnitude and temporal dimensions of each outcome category. Readers are encouraged to explore the interactive database for more examples, and references of specific, geographically anchored case studies (https://gedb.shinyapps.io/OceanInteractions/).

Figure 3 illustrates examples of synergistic (green arrows) and antagonistic (red arrows) effects related to the four different categories of outcomes. The most common type of interaction among ocean sectors occur through crowding. Antagonistic outcomes represent the bulk of such ***spatially related*** outcomes and are entirely dominated by various forms of exclusion or crowding occurring between sectors, such as cables or oil rigs precluding other uses, or MPAs implemented for tourism purposes excluding fishing and other uses (see database). However, beyond the focus on spatial conflicts by the extensive marine spatial planning literature, figure 3(A) instead highlights synergistic interactions, which are much less discussed. It shows all documented synergistic spatial interactions uncovered by the systematic review. Most are bidirectional, meaning benefits derived from the interaction are mutual. Without exception, these mutually beneficial interactions are the result of co-location benefits between renewable energy sectors and tourism related MPAs, or co-location of energy sectors in so called multi-use platforms; areas at sea designated for a combination of activities, either completely integrated or next to each other, and which benefit from each other in terms of infrastructure and maintenance [45]. Only two beneficial spatial interactions are not mutual (one-sided arrow) and these are shipping interactions with wave energy and drilling, where the drilling and wave energy sectors are both reported to benefit from the port infrastructure, but shipping derives no co-location benefits from oil or wave energy [46–48].

Figure 3(B) uses fisheries to exemplify the commonly observed benefit from positive ***natural capital*** impacts of other sectors, such as physical infrastructure associated with certain sectors, or aquaculture hatcheries to support wild populations. Infrastructure is often reported to positively impact fisheries by providing hard substrate for benthic communities and thus increasing food abundance and shelter for fisheries related species [21]. Fisheries can also serve as an example of negative impacts to a sector from degraded natural capital. This happens through a range of mechanisms (SM section S3.4), but notably often via an impact to the ecosystem. Examples include effluents and escapee individuals from aquaculture polluting the environment and gene pools respectively [49, 50], increased turbidity and damage to the benthos from aggregate mining which negatively impacts foraging capacity of fish [51], or oil spills from drilling platforms, oil tankers and pipelines polluting the environment [20, 27] (figure 3(B), dashed red arrows).

Figure 3(C) shows positive and negative impact on perceived ***touristic value*** of another industry. Tourism is the only sector reported to be impacted via the increase or decrease in value of its operations, resulting from interaction with other sectors. Examples of enhanced value include decommissioned infrastructure or vessels that become artificial reefs for dive tourism [39], or the increased touristic interest

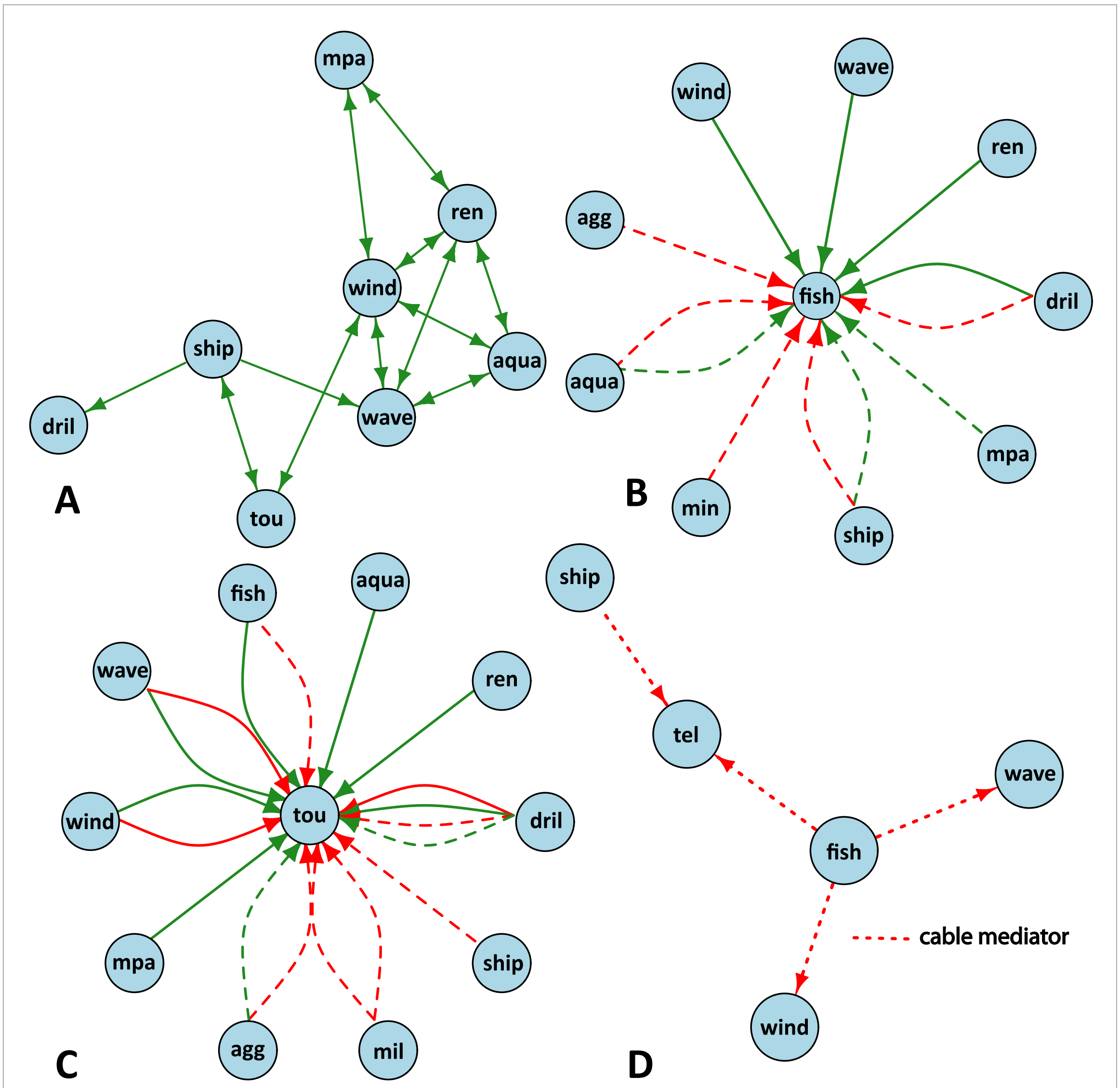

Figure 3. Examples of sector interactions associated with each outcome type. Synergistic outcomes are shown in green, whereas antagonistic outcomes are shown in red. Dashed lines represent interactions mediated by another activity. (A) *Space*—positive spatial interactions occur through synergistic use of space. (B) *Natural Capital*—the fishing sector inherently relies on the ecosystem and is thus impacted by many sectors through enhancement or diminishment of natural capital. (C) *Touristic Value*—multiple sectors affect the tourism sector by positively or negatively impacting values held by tourists. (D) *Operations*—cables mediate antagonistic interactions amongst sectors through effects on operation, e.g. cable damages.

ensuing from spatially overlapping sectors, such as small-scale fisheries, aquaculture, and wind farms [10, 43]. Interactions observed to diminish touristic value are all related to reduced aesthetic values, such as drilling platforms, and wave and wind energy facilities [27, 52]. Wind farms thus appear to be both beneficial and unfavorable to tourism and show how context dependent many of the outcomes of sector interactions can be. It is imperative to note, nonetheless, that there are multiple other forms of value associated with ocean ecosystems, such as those that relate to aesthetic services, religious ceremonies, or local community recreation and education. Yet these are not captured by a framework focused on interactions between ocean sectors of a primarily economic nature. We recognize this limitation, and the importance of nonetheless keeping non-commercial value present in any discussions of trade-offs between ocean sector development.

Impacts of one sector on the ***operations*** of another mostly happen via a mediating activity. Figure 3(D) illustrates this, by showing the indirect negative interactions between fisheries and wind energy, wave energy and telecommunications, as well as between telecommunications and shipping. Each of these interactions is mediated by cables, which are laid on the ocean floor and interfere with the operations of the other sectors. Cables are an impediment to fisheries that use gears in contact with the seafloor, and they can interfere with shipping in coastal areas by preventing anchoring [53]. Direct enhancement of operations is much less common but one example is the use of decommissioned drill rigs as a base for aquaculture [26].

3.4. Cross-cutting themes of relevance for interpreting interactions and trade-offs

The qualitative element of the literature review revealed three themes emerging from across a majority of interactions. These relate to (a) the cumulative nature of many antagonistic natural capital outcomes observed; (b) observed time-lags in how outcomes are manifested; and (c) differential power of ocean sectors and other relevant and affected actors to exert their rights or demands in the development of the ocean domain. All three signal important trade-offs associated with many current and future sector interactions. As such, they provide an important supplement to the quantitative description of sector interactions above, highlighting issues of key importance for any strategic decision-making process in the ocean domain aiming to promote sustainability and justice alo us use of space and resources.

3.4.1. Cumulative impacts

The many impacts mediated via 'ecosystem' (figure 1(B)) clearly show that a healthy ocean biosphere is fundamental for supporting many ocean sectors. Our analysis above shows 13 out of 14 ocean sectors have interactions resulting in unidirectional negative ecosystem impact. Such a high number of different and growing sectors simultaneously affecting ocean ecosystems emphasizes the importance of recognizing cumulative impacts, something already increasingly recognized by marine scientists [54]. Our review shows that some ecological impacts may be transient and reverse themselves without remedial action, such as local impacts on the seabed from burying telecommunications or power cables [55]. Some are acute but with long-term and widespread effects, such as the BP Deep Sea Horizon oil spill in 2010 [27]. Countless others, such as pollution, biodiversity and habitat loss or degradation may leave relatively localized impacts, but are often cumulative and exert a growing pressure on the natural resource base [8, 54]. Some ocean sectors are particularly likely to incur a mix of these local but, over time cumulative impacts, such as drilling, mining, aggregates, shipping, fishing and aquaculture. One example is repeated accidental release of fingerlings and broodstock from fish farms that result in loss of genetic diversity among wild populations [56]. Another example is the increase in artificial ocean structures that combines with other anthropogenic stressors to affect intensity and frequency of jellyfish blooms [57], with impacts on both fisheries and tourism [18]. In the Black Sea, invasive species from ballast water, overfishing, and eutrophication from nutrient runoff have interacted to result in a regime shift, with a novel regime characterized by dinoflagellates and jellyfish and low fish catch [58], which affects the perceived value of the sea. Where use of space is not mutually beneficial, cumulative impacts are also manifested via increased crowding. These threaten to become ever more acute as the aggregate and cumulative space used for different ocean sectors increases. Energy facilities that can act as artificial reefs and increase fish biomass [42], also pose increasingly frequent navigational hazards which interfere with operations and preclude fishing [59]. Other cumulative effects on operations include anchor damage from fishing or shipping, which represent the majority of cable damage in shallow waters (<200 m) [60]. Increased amount of underwater cables naturally means increasing risks of such damages.

3.4.2. Impacts over short and long timescales

Several of the impacts from interactions uncovered by this review are not directly discernable today, but represent loss of future opportunities. Damage incurred through seabed (particularly seamount) mining is often associated with permanent loss of biodiversity and genetic resources underpinning future bioprospecting and other societal benefits [61–63]. Likewise, bycatch and biodiversity loss associated with seafood production have externalities that diminish future prospects for the industry itself [64], but also for other sectors [65, 66]. These types of opportunity costs are not novel in themselves, but highlight the temporal dimension and spill-over effect on both value and operations of other sectors, often mediated via negative ecosystem effects.

However, temporal impacts can also be associated with effects that are manifested as a result of competing use of space. Well-established sectors tend to enjoy a biased access to ocean space stemming from a historical presence. Some sectors are also closely associated with long-lived infrastructure. This historically biased access can make it hard for new sectors to compete for space. Examples include renewable energy sectors that often have to adapt to, and work around, existing oil and gas infrastructure [47]. Similarly, cables laid in the past still affect the operations (through limited use of space) of multiple other sectors today [5, 67]. While some of these long-term effects of crowding on future operations may not be explicit in Blue Economy planning documents, they deserve explicit consideration in decision frameworks guiding ocean resource use.

3.4.3. Inequitable power and the distribution of ocean costs and opportunities

Any conflict over the use of natural resources or space will have winners and losers. But who is likely to benefit from the emerging rush to develop the blue economy? Österblom *et al* [68] outline the multiple ways in which inequalities are manifested in the ocean domain, from differential power and access to resources and markets, to historical and colonial legacies that reproduce inequities in the ocean economy. While social equity and environmental sustainability have often been featured centrally by

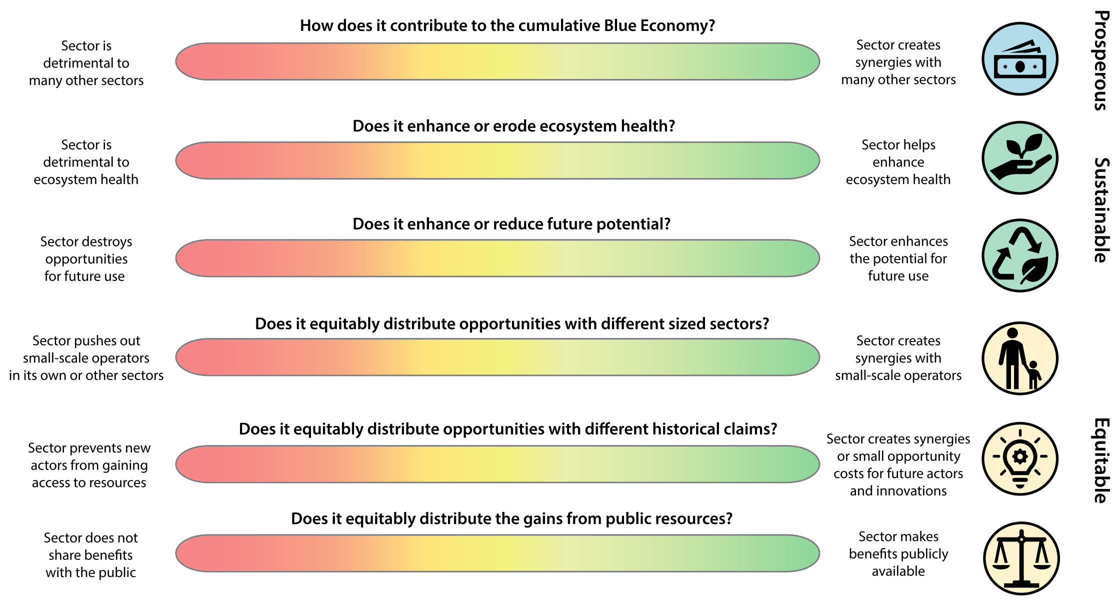

Figure 4. Guiding principles for delivering a prosperous, sustainable and equitable Blue Economy. The principles are operationalized through questions which put focus on six key economic, environmental and social dimensions brought to the fore by our analysis of ocean sector interactions. These should be seen as a deliberation tool to compare and contrast sectors and actors in the ocean domain, helping to highlight potentially costly trade-offs, or indicate opportunities for synergies in any decision situation.

developing coastal states and SIDS pursuing ocean-based growth [69], there is real risk that a tendency to prioritize economic growth results in equity and sustainability becoming secondary or entirely sidelined in ocean policy and practice [4].

As noted above, the biased access to space based on historical presence, size, or current economic influence, may lead to unequal ability among ocean sectors to develop the ocean space, and differential power of affected actors to exert their rights or demands over natural capital. The difference in power is often related to endowment of human, financial or technical capital. For instance, between 2000 and 2010, only ten nations generated over 70% of the USD 12 billion global fisheries catch value from ABNJ [70], where vessels flagged to high-income nations are responsible for 97% of trackable industrial fishing [71]. These high seas fisheries include deep-sea fishing with known severe negative and long-lasting environmental impacts on the seabed and biodiversity [72], thus affecting the future ability of other nations to benefit from these resources. Similarly, the capacity to collect and analyze genetic material from ABNJ is currently limited to a handful of countries, and development of commercial applications based on these materials is similarly concentrated, with 98% of marine genetic resources patents registered by entities in just ten countries [73, 74]. Power asymmetries between industrial or otherwise better-endowed actors within a sector are also well-documented, particularly within the fisheries and aquaculture sector. Promotion of industrial-scale operations at the cost of small-scale actors is a commonly observed inequity manifested through both crowding (out) and effects on operations, such as destruction of gears or vessels [75–79]. However, small-scale fisheries actors notably often find themselves in conflict with conservation interests (MPAs) and the tourism sector [80–84].

Our analysis also shows that some sectors are more commonly interacting in ABNJ (see table S1 for fully referenced examples). These include industries reliant on cables (such as telecommunications and energy), mining (currently exploratory), shipping and fishing. Trade-offs resulting from sector interaction in ABNJ are particularly important to highlight because of the notable gaps in institutions for negotiating conflicting interests in this commons territory, and the continuing legal and regulatory uncertainty pending the conclusion of negotiations on an international legally binding instrument on conservation of biodiversity in areas beyond national jurisdiction (BBNJ) [17, 18, 85].

4. Conclusions

To date, marine spatial planning has been the primary tool for addressing responsible marine management [13], with a predominant focus on spatially explicit interactions. Our combined analyses show that many sector interactions are mediated through ecosystem effects, or manifested through interference with how a sector is valued, or its operations. Our findings thus support both the user-environment and the user-user conflicts noted in the introduction [7], and uncover likely trade-offs occurring as a result of the incompatibility of many ocean sectors, and the foregone opportunity for one sector in the wake of another. Furthermore, our analysis indicates that some sectors are more often involved in synergistic interactions, while others have a bias towards antagonistic interactions and outcomes.

The ocean governance landscape is not currently well-equipped to deal with the full range of trade-offs, and opportunities, likely to arise in the pursuit of a Blue Economy in a rapidly changing ocean context [1, 4, 86]. Nor does the primary tool used, marine spatial planning, address the differential power of the sectors it aims to manage [4]. Grounded in our analysis, and based on the themes outlined above, we therefore propose a set of principles we argue should guide strategic decision-making as governing actors plan for the future of the ocean (figure 4). These are applicable at any scale—from local development plans to national strategies or international sustainability agendas—and can provide support when considering the development of ocean uses, and when analysing sector-sector interactions in specific local contexts. We acknowledge that most sectors and actors are found somewhere along a spectrum, ranging from activities associated with grave concern, to other displaying best available practices. Supported by systematic assessments, such as the database of sector interactions presented here (https://gedb.shinyapps.io/OceanInteractions/), the principles should be seen as a deliberation tool to compare and contrast sectors and actors, helping to highlight potentially costly trade-offs, or indicate opportunities for synergies in any decision situation. Given the growing complexity of ocean sector interactions, engagement with these principles can be a start towards promoting a transparent debate around the trade-offs and benefits at hand, and ensure the Blue Economy is not just economically prosperous, but also sustainable and equitable.

Data availability statement

Authors declare no competing interests.

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.7910/DVN/SI6TUS. Data will be available from 19 January 2021.

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