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Options for managing human threats to high seas biodiversity

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ABSTRACT

Areas beyond national jurisdiction (ABNJ) constitute 61% of the world's oceans and are collectively managed by countries under the United Nations Convention on the Law of the Sea (UNCLOS). Growing concern regarding the deteriorating state of the oceans and ineffective management of ABNJ has resulted in negotiations to develop an international legally binding instrument (ILBI) for the conservation and sustainable use of biodiversity beyond national jurisdiction under UNCLOS. To inform these negotiations, we identified existing and emerging human activities and influences that affect ABNJ and evaluated management options available to mitigate the most pervasive, with highest potential for impact and probability of emergence. The highest-ranking activities and influences that affect ABNJ were fishing/hunting, maritime shipping, climate change and its associated effects, land-based pollution and mineral exploitation. Management options are diverse and available through a variety of actors, although their actions are not always effective. Area-based management tools (ABMTs), including marine protected areas (MPAs), were the only consistently effective option to mitigate impacts across high-ranked activities and influences. However, addressing land-based pollution will require national action to prevent this at its source, and MPAs offer only a partial solution for climate change. A new ABNJ ILBI could help unify management options and actors to conserve marine biodiversity and ensure sustainable use. Incorporating a mechanism to establish effective ABMTs into the ILBI will help deliver multiple objectives based on the ecosystem approach.

1. Introduction

Areas beyond national jurisdiction (ABNJ) constitute international waters outside the 200 nautical mile limits of national jurisdiction and cover 61% of the world's oceans. ABNJ are governed under the United Nations Convention on the Law of the Sea (UNCLOS) which assigns countries the right to exercise "freedoms" to fish, navigate and conduct scientific research amongst others, while obliging them to protect the marine environment and conserve living resources through national action and regional and international cooperation. ABNJ legally comprise the 'High Seas', waters beyond the Exclusive Economic Zones (EEZ) of national jurisdiction, and the 'Area', the seabed, the ocean floor and subsoil thereof beyond national jurisdiction (UNCLOS Articles 1 and 86). Colloquially, ABNJ are often referred to as the 'high seas'. Many human activities and influences reach far into the open waters and deep-sea of ABNJ, despite their isolation, and their impacts have grown rapidly in recent decades (Halpern et al., 2019; IPCC, 2019; Merrie et al., 2014; Pauly et al., 1998; United Nations, 2015; Watson and Tidd, 2018).

Existing sector-focussed management organisations have largely failed to protect biodiversity in the high seas given their narrow remits, governance gaps and limited coordination and cooperation, and inherent difficulties in managing human activities across a global commons (Freestone, 2018; Wright et al., 2015, 2018). These limitations have led to loss of ocean life, resulting in international negotiations to develop an international legally binding instrument (ILBI) for the conservation and sustainable use of biodiversity beyond national jurisdiction under UNCLOS (UNGA, 2015; Wright et al., 2018).

Four elements frame the UN negotiations: marine genetic resources, including benefit sharing; area-based management tools, including Marine Protected Areas (MPAs); environmental impact assessments; and capacity building and the transfer of marine technology (UNGA, 2015). Following two years of formal discussions, the Preparatory Committee

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recommended to the UN General Assembly to hold an Intergovernmental Conference (IGC) to consider their findings and draft a potential ILBI (UNGA, 2017). Three meetings have been held since September 2018, with the final meeting planned for April 2020. The draft text of an agreement was issued in July 2019 which lays out a potential framework and obligations for each of these four elements, although many of the details remain to be decided upon (UNGA, 2019).

The ILBI, once agreed and adopted, is intended to enhance cooperation and coordination of management to ensure conservation and sustainable use of marine biodiversity in ABNJ. To inform ongoing UN negotiations and identify governance challenges and opportunities in ABNJ, we sought to answer the following key questions: What human activities and influences affect the high seas and to what degree? What measures are available to mitigate the impacts arising from those with the greatest pervasiveness, potential for impact and probability of emergence? How effective are these measures?

We undertook a scoping exercise to identify existing and emerging human activities and influences that affect ABNJ, building on Merrie et al. (2014). We identified eleven activities and influences as having the potential to affect marine ecosystems within ABNJ (Table 1); although, it is worth noting that prospective activities such as offshore server farms, rocket launches, and ocean cleanup projects/devices may become increasingly relevant and to future proof the ILBI, this table should be considered a live assessment. Using existing literature, we assessed for each activity and influence identified, the pervasiveness or extent to which they currently cover ABNJ, their potential for impact at different scales (local, regional and global) and their probability of emergence (within the next decade or two) on a three-point scale broadly corresponding to high, moderate and low. Of the eleven activities and influences initially identified, five scored highest across all three categories and were subjected to detailed evaluation of management options: fishing/hunting; maritime shipping; climate change and its associated effects; land-based pollution; and mineral exploitation. We summarise the current and emerging status of each of these five activities and influences and evaluate the effectiveness of management options available. Finally, we make recommendations in light of ongoing UN negotiations.

2. Human activities and influences in ABNJ

2.1. Fishing/hunting

Historically, significant human influence on the high seas dates back to the origin of industrial whaling in the 17th century (Roberts, 2007). For example, Fig. 1 shows the distribution of 159 years (1761–1920) of sperm, right, humpback and bowhead whale catches compiled from pelagic whale vessel log books (WCS Canada, 2003), showing high catches from the high seas. Following the global whaling moratorium of 1994, many whale populations are recovering (Magera et al., 2013), but effects linger from historical depletion, for example on nutrient cycling, primary productivity and deep-sea life from 'whale falls' (see O'Leary and Roberts, 2017 and references therein).

As whaling declined, fishing in international waters has intensified. Spatially, and by fishing hours the main fishing methods in ABNJ are longlines, purse-seines, and, to a lesser extent, deep-sea trawling (Kroodsma et al., 2018; Sala et al., 2018b). Currently, fishing is considered to be the largest direct threat to marine life in ABNJ (Lascelles et al., 2014) (Fig. 2a). Targeted fisheries remove large volumes of marine life from the oceans each year changing the structure and function of open ocean (O'Leary and Roberts, 2017) and deep-sea ecosystems (Clark et al., 2016). Despite this, catches in the high seas make up less than 5% of global marine catch each year (Schiller et al., 2018), are experiencing decreasing returns on effort (Merrie et al., 2014) and are largely unprofitable without government subsidies (Sala et al., 2018b). Moreover, high seas fishing is limited to wealthy countries and industrial corporations (McCauley et al., 2018; Sumaila et al., 2015).

Table 1
Assessment of the pervasiveness or extent to which they currently cover ABNJ, potential for impact at different scales (local, regional and global) and probability of emergence (within the next decade or two) of eleven human activities and influences in areas beyond national jurisdiction. Colours represent assessment results based on a three-point scale: Pervasiveness - highly pervasive (red), moderately pervasive (amber), localised (beige); Potential for impact – high (red), moderate (amber), low (beige); Probability for emergence - very likely (red), likely (amber), unlikely (beige). Where an assessment was not possible, cells are not shaded. * indicates those activities/influences we consider to have the greatest potential and probability of adverse environmental effects in the high seas and therefore subject to greater evaluation of the potential for management measures to mitigate adverse environmental effects. Section 1 of Supplementary Material File 1 summarises assessments for activities and influences judged as having limited likelihood of becoming significant outside national waters in the foreseeable future.

Activity/influence	Pervasiveness	Potential for impact	Probability of emergence
Fishing/hunting*	Fishing activity is already present across much of ABNJ.	Fishing is currently the most significant direct threat to biodiversity beyond national jurisdiction with high and widespread environmental impacts recorded for species, habitats, and ecosystem structure and function.	New fisheries (e.g. mesopelagic fish) are likely to develop, driven by falling global marine fisheries catches alongside increased demand for fish meal and oil.
Maritime shipping*	Shipping, the movement of goods, resources and people, covers much of the world's oceans.	Given the large spatial extent of shipping activities, environmental impacts are likely to be high.	New shipping routes are likely, particularly in polar oceans with melting of sea ice, as well as shipping volumes increasing in step with global economic growth and international trade.
Climate change and associated effects*	The impacts of climate change are global and pervasive affecting all the world's oceans.	Ocean ecosystems are already experiencing change because of ocean acidification and warming, and changes will continue to extend across ABNJ.	Climate models and measurements indicate that effects are growing more rapidly than in the past.
Land-based pollution*	Although the effects of many land-based pollutants are concentrated in EEZs, many are transported by winds or ocean currents to ABNJ.	Environmental impacts from land-based pollution are high and affect all aspects of marine life.	Land-based pollution is likely to remain a problem in ABNJ without adequate national policies to reduce sediment, nutrient and pollutant transport to the sea.
Deep-sea mineral exploration and exploitation*	2.2 million km^2 of the seabed in ABNJ has already been leased or reserved for deep-sea mining.	Environmental impacts are likely to be high, broadly distributed and impact the entire seabed to surface ecosystem.	Deep-sea mining is highly likely to proceed in ABNJ.
Oil and gas exploration and exploitation	No offshore oil and gas drilling operations currently take place in ABNJ.	Local and regional impacts are experienced which can have high negative environmental effects and impact the entire seabed to surface ecosystem.	The assignation of mineral rights over extended continental shelves makes it likely that oil and gas exploitation will remain under national jurisdiction. Nonetheless, with the overlying water column still high seas, cross-jurisdictional management will be required to limit adverse effects.

Activity/influence	Pervasiveness	Potential for impact	Probability of emergence
Bioprospecting for marine genetic resources and scientific research	Typically, bioprospecting and scientific research activities have a small scope and temporal and spatial footprint.	Largely localised, but potentially high environmental impact, particularly from large-scale manipulations testing options such as geoengineering.	Of increasing interest and one of the four issues framing UN negotiations for a new ABNJ international legally binding instrument. Although an emerging issue, this is not currently considered a key threat to ABNJ.
Aquaculture	Currently, aquaculture activities are mainly concentrated near to shore in EEZs.	Likely to result in ecological and environmental impacts but significance in, for example, pelagic settings which dominate ABNJ is unknown.	Much of the expansion of aquaculture offshore is likely to be contained within national waters for the foreseeable future.
Renewable energy	Currently, marine renewable energy installations remain concentrated close to shore in EEZs, mostly around Europe.	Likely to result in localised ecological and environmental impacts but significance in, for example, pelagic settings which dominate ABNJ is unknown.	New technologies such as floating wind turbines could enable expansion further offshore, but it is unlikely they will enter ABNJ given that energy generation is currently a matter of national importance.
Military	Military activities are typically subject to secrecy, even in EEZs. The extent of military activities in ABNJ are unknown, preventing detailed assessment of impacts.	Unknown but some impacts, such as sonar, could be high where activities occur.	Unknown
Submarine cables and pipelines	Active telecommunication cables only cover 0.00002% of the seabed within ABNJ. No power cables have been laid. Pipelines in ABNJ are highly unlikely given the lack of oil and gas drilling operations here.	Likely to be limited given the small operational area and because cables are laid directly onto the seabed.	Use of submarine telecommunication cables will increase with demand for internet bandwidth.

Fisheries are unselective to varying degrees, and the incidental capture of non-targeted species (bycatch) further contributes to the removal of biomass and depletion of vulnerable species. Bycatch rates in ABNJ are difficult to ascertain due to poor observer coverage and data recording but are certainly significant. For example, longline vessels in the high seas caught *c.*32,000 seabirds annually between 2001 and 2008 (Anderson et al., 2011), and have historically constituted nearly half of global shark catches (Bonfil, 1994). Between 2002 and 2013 the Taiwanese longline fleet caught nearly 800 turtles in the high seas of the Atlantic Ocean alone (Huang, 2015), and high seas longlining has been strongly implicated in the more than 97% decline of eastern Pacific leatherback turtle (*Dermochelys coriacea*) populations since the 1980s (Wallace et al., 2013).

While deep-sea bottom trawling has a smaller spatial footprint in the high seas than longline or purse-seine fisheries, where they do occur they usually result in severe environmental impacts through physical contact with the seabed and indiscriminate catches (Clark et al., 2016; Victorero et al., 2018). The spatial footprint of a fishery tells us the likely area of impact, however deep-sea trawling disproportionately concentrates on particular habitat types such as ocean ridges, slopes and seamounts, in part because these are shallow enough to be targeted (deep-sea trawls can reach at least 2,000 m deep) and in part because they aggregate marine life (Clark et al., 2016; Victorero et al., 2018; Watling and Auster, 2017). Such habitats support species considered to be of particular vulnerability to trawling, such as cold water corals and deep-sea sponges (FAO, 2016). Collectively, these vulnerable marine ecosystems (VMEs) are internationally recognised as being of immense importance and value both for their unique biodiversity and their contribution to ecosystem services (Watling and Auster, 2017). However, deep-sea bottom trawling is highly destructive for VME species, with their often fragile structures, long-lifespan and slow growth rates, and recovery from trawling to pre-disturbance states has so far been shown to be minimal (Clark et al., 2019; Huvenne et al., 2016).

2.2. Maritime shipping

Shipping, the movement of goods, resources and people, covers much of the world's oceans (Fig. 2b). Rapid shipping growth was initially driven by containerisation in the 1960s (Bernhofen et al., 2016) and continued growth is predicted (Kaplan and Solomon, 2016). Associated threats include noise (Kaplan and Solomon, 2016), facilitation of bioinvasions (Seebens et al., 2016), collisions with wildlife (Rockwood et al., 2017), pollution (Vollaard, 2017), and greenhouse gas emissions (Johansson et al., 2017). Shipping routes are already extensive within ABNJ and new routes are likely, particularly in polar regions as ice

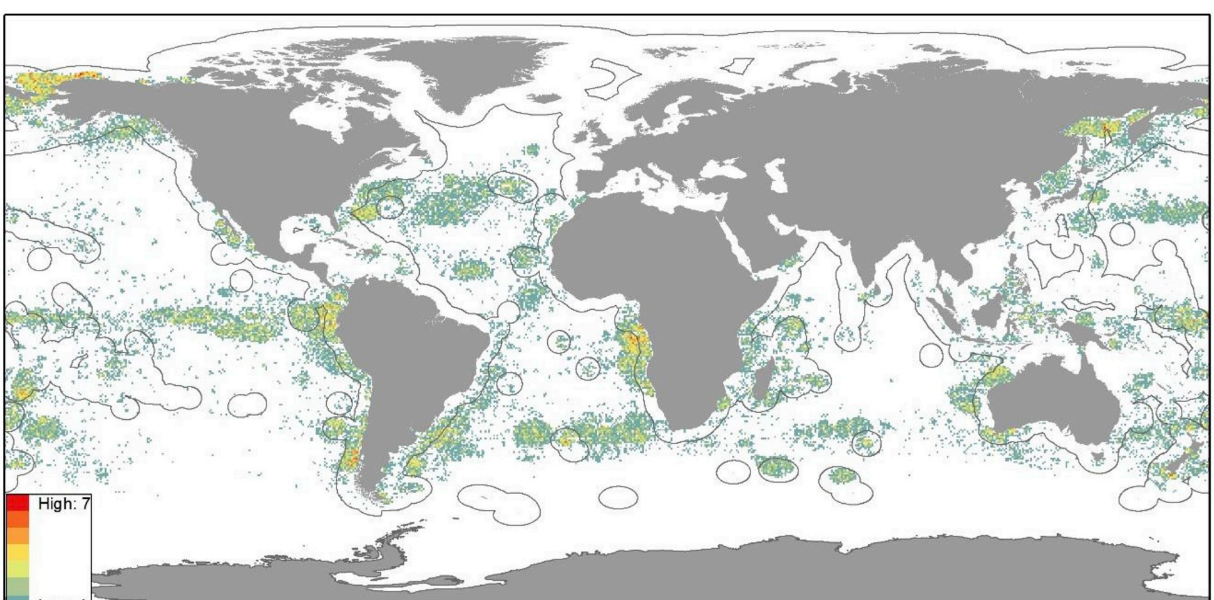

Fig. 1. Global density of humphead, bowhead, right and sperm whale catches by American whalers from 1761 to 1920 (data from WCS Canada, 2003). Density calculated using a 0.5° grid cell size. Land shown in grey. Exclusive economic zones outlined in black (Flanders Marine Institute, 2018).

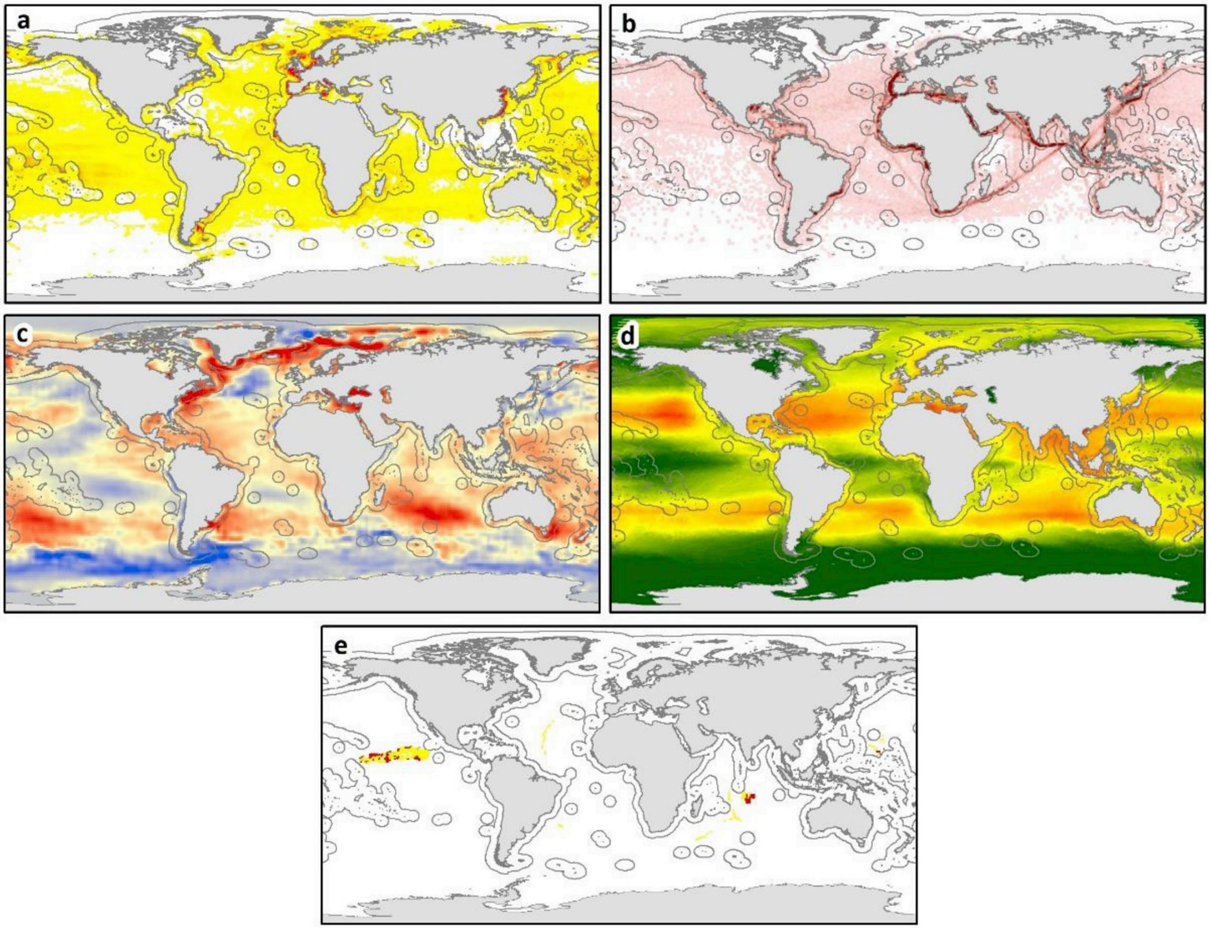

Fig. 2. Spatial extent of data layers representing key human activities and influences in ABNJ (a) average total annual fishing hours (2015–2017) – red indicates areas of higher effort; (b) shipping traffic density (2010) – red indicates areas of higher density, (c) monthly sea surface temperature trend (August 1988–July 2018, °C) - red indicates areas of greater warming, blue areas that are cooling; (d) global distribution and density of floating plastics by weight – red indicates areas of greater density; and (e) deep sea mining exploration (yellow) and reserve (red) areas. Data sources: (a) longline, purse-seine and trawl fishing data from Global Fishing Watch (2018). (b) density of cargo-vessels and tankers over a three month period in 2010, European Commission (2017). (c) International Research Institute for Climate and Society (2018). (d) modelled data from the Ocean Health Index (2015). (e) International Seabed Authority (2018). Exclusive economic zones outlined in black (Flanders Marine Institute, 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

retreats.

2.3. *Climate change and associated effects*

Climate change impacts are global, pervasive and intensifying (Hoegh-Guldberg and Bruno, 2010; IPCC, 2019). Future marine ecosystems are likely to differ from todays, reshaped by ocean acidification and warming (e.g. Fig. 2c), decreased productivity and oxygen availability, ocean stratification and changes in ocean currents (Breitburg et al., 2018; Hays, 2017; Hoegh-Guldberg and Bruno, 2010; IPCC, 2013). Impacts from climate change now extend throughout the deep-sea and open ocean of ABNJ (e.g. Breitburg et al., 2018; Sweetman et al., 2017).

2.4. *Land-based pollution*

Land-based pollution continues to threaten marine life. Excess nutrient discharge, for example, promotes harmful algal blooms and hypoxia amongst other effects, in waters over the continental shelf (Breitburg et al., 2018). A recent study, however, estimated that 75% of nitrogen and 80% of phosphorus from rivers could eventually reach the open ocean (Sharples et al., 2017), although the effects were not quantified. Between 4.4 and 12.7 million metric tonnes of plastic make it into the oceans each year from land-based sources (Jambeck et al., 2015), with just ten rivers, largely in Asia, estimated to transport up to 95% of plastic debris (Schmidt et al., 2017). Plastic pieces move with oceans currents into ABNJ, most visibly concentrating in "garbage patches" in ocean gyres (Cózar et al., 2014) (Fig. 2d), and microplastics are increasingly of concern having been found in many marine species from deep-sea life through to ocean going predators (Romeo et al., 2015; Taylor et al., 2016). Chemical pollutants such as persistent organic pollutants have been found to concentrate along ocean frontal zones (Lohmann and Belkin, 2014), and mercury contamination is significant in pelagic marine life (e.g. Drevnick et al., 2015).

2.5. *Deep-sea mineral exploration and exploitation*

Although nearly all mineral resources used today are obtained from onshore deposits, rising demand and the relative rarity of some minerals have increased interest in deep-sea manganese nodules, cobalt crusts, and massive sulphides and exploration of ABNJ is well underway (Miller et al., 2018) (Fig. 2e). Deep-sea mining is likely to impact the entire seabed to surface ecosystem through resuspension and compaction of sediments, removal of seafloor nodules or cutting away of crusts, discharge of debris and spillage, noise and vibration (Jones et al., 2017; Miller et al., 2018). Operations would likely directly impact suitable seabed areas with near complete coverage (Jones et al., 2017), most of which coincide with areas of high biodiversity importance (Harfoot et al., 2018). Recovery potential once mining operations have ceased is likely to be extremely low, on the order of centuries to millennia (Jones et al., 2017).

3. Managing human impacts in ABNJ

3.1. Fishing

Fish stocks in ABNJ are managed under UNCLOS and the UN Fish Stocks Agreement (UNFSA [1995]), an implementing agreement to UNCLOS, by Regional Fisheries Management Organisations (RFMOs) and Regional Fisheries Bodies. The UNFSA obliges states to cooperate through RFMOs to sustainably manage fish stocks and deliver ecosystem conservation. However, while UNFSA strengthened obligations, the limitations of RFMOs are well-recognised and include gaps in geographic coverage, jurisdiction only over states which are parties to the RFMO, consensus voting to determine management measures, often with opt outs, and a restricted focus by most to particular species rather than ecosystems (Freestone, 2018; Wright et al., 2018). Most RFMOs are therefore poorly placed to deliver sustainability or broader environmental protection (Cullis-Suzuki and Pauly, 2010; Gilman et al., 2014; Gjerde et al., 2013; Wright et al., 2015). During UN negotiations for the ILBI on marine biodiversity in ABNJ, some countries have argued that fish and fisheries should be excluded from any agreement to avoid undermining existing frameworks and instruments, namely RFMOs (Wright et al., 2018). However, while fishery management measures can be effective in some contexts, their implementation has, so far, proved ineffective for many stocks in ABNJ (Cullis-Suzuki and Pauly, 2010; Gjerde et al., 2013; Juan-Jordá et al., 2018).

To explore the scope for fishery management measures to reduce biodiversity and ecosystem impacts of fishing, we evaluated the effectiveness of bycatch mitigation measures, focusing on bycatch of seabirds, turtles, sharks and rays, and marine mammals using longline, purse-seine, and deep-sea trawl fishing gear (see Section 2 of Supplementary Material File 1 for detailed methods).

We identified 52 relevant articles evaluating the effectiveness of various bycatch mitigation measures in longline fisheries published between 2000 and 2017 yielding 149 studies (Supplementary Material File 2). We found that bycatch of seabirds with a high seas distribution can be effectively mitigated against in longline fisheries using a variety of techniques (Fig. 3). There was only one exception, where an increase in bycatch during night setting was reported because fishing activity overlapped with a nocturnal species, the northern fulmar, *Fulmarus glacialis* (Melvin et al., 2001). Several mitigation measures also reduced turtle bycatch on longlines, although sample sizes for each mitigation technique were low, limiting the robustness of our conclusions (Fig. 3). However, current mitigation techniques were inadequate to reduce elasmobranch bycatch in longline fisheries, with substantial heterogeneity among studies in reported capture risk including increased elasmobranch bycatch in many cases (Fig. 3). Insufficient data were located for marine mammal bycatch mitigation in longline fisheries to draw conclusions.

We identified 9 articles quantifying bycatch in purse-seine fisheries published between 2000 and 2017, yielding 73 studies (Supplementary Material File 2). We found that purse-seines set around drifting fish aggregating devices (FADs) produced by the greatest bycatch for all species examined (Fig. 4). In the open ocean, marine life naturally associates with objects drifting on the surface, such as logs or branches, and FADs mimic this effect attracting target and non-target species (Dagorn et al., 2013). Reducing purse-seine sets around FADs would therefore reduce global bycatch rates, particularly for teleost fish and sharks and rays. However, if the number of sets around free-swimming tuna schools or other animals are increased, there may be limited reductions in turtle or marine mammal bycatch (Fig. 4). Furthermore, although fishing around FADs is less selective than targeting free-schools, FADs can reduce the fuel costs and carbon footprint of fishing, as well as the number of sets where catches are zero or low (Dagorn et al., 2013). However, there is a lack of quantitative data on the ecological impacts of FAD fisheries and improved research and monitoring by RFMOs is required (Dagorn et al., 2013). Given that estimates suggest that around 100,000 FADs are deployed worldwide each year by tuna fisheries (Gershman et al., 2015; Scott and Lopez, 2014), research is urgent and overdue.

Opportunities to reduce bycatch in purse-seine fisheries, beyond limiting the use of FADs, include gear modification (Restrepo et al., 2016), time/area closures (Watson et al., 2009) and safe handling and release practices to improve survival (Poisson et al., 2014). For example, 'ecological', or non-entangling FADs may reduce shark and turtle entanglement or release panels, cetacean bycatch (Hamilton and Baker, 2019; Restrepo et al., 2016), however, substantial development and research is required to develop effective technological modifications. Use of area closures therefore currently offer a simpler and more effective option: several RFMOs have already adopted time-area closures for commercial target species, however these could be adopted for bycatch species more broadly (Boerder et al., 2019). For example, one study estimated that in the eastern Pacific Ocean closures could reduce silky shark bycatch by up to one-third, while compromising only 12% of tuna catch (Watson et al., 2009).

Good handling practices may help reduce mortality of captured sharks (Poisson et al., 2014) although greater understanding of post-release mortality is needed. We identified 20 articles which yielded 33 studies of post-release mortality in longline ($n = 27$) and purse-seine ($n = 6$) fisheries published between 1998 and 2018 (Supplementary Material File 2). On average, 19% of individuals ($n = 488$) released following capture on longlines died while 48% of individuals ($n = 74$) died following release from purse-seines. Data were predominantly for elasmobranchs which accounted for 79% of all studies and all of the purse-seine studies, limiting general conclusions. Greater research into post-release mortality is therefore required.

We identified 21 articles that suggested ways to mitigate the effects of deep-sea trawling published between 2000 and 2017 (Supplementary Material File 2). No standardised measure of bycatch was identified preventing further analysis, however primary bycatch mitigation measures suggested were recorded. These focussed on area closures or spatial restrictions to activities and precautionary management. Deep-sea trawl fisheries are highly destructive causing serious, long-lasting impacts to seabed life and steep depletions of target species (Clark et al., 2016). Restricting the geographic extent of these fisheries is therefore the only effective bycatch mitigation option currently available, through either area closures/restrictions, or by constraining fishing activity to previously impacted areas. Areas left open to fishing risk irreparable damage and timescales of decades to centuries for recovery (Clark et al., 2016).

In response to UN General Assembly Resolution 59/25 of 2004 and others (e.g. 61/105 [2006], 64/72 [2009], 66/68 [2011]), several RFMOs have established area closures to protect Vulnerable Marine Ecosystems (VMEs)[1] and use 'move-on rules' to try to reduce bycatch in data poor areas (Gianni et al., 2016; Wright et al., 2019). Others are long overdue to introduce such protection (Gianni et al., 2016; Wright et al., 2015). Such rules require vessels to cease fishing within a set distance (e.g. two nautical miles in the North East Atlantic Fisheries Commission-managed area) if evidence of an interaction beyond a predefined threshold with a VME is recorded. However, at present, no studies have evaluated the effectiveness of move-on rules for the protection of VMEs and there are concerns that that their use is ineffective and inconsistent with the UNGA Resolution with VMEs being under-reported (Wright et al., 2015). Moreover, smaller, more fragile species may be broken and crushed and left in situ rather than being brought up

[1] Food and Agriculture Organization (2017) Vulnerable Marine Ecosystem Database. Available at: www.fao.org/in-action/vulnerable-marine-ecosystems/vme-database/en/vme.html [accessed 14 August 2019].

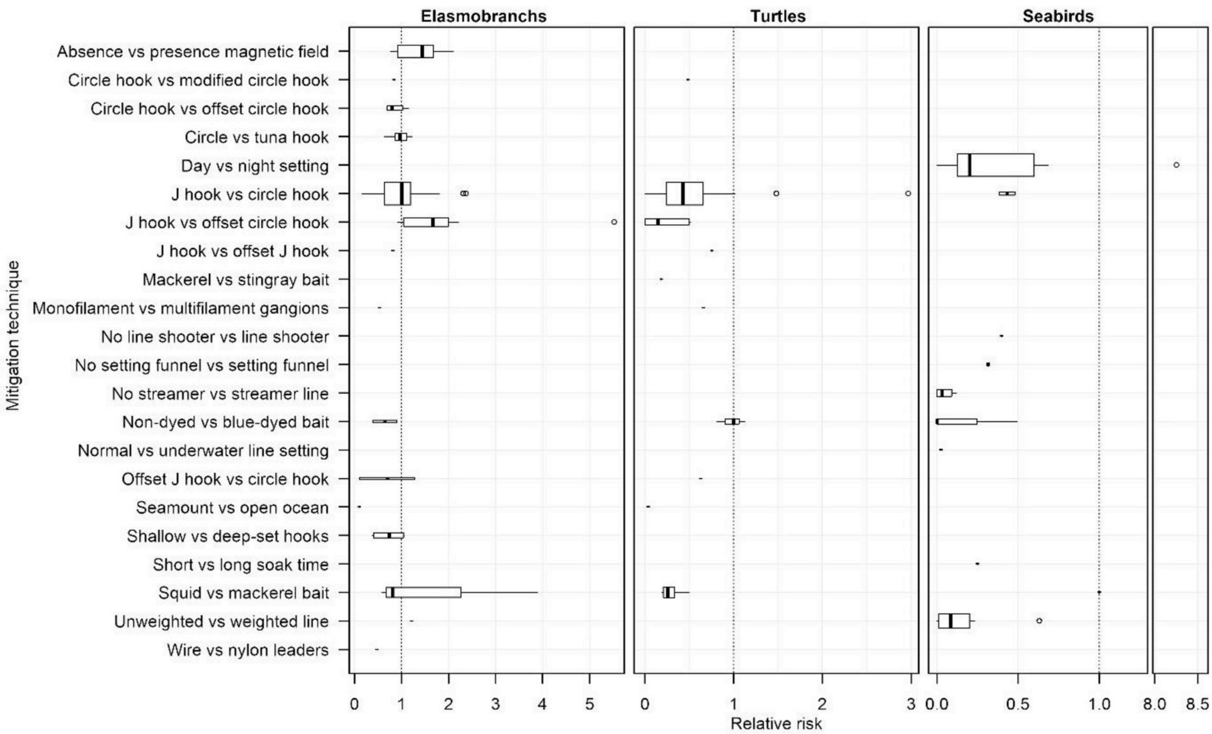

Fig. 3. Tukey boxplots showing the effect of various bycatch mitigation techniques on the risk of capturing sharks and rays (elasmobranchs), seabirds, and turtles in longline fisheries. Dotted lines denote a relative risk of 1, i.e. no difference in bycatch between control and treatment. Relative risk <1 indicates a lower risk, and >1 a higher risk, of capture for each mitigation measure. The width of boxes is proportional to the total number of observations in each group, with larger boxes signifying greater sample sizes. Outliers are marked by open circles. Data available in Supplementary Material File 2.

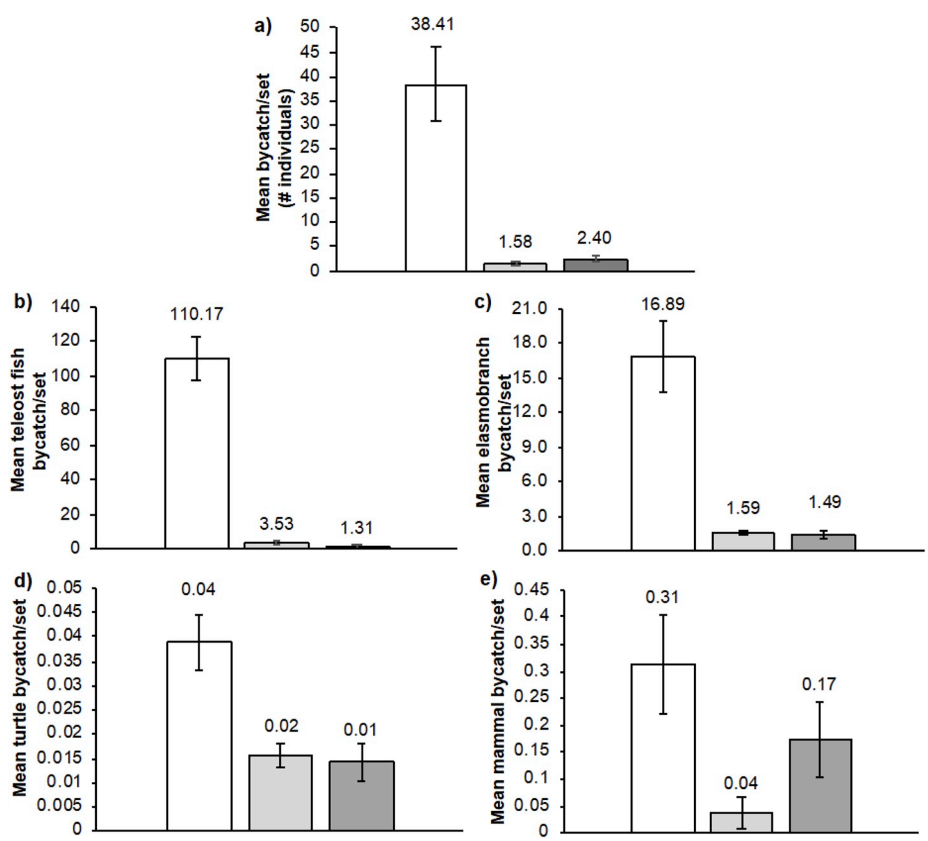

Fig. 4. Mean number ± standard error of individuals caught as bycatch per set around fish aggregating devices (FADs, white), free swimming schools (light grey) and animals (dark grey) for (a) all species, (b) teleost fish, (c) elasmobranchs, (d) turtles, and (e) mammals. Data available in Supplementary Material File 2.

and recorded as bycatch and counting towards management thresholds (Clark et al., 2016; Watling and Auster, 2017). While move-on rules may be a useful complementary tool to protect VMEs, particularly when their location is not yet known, the Scientific Council of the Northwest Atlantic Fisheries Organisation has concluded that establishing closed areas to bottom fishing is preferred to reduce scientific (e.g. determination of species-specific appropriate thresholds) and management complexity (Bergstad, 2012; NAFO, 2013). Some efforts have been made to modify gear to reduce the severity of effects on the seabed (e.g. reducing the weight and size of parts or elevating gear above the seabed), but their effectiveness is uncertain (Clark et al., 2016; Watling and Auster, 2017).

Common across all fishing gears examined, area-based management tools (ABMTs), including fishery closures and MPAs, offer opportunities for effective bycatch mitigation while also supporting other fishery and conservation objectives.

3.2. Shipping

The International Maritime Organisation (IMO) is responsible for regulating international shipping to set standards, improve safety and security and prevent pollution. The IMO's mandate is only to facilitate enforcement and therefore it has no direct monitoring or enforcement powers (IMO Convention [1948]).

Measures to reduce shipping impacts include improved technology, speed restrictions, changes to shipping lanes, and area-based management. For example, the IMO has agreed a global sulphur cap for marine fuels that will come into effect by 2020 (IMO, 2017) and intends to adopt a strategy for the reduction of greenhouse gas emissions from ships in 2023 (IMO, 2018). Retiring the noisiest ships and bringing in quieter ships would result in large reductions in ambient noise, particularly as the global fleet expands (Kaplan and Solomon, 2016; Williams et al., 2015). Slowing ships would reduce fuel use and the industry's carbon footprint (Bows-Larkin, 2015) as well as reducing risk of collisions with marine mammals (Vanderlaan and Taggart, 2007) and ambient noise (Kaplan and Solomon, 2016). Shipping lanes could be altered to redirect vessels from sensitive areas (NOAA, 2009). Area-based management tools, such as Emission Control Areas/Special Areas and Particularly Sensitive Sea Areas that may be designated by the IMO, could also be used to direct vessels away from areas of greater collision risk with marine mammals (Di Sciara et al., 2016) and reduce ship-generated pollution (Backer, 2018) and noise in sensitive areas (Williams et al., 2015), although only two Special Areas have been designated overlapping ABNJ so far. However, as low-frequency noise, such as that produced by shipping, travels long distances underwater with little attenuation, activities outside any spatial management measure could substantially raise noise levels within a managed area, therefore requiring larger-scale restrictions.

Environmental impact assessments (EIA) are under consideration within UN negotiations to protect marine biodiversity in ABNJ (UNGA, 2015; Wright et al., 2018) and conduct of an EIA could therefore be required prior to opening new shipping routes which may help mitigate future impact (Ma et al., 2016). However, with no enforcement mandate, the IMO requires contracting parties to implement national legislation to enact regulations. Should continued management of shipping activities fall solely to the IMO, global accountability will remain limited.

3.3. Climate change and associated effects

Whether we choose to act on a given human impact on the environment is based on a combination of scientific information and subjective value judgements: do we value something today more than tomorrow, what is fair for different nations or people, or what value do we place on non-human species? While science cannot resolve the value debate, it can provide insight into the management options to counter climate change and its associated effects:

(1) Mitigation: reducing greenhouse gas emissions is clearly necessary to slow climate change (Rogelj et al., 2016). In ABNJ, increasing the energy efficiency of ships, reducing ship speeds and incentivising low carbon would reduce greenhouse gas emissions (Bows-Larkin, 2015). Reducing capacity enhancing fishing subsidies (Sala et al., 2018b) would also help drive innovation towards more efficient ships.
(2) Mitigation: Another option is to promote carbon sequestration and storage. Policy measures relevant to ABNJ might include geoengineering or preservation of habitats that store carbon and species that facilitate carbon export to the deep sea such as mesopelagic fish. Geoengineering, deliberate manipulation of the Earth system to try to counteract some effects of rising greenhouse gas concentrations, is high-risk because of the likelihood of unforeseen negative consequences and the irreversibility of actions (Robock, 2008). There is nonetheless considerable interest as climate change risks escalate. An alternative low-risk strategy is increased use of highly and fully protected MPAs extending from surface to seabed (O'Leary and Roberts, 2018). Such MPAs already help mitigate the effects of climate change, deliver carbon sequestration and storage, and promote the biological processes that underpin these ecosystem services (O'Leary and Roberts, 2017; Roberts et al., 2017).
(3) Adaptation: Increase society's capacity to cope with environmental change. Multiple policy measures will be required to increase societal adaptability, and thereby reduce vulnerability, to changing conditions. In ABNJ, highly and fully protected MPAs could help promote coherent management across oceans for highly migratory species, bolstering national conservation efforts.
(4) Adaptation: increase nature's resistance (ability to persist) and resilience (recovery ability) to environmental change. Highly and fully protected MPAs that encompass the water column will help safeguard ecological processes and ecosystems (O'Leary and Roberts, 2017, 2018), promote ecosystem resilience and improve the potential for ecosystem adaptation to changing environmental conditions (Roberts et al., 2017). Effective sectoral management in the areas surrounding MPAs will also be essential to ensure the full benefits of protection and ecosystem management are achieved.

These management strategies will not halt climate change. The effects of already emitted greenhouse gases will be felt for decades to centuries irrespective of management put in place now. However, while some change is inevitable, a comprehensive risk-management strategy is likely to include all the identified management options.

3.4. Land-based pollution

Although the effects of many land-based pollutants are concentrated in EEZs, many are transported by winds or ocean currents to ABNJ (Jambeck et al., 2015; Schmidt et al., 2017; Sharples et al., 2017). Limited options exist in ABNJ governance to reduce the extent or impact of land-based pollution; instead, national policies are required to reduce sediment, nutrient and pollutant transport to the sea. Such measures include improved land-use practices in watersheds, limiting agrochemical inputs, implementing adequate sewage and storm water management and sustainable development practices. Policies are also required to reduce use and atmospheric or water discharge of harmful chemicals, reduce excessive materials in, for example, packaging, improve waste management including encouraging recycling and the use of recyclable materials, and technological development of new materials. Clean-up operations targeting existing pollution would also be beneficial to prevent their transfer offshore, particularly in regions such as Asia which are the dominant source of plastic debris to the oceans (Schmidt et al., 2017). Methods suitable for application in ABNJ have yet to be developed for most forms of pollution. Although new technologies are emerging, research is needed to establish benefits and ecological impacts (e.g. Rochman, 2016).

3.5. Deep-sea mineral exploration and exploitation

Seabed mining of the Area (the seabed, ocean floor and subsoil thereof beyond the limits of national jurisdiction) is regulated by the International Seabed Authority (ISA). To date, the ISA has issued 15-year exploration licenses (with an extension possible for 5 further years) for the Area to 29 contractors[2] offering spatially-defined prospecting for the specified resource (Fig. 2e). Concurrently, the ISA is developing the regulatory framework for exploitation, including mining standards, operational safety, and environmental protection (Miller et al., 2018). Draft regulations were published in August 2017 for public consultation with a revised draft issued in July 2018.[3] These guidelines articulate the pathway from exploration to exploitation, laying out the requirement for contractors to complete Feasibility Studies, Environmental Impact Assessments, Environmental Management and Monitoring Plans and Closure Plans, as well as several financial and health and safety plans, prior to a licence being issued for exploitation.[4] At this stage it appears that the ISA Commission will be responsible for ensuring the adequacy of these documents prior to issuing any licences through internal review informed by public consultation, as well as enforcing them following commencement of operations.

Following initial exploration of areas up to 150,000 km^2, each contractor is required to relinquish half of this area after the first eight years of the contract to ensure areas are not monopolised by particular contractors.[5] However, exploitation will be limited to economically viable areas determined by the type of resource, its abundance and technological efficiency (Sharma, 2011). The direct mining footprint will therefore likely be smaller than the 75,000 km^2 exploration area, although the geographic and temporal extent of indirect impacts will be much larger (Miller et al., 2018). The mitigation hierarchy is applied to limit impacts on biodiversity (Miller et al., 2018; Niner et al., 2018; Van Dover et al., 2017) advising measures to (1) avoid impacts, (2) minimise duration, intensity and/or extent of unavoidable impacts, (3) to restore/remediate unavoidable impacts, and (4) as a last recourse to employ biodiversity offsetting (protecting biodiversity similar to that affected that would otherwise be lost).

The ISA is now developing regional environmental management plans to address potential impacts from deep-sea mining. In 2012, it approved the first plan for abyssal polymetallic nodule fields in the Clarion-Clipperton Zone in the central Pacific Ocean (International Seabed Authority, 2011). This plan aims to facilitate environmentally responsible exploitation by improving scientific understanding of impacts to inform mitigation and restoration, and implementing area-based management including networks of no-mining areas known as "Areas of Particular Environmental Interest" or APEIs. The plan sets out that 30–50% of the total management area should be protected within APEIs. To assess the environmental impacts of each contractor's mining activities the ISA can also designate experimental sites known as impact reference zones (IRZ) and control sites as preservation reference zones (PRZ) in the Area (Jones et al., in press). Nonetheless, there are serious concerns that political placement of APEIs outside of areas of commercial interest will reduce their effectiveness (Cuyvers et al., 2018) and that avoidance of impacts and restoration of ecosystems following damage from mining activities is largely unachievable (Niner et al., 2018; Van Dover et al., 2017). The high costs of working in the deep-sea and with deep-sea species, the time required to evaluate success of restorative action, the large spatial extent of mining operations, poor information on ecosystem baselines and functioning, and the characteristics of deep-sea life that make them slower to recover than many terrestrial or coastal species all present obstacles to effective restoration (Da Ros et al., 2019; Van Dover et al., 2014, 2017). We know, reactive protection alone will not enough to promote recovery following human impact in the deep-sea (Huvenne et al., 2016) and developing methods for ecological restoration are considered a priority in the coming decades (Da Ros et al., 2019), Where restoration options are not feasible, in-kind or out-of-kind offsets could be considered. However, lack of knowledge presents challenges for selecting like-for-like offsets, and out-of-kind offsets assumes that loss of biodiversity, ecosystem functioning and services provided by the affected deep-sea ecosystem is acceptable (Van Dover et al., 2017). At the very least, limits on the mining footprint with some habitats (including exploitable mineral resources) left undisturbed, together with technological innovation to reduce sediment dispersal and persistence will be needed.

There are great uncertainties over our present ability to contain mining impacts, and growing concern that the ISA's combined role as promoter, regulator and possible contractor of mining is a conflict of interest (Deep Sea Mining Campaign et al., 2019). Furthermore, while the UN has consistently recommended since 2013 that the ISA should develop environmental management plans for areas outside the Clarion-Clipperton Zone, particularly those subject to exploration licenses (UN resolution 68/70, 69/245, and 70/235), little progress has been made (ISA, 2018)

Should deep-sea mining activities proceed, permanent and long-term biodiversity losses are inevitable (Miller et al., 2018; Niner et al., 2018). Given that extinctions and fundamental changes to deep-sea ecosystems from mining will be unavoidable, if mineral extraction does go ahead, there are growing calls for a moratorium on deep sea mining while the risks, likely damage and mitigation options are considered more fully (European Parliament, 2018; Laffoley et al., in press). Ensuring transparency to allow public scrutiny of decision-making, regulation and enforcement of mining activities of both the ISA and contractors is critical. At present, area-based management offers the only feasible way to ensure ecosystems are preserved if mining goes ahead. Their design will need to account for habitat distributions, species' ranges and connectivity patterns, and the long-distance impacts of mining, amongst others, which will be difficult in such a data-poor environment (Dunn et al., 2018); the precautionary approach is essential (Niner et al., 2018). Finally, it will be critical to ensure area-based management tools, such as APEIs, effectively target areas of commercial value as well as achieving biodiversity representation more broadly to reduce the chance of such tools being misplaced and ineffective.

4. Conclusions

Areas beyond national jurisdiction are an international resource, a global commons, and a public good of growing interest and importance as the human population grows and material aspirations increase (OECD, 2016). The highest-ranking human activities and influences that affect ABNJ are fishing/hunting, shipping, climate change and its associated effects, land-based pollution and deep-sea mineral exploration and exploitation, although this assessment will require updating as activities change and emerge over time. The management options we

[2] International Seabed Authority, Deep Seabed Minerals Contractors. Available at: www.isa.org.jm/deep-seabed-minerals-contractors [accessed 15 March 2019].

[3] International Seabed Authority, Ongoing development of regulations on exploitation of mineral resources in the Area. Available at: https://www.isa.org.jm/instruments-juridiques/ongoing-development-regulations-exploitation-mineral-resources-area [accessed 13 August 2019].

[4] International Seabed Authority, Revised draft Regulations on Exploitation of Mineral Resources in the Area. ISBA/23/LTC/CRP.3*. Available at: www.isa.org.jm/legal-instruments/ongoing-development-regulations-exploitation-mineral-resources-area [accessed 15 January 2019].

[5] International Seabed Authority, Overview. Available at: www.isa.org.jm/deep-seabed-minerals-contractors/overview [accessed 15 March 2019].

identified to address these threats are diverse and available through a variety of actors, although their actions are not always effective. Area-based management tools (ABMTs) were the only effective option consistently identified to mitigate impacts across these high-ranked activities and influences, except for land-based pollution which will require national action to control sources.

Existing organisations tasked with managing specific human activities in ABNJ can already designate sectoral ABMTs, but these typically address only specific threats (Freestone, 2018). Comprehensive management of an area is presently only possible through cross-sectoral international agreement and requires effective enforcement mechanisms and complete membership to be worthwhile (Freestone, 2018). Discussions for a new international legally binding instrument for ABNJ are currently considering the role ABMTs, including marine protected areas (MPAs), might play in future high seas management. To tackle the integrated management issues of the 21st century, the new instrument should enable creation of highly and fully protected MPAs to safeguard vulnerable habitats and wildlife and promote ecosystem resilience. This means adopting an agreement that covers all marine species, including fish, regardless of their commercial status or life history (O'Leary and Roberts, 2017; Ortuño Crespo et al., 2019; Wright et al., 2016). While the level of benefits MPAs can produce have consistently been linked to the level of protection given to an area amongst other factors (Edgar et al., 2014; Gill et al., 2017; Oregon State University et al., 2019; Sciberras et al., 2015), most of the world's MPAs remain multiple-use or partially-protected (Costello and Ballantine, 2015; Sala et al., 2018a). Multiple-use MPAs may be of some benefit in the high seas, particularly when balancing social or economic impacts, but they cannot be relied upon as a primary tool for effective conservation.

Use of MPAs is often framed as an either/or choice to alternative management, particularly with regards to fisheries, but they are complementary tools designed to achieve overlapping and mutually supporting goals (O'Leary et al., 2018). Given the fluid nature of the marine environment, and the long-distance movements of many of the inhabitants of ABNJ, we conclude that MPAs should form the foundation of management but sectoral measures will be essential as well. However, developing a high seas network of MPAs will require global coordination in order to produce a cost-effective, transparent network design that blends top down strategic conservation planning with bottom up site nomination based on local knowledge and stakeholder interests. None of the regional bodies in existence at the moment is a candidate to lead this effort, and nor would a devolved process be likely to work, given the limited mandates and poor historical record of existing management organisations.

There are many challenges for a new global governance regime in the high seas. Questions of mandate, responsibilities and enforcement persist, and there will almost certainly be conflict and tensions as we move to a regime that places conservation and sustainability at its core, rather than exploitation and profit maximisation. However, the lack of integration and coordination across organisations from the same and different sectors currently undermine our ability to protect marine biodiversity beyond national jurisdiction and there is an urgent need to step up management in ABNJ (Freestone, 2018). A new international legally binding instrument for ABNJ must therefore clearly define roles, responsibilities and hierarchies of existing and new organisations under the ILBI, enhance intra- and cross-sectoral cooperation and coordination, emphasise responsibility and liability for environmental damage in ABNJ, and ensure the implementation of a precautionary ecosystem approach to sustainably manage marine resources (Long, 2019). Incorporating a robust and transparent mechanism into the new instrument to establish effective ABMTs together with strong complementary measures in surrounding areas including, for example, fishing gear restrictions or bycatch mitigation measures as well as comprehensive environmental impact assessments, will help align management across sectors and address cumulative impacts thereby delivering multiple conservation and sustainability objectives.

Author contributions

BCOL and CMR conceived and designed the study; BOL, GH, AT, HLA, CJM collected and analysed data. BOL and CMR wrote the first draft. All authors contributed to later drafts. All authors have seen and approved the final manuscript.

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The funder had no involvement in the study design, collection, analysis and interpretation of data or in the writing and submission of this manuscript.

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Appendix A. Supplementary data

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