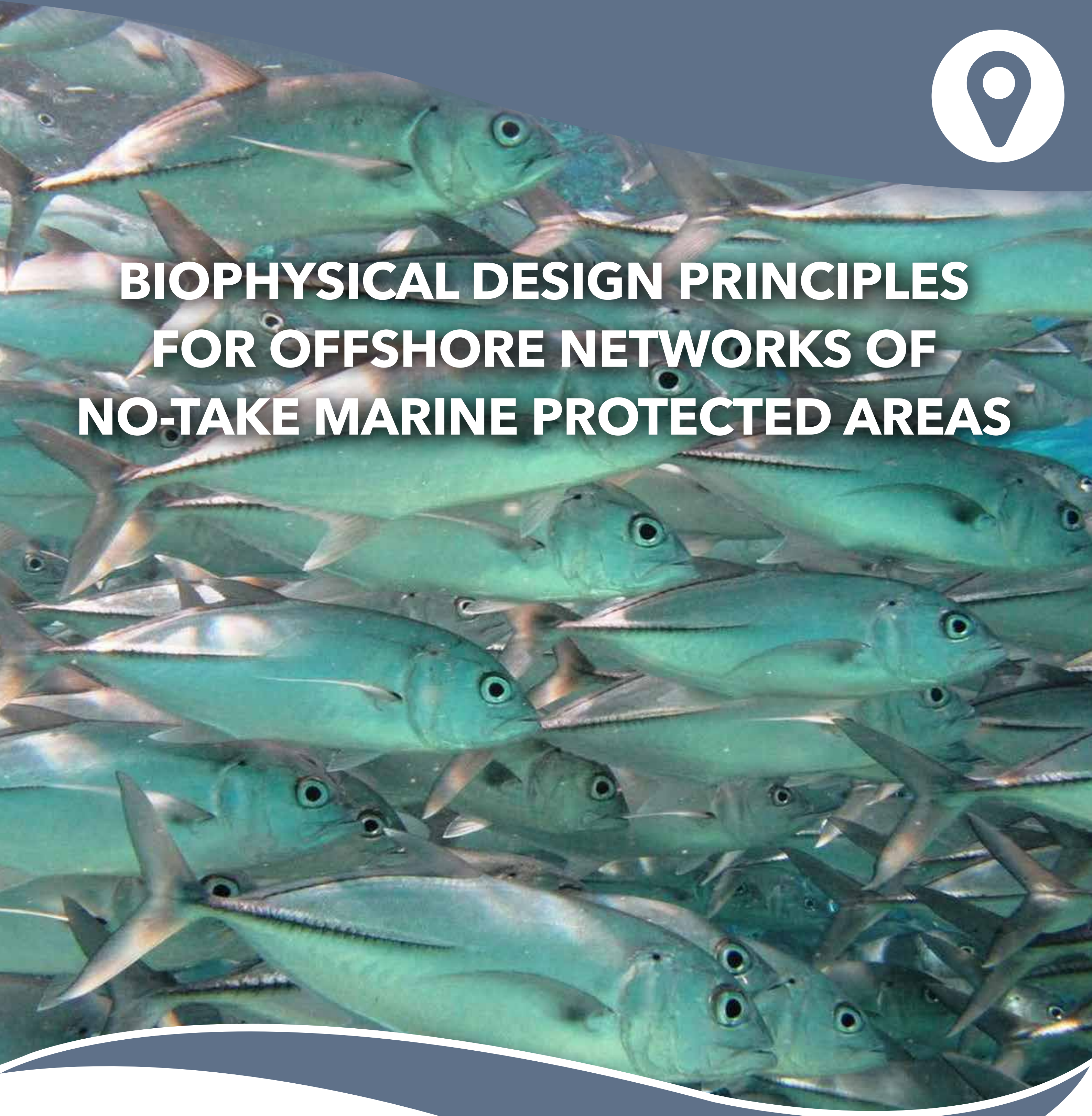
BIOPHYSICAL DESIGN PRINCIPLES FOR OFFSHORE NETWORKS OF NO-TAKE MARINE PROTECTED AREAS



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Marine and Coastal Biodiversity Management in Pacific Island Countries

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CONTENTS

BOX

FIGURE

TABLES

EXECUTIVE SUMMARY

Many types of Marine Protected Areas (MPAs) exist and contribute to sustainable marine resource use, but no-take MPAs, where all extractive activities are prohibited, are the most effective tool managers can use to protect marine ecosystems from destructive and unsustainable extractive human activities. No-take MPAs have been widely advocated and implemented in coastal seas all over the world. The success of MPAs has been significantly enhanced where science-based biophysical design principles or guidelines have been used to assist in the MPAs and MPA network design. Increasingly across the globe, as human pressure is expanding further offshore, some governments have established very large MPAs (>150,000 km^2). In addition to establishing large individual MPAs, some jurisdictions have chosen to declare networks of open-ocean MPAs. Given that most of the ocean is offshore, this is the only way to reach global targets for ocean protection.

Achievement of most MPA objectives, including socio-economic and cultural objectives, requires a positive response from the marine environment. To this end, biophysical design principles to guide the design of MPAs and MPA networks are needed to enable the maintenance or restoration of native species diversity and abundance, habitat diversity, keystone species and biological connectivity. While some of the guidelines used in the design of coastal MPA networks can be used offshore, the size and placement of offshore MPAs requires a substantially different emphasis. Appropriate biophysical design principles therefore need to be tailored to offshore ecosystems.

This paper outlines generic, detailed and comprehensive biophysical design principles for no-take MPAs in offshore environments. Our approach was to collate the existing biophysical design principles that have been successful in coastal and/or continental shelf ecosystems, review the literature about offshore ecosystems and species, and modify the existing guidelines to meet the specific ecological needs of open ocean ecosystems and species. The synthesis of both areas of knowledge provides the basis for comprehensive biophysical design principles for offshore MPA networks.

Offshore ecosystems differ from coastal habitats in that they are organised at larger spatial scales, have a greater three-dimensional component and host larger pelagic species that tend to range more widely, both horizontally and vertically. While large, migratory or highly mobile species have attracted the most attention in terms of both research and conservation efforts, the bulk of pelagic biodiversity and abundance comprises innumerable small pelagic species – including zooplankton and nekton – with a smaller capacity for movement. Biophysical design principles for offshore MPAs and MPA networks need to take both types of organisms into account. Connectivity across open ocean habitats also occurs on a larger scale compared with coastal environments. Benthic communities in the deep sea often have sparse and/or patchy distributions over wide expanses, or aggregate around sources of food (e.g. sunken whale carcasses, hydrothermal vents), topographic features (e.g. seamounts, canyons). These benthic features interact with hydrographic features such as currents, fronts, eddies and upwellings to influence pelagic habitats.

The biophysical design principles described in this paper draw on an extensive literature review of work that is relevant to the design of no-take MPAs in offshore environments within the Exclusive Economic Zones (EEZ) of maritime nations. These principles may also be applied to high seas and deep ocean MPAs.

The biophysical design principles for offshore no-take MPAs are summarised on the following page.

BIOPHYSICAL DESIGN PRINCIPLES FOR OFFSHORE NO-TAKE MPAS

1. Represent at least 20–30% of offshore bioregions and offshore bioregional transition boundaries in no-take MPAs, within and outside the EEZs of maritime nations.
2. Represent at least 10–30% of each known habitat in no-take MPAs, with special considerations where bioregions are unknown.
3. Represent whole features / habitats, wherever possible.
4. Have at least three replicate no-take MPAs within bioregions, and include at least one example of each habitat or feature (e.g. hydrodynamic front, seamount, hydrothermal vent, migration bottleneck, resting areas, nesting, breeding or spawning area, other aggregation area, etc.).
5. Ensure that no-take MPAs include critical habitats and biologically or physically special or unique sites.
6. Make no-take MPAs larger rather than smaller.
   - Make inshore (coast to edge of shallowest habitats surrounding the coast, e.g. coral reefs) no-take MPAs 400m–2km in diameter.
   - Make nearshore (edge of slope or reef to 80m depth contour) no-take MPAs 2–10 km in diameter.
   - Make offshore (beyond 80m depth contour) no-take MPAs 50–200 km in diameter.
7. Use simple MPA shapes that maximize area to edge ratios (e.g. square rather than rectangle).
8. Maximise connectivity between no-take MPAs in an MPA network.
   - Inshore (coast to edge of shallowest habitats, e.g. coral reefs) no-take MPAs should be between 500m and 5km apart.
   - Nearshore (edge of slope or reef to 80m depth contour) no-take MPAs should be between 5 and 20km apart.
   - Offshore (beyond 80m depth contour) no-take MPAs should be between 20 and 200 km apart.
   - Where possible, place offshore no-take MPAs adjacent to existing coastal MPAs.
9. Choose permanent over temporary protection.
10. Reduce or eliminate threats across the area that the entire no-take MPA network lies within by applying other categories of MPAs or spatial management areas throughout it.

INTRODUCTION

Marine protected areas (MPAs), especially no-take areas, are the best conservation tools available to help protect marine species and habitats from exploitation and damage, and to conserve marine biodiversity (Costello, 2014; Graham et al., 2011). Common biophysical goals of MPAs are to maintain or restore native species diversity, fish stocks, habitat diversity and heterogeneity, keystone species, connectivity and important ecological processes (Green et al., 2013). Usually, achievement of these biophysical goals allows the consequent achievement of socio-economic and cultural objectives (Gilman et al., 2011).

There has been some resistance to applying spatial protection to offshore environments. This resistance stems from perceived difficulties related to the dynamic nature of offshore ecosystems, the lack of detailed knowledge about pelagic communities, the highly mobile nature of some larger high-profile species, and the physical and biological complexity in both horizontal and vertical planes. These concerns extend to, the challenges of MPA design, enforcement and governance in remote areas, both within the Exclusive Economic Zones (EEZs) of individual nations and in areas beyond national jurisdiction (Ban et al., 2014; Game et al., 2009).

However, our knowledge of oceanic ecosystems is increasing rapidly, as is our understanding of their value and threats to their integrity. Consequently, the number and size of offshore MPAs is expanding as the planet's "last frontier of conservation management" (Game et al., 2009; Micheli et al., 2004; Pala, 2009). Ensuring compliance, however, remains challenging (Arias et al., 2016).

While there are still gaps in knowledge (Claudet et al., 2010; Dunne et al., 2014; Palumbi, 2004), increasing evidence shows that offshore MPAs can work, especially no-take MPAs or reserves (Davies et al., 2012; Koldewey et al., 2010; Mills and Carlton, 1998). In fact, recent research suggests that offshore no-take MPAs can not only promote the recovery of highly mobile species (e.g. tuna), but also enhance fish stock availability to local fisheries and help to stabilize local catches outside the boundaries of MPAs, even for mobile species (Boerder et al., 2017). Offshore MPAs have the capacity to protect high diversity, large habitats, entire trophic webs and ecological processes (Maxwell et al., 2014). Along with pelagic ecosystems, offshore MPAs can protect deep-sea benthic and demersal ecosystems that are often predictable in space as well as highly fragile and closely linked to the entire vertical pelagic realm above them (Davies et al., 2007; Huvenne et al., 2016; Norse, 2005; Williams et al., 2010b). Careful design of, and compliance with, networks of MPAs can also ensure the protection of ecosystem services that people value (IUCN WCPA, 2018; The Ecology Centre, The University of Queensland, 2009). In recent years, partly due to this increased knowledge, the number of large-scale MPAs has grown (Lewis et al., 2017), and, worldwide, there are now 16 no-take MPAs larger than 150,000 km^2.

In Lewis et al. (2017), existing very large (>150,000km^2) offshore MPAs were shown to cover 11 million km^2 or ~3% of the ocean, and at least 10% of the range of 26.9% of species assessed worldwide; the remaining 73.1% of species fell short of a target of 10% coverage within MPAs (Davies et al., 2017). This is thought to be because, so far, very large MPAs have been placed mostly in remote areas to avoid interfering with commercial interests, rather than systematically designed to adequately include species' ranges (Leenhardt et al., 2013). The need to design offshore MPA networks according to robust biophysical design principles is clear (Davies et al., 2017).

There is now an increasing body of scientific research devoted to understanding the offshore environment and to defining designs of networks of MPAs that achieve conservation and other management goals (Ban et al., 2011; Berglund et al., 2012). The open ocean contains a wide variety of ecosystems and species assemblages, from the pelagic habitats that start at the surface and extend to the deepest realms to the seabed. The view that the deep sea is physically and biologically homogeneous has been dispelled (Benoit-Bird et al., 2016), and the deep sea is now known to host levels of biodiversity that rival those of coral reefs (Van den Hove et al., 2007).

Noteworthy offshore topographic features include seamounts, rises, shelf breaks, canyons, ridges and trenches. These benthic features interact with hydrodynamic features such as currents, fronts, eddies and upwellings to influence pelagic habitats and aggregate marine life into distinct communities or "hotspots" of productivity and biodiversity (Davoren, 2013; Hyrenbach et al., 2000; Morato et al., 2010). The seabed in the open ocean hosts unique features and communities, and varies dramatically in physical (especially light, temperature and pressure) and biological / ecological characteristics with depth (Baker et al., 2007). In some cases, the geomorphic features may be dynamic, for instance through the eruption of new undersea volcanoes (Baker et al., 2002).

Far from being resilient, the open ocean is home to some of the most long-lived, poorly understood and vulnerable marine animals and ecosystems on earth. The open ocean is under increasing pressure from human impacts, especially overfishing, bycatch of non-target species, destructive fishing methods, noise, pollution and litter associated with shipping (including cruise shipping), lost, abandoned and discarded fishing gear, as well as from land-based sources, non-renewable resource extraction and climate change (causing changes in weather and oceanic currents, salinity, temperature and acidity) (Halpern et al., 2008; Ramirez-Llodra et al., 2011; UN, 2017; UN Environment, 2017; Verity et al., 2002).

As coastal fisheries become depleted, and technological improvements allow fishing vessels to venture further offshore, pelagic fish stocks are more at risk of overexploitation than ever before (Baum et al., 2003). Numerous heavily exploited species are now of conservation concern, including tuna, billfish and sharks (Collette et al., 2011; Ferretti et al., 2010). In the open ocean, overfishing affects species ranges, ecological linkages, community composition and trophic functioning in both the horizontal and vertical dimensions (Ortuño Crespo and Dunn, 2017; Roberts, 2002; Worm and Tittensor, 2011). The relatively low productivity, weaker governance and data deficiency of the open ocean makes it likely that much of the fishing activity targeting pelagic and deep-sea species is unsustainable (Collette et al., 2011; Norse et al., 2012; Ortuño Crespo and Dunn, 2017). Furthermore, the two-way coupling between benthic and pelagic systems means that impacts in the upper parts of the open ocean impact the entire vertical span of offshore assemblages (Grober-Dunsmore et al., 2008).

MPAs may have carefully articulated socio-economic and/or cultural objectives as well as interlinked biological objectives (e.g. Commonwealth of Australia, 2003)Australia", but it is thought to be more effective to determine biophysical criteria first, because if there is no positive environmental response, no objectives can be achieved, socio-economic or otherwise (Gilman et al., 2011). Overall, MPA guidelines should consider socioeconomic and cultural values together with biophysical values (Agostini et al., 2010; Fernandes et al., 2009; Jessen et al., 2011). The scope of this report, however, is restricted to the biophysical aspects of MPA design.

This paper describes a set of biophysical design principles that managers can use to design effective no-take MPAs in offshore environments. In this paper 'offshore' is defined as pelagic and benthic habitats which occur beyond the shelf edge, or shelf 'break' (often beyond 80m depth), of continents or major islands. The 60–80m depth contour was chosen because sunlight dependent coral reef ecosystems and reef-associated ecosystems in the Pacific are unlikely to form at depths greater than 60m; of course, individual species that are found in these habitats may be found at greater depths (Bridge et al., 2012; Brokovich et al., 2010; Slattery et al., 2011).

Terms such as 'deep sea', 'deep ocean' or 'open ocean' are synonymous, in this report, with the term 'offshore'. The layout of this report begins with a review of MPA objectives in general, then outlines the existing guidelines currently in use for coastal MPAs and MPA networks, continues with a review of knowledge about offshore species and ecosystems, and finally combines the existing principles with this knowledge to produce the biophysical design guidelines for offshore MPAs and MPA networks. The report is therefore guided by the following questions:

1. What are the general objectives sought for all MPAs and MPA networks and common strategies of implementation?
2. What are the existing biophysical design principles for coastal and/or continental shelf MPA networks (or no-take MPA networks)?
3. What are the characteristics of offshore species and ecosystems that will form the basis of more appropriate guidelines?

Finally, the review of information guided by these questions led us to:

4. Provide a new and justified list of ten biophysical principles for the design of offshore, no-take MPA networks.

1 GENERAL MPA DESIGN OBJECTIVES

Generally, establishing an MPA consists of a series of steps that relate to planning, design, declaration and management (Kelleher and Kenchington, 1992). The biophysical principles to guide this process should have, at their core, the goal of maintaining or restoring native species diversity (which may include fish stocks), habitat diversity and heterogeneity, key species, and connectivity; as well as a way to account for context and uncertainty (Foley et al., 2010). This is to ensure a positive ecological response from the marine environment so that other MPA objectives (socio-economic, cultural and biological) can be achieved.

1.1 MPA NETWORKS AND ZONING

It is increasingly well-recognised that carefully designed networks of MPAs perform better than individual, stand-alone MPAs, especially in areas where the need for protection must be balanced with commercial interests and social and cultural needs, which can make very large MPAs impractical (Gaines et al., 2010). Networks of MPAs increase the chance of protecting multiple examples of features of interest, enhance the probability of overall persistence of habitats, populations and species and spread the risk from threats across a larger spatial scale (Gaines et al., 2010).

A network is best developed upon a representative basis (Fernandes et al., 2005; Harris, 2007; Jones and Carpenter, 2009), whereby each bioregion or habitat of relative homogeneity is represented within the MPA network. There also needs to be functional connectivity between sites in a way that encompasses ecological processes and/or species ranges over large scales.

Marine bioregions provide a framework for designing ecologically representative MPAs where there are imperfect data on habitats and species (Day and Roff, 2000). Bioregions are described as areas which contain habitats and species that are more similar to each other than to habitats and species that might occur in other bioregions; a bioregion is defined by a combination of biological and geographic criteria and generally encompasses systems of related, inter-connected ecosystems (adapted from ANZECC, 1996). In practice, the identification of bioregions relies on physical data proxies for habitats and species, because in many cases the biological observations are not available. This is particularly true for the deep sea, where data are most sparse (Harris and Whiteway, 2009; Sayre et al., 2017).

Both stand-alone MPAs and networks of MPAs can allow for multiple-use zoning (Fraschetti et al., 2009), and for a proportion of each MPA to be designated as no-take (Bohnsack et al., 2004). This report focuses on principles for no-take MPAs, but as the declaration of no-take MPAs is not always possible for political, cultural or socio-economic reasons, some thought is also given to MPAs that allow a degree of human use. Guidelines for this exist; the International Union for the Conservation of Nature (IUCN) sets out categories for MPAs with different levels and types of permitted use (Table 1; see also Principle 10 below).

MPAs that are zoned for multiple use typically include a series of protection levels ranging from no-go (no entry) or no-take (where all extraction is prohibited), to very minimal management, perhaps limiting the most damaging activities (Table 1; Day et al., 2012). This type of zoning allows for many sustainable uses while minimising or excluding threats (Day, 2002; Grantham and Possingham, 2011; Wilson et al., 2011). No-take MPAs, where all forms of extraction and industrial activity are excluded (IUCN categories Ia, Ib and II), provide the best marine protection available (Beger et al., 2003; Lester et al., 2009).

TABLE 1. Definition and Primary Objectives of IUCN Protected Area Categories, specific to MPAs. (Day, 2017; Dudley, 2008, in Day et al. 2012)

IUCN Category	Definition and Primary Objective	Notes
Ia	Scientific reference area (or scientific baseline) set aside for scientific research and monitoring, where human visitation, use and impacts are strictly controlled and limited to ensure protection of the conservation values; may be a 'no-go' area.	Fishing generally NOT allowed
Ib	Large unmodified areas (aka wilderness), retaining their natural character and influence, without permanent or evidence of significant human use, which are protected and managed so as to preserve their natural condition.	
II	Large natural or near-natural no-take areas set aside to protect large-scale ecological processes, along with the complement of species and ecosystems characteristic of the area; also provide for environmentally and culturally compatible spiritual, scientific, educational, recreational and visitor opportunities.	
III	A specific natural monument (e.g. seamount, submarine feature, a cave or even a living component such as a specific coral reef or feature). They are generally small protected areas and often have high visitor values.	Fishing may or may not be allowed
IV	Set aside to protect particular species or habitats and management reflects this priority (e.g. regular active management interventions to address the requirements of particular species or to maintain habitats).	
V	Area where the interaction of people and nature over time has produced an area with some distinct character with significant ecological, biological, cultural or scenic value, and where safeguarding the integrity of this interaction is vital to protecting and sustaining the area and its associated values.	Fishing may occur legally, subject to other controls
VI	Generally large areas, mostly in a natural condition, where a proportion is under low-level sustainable natural resource management (i.e. multiple use MPA) and where such use of natural resources is compatible with conserving ecosystems and habitats, together with associated cultural values and traditional natural resource management systems.	
MMA	Marine-managed area: an area or ocean, or a combination of land and ocean, where human activities are managed and all elements – biophysical, human and institutional – of the system are considered together but conservation is not the primary purpose.	
EEZ	Exclusive economic zone: area prescribed by the UN Convention for the Law of the Sea (UNCLOS) over which a state party / country has special rights regarding the exploration and use of its marine resources, out to 200 nautical miles from its coast.	
ABNJ	Areas beyond national jurisdiction are defined by UNCLOS as the water column beyond the EEZ, or beyond the Territorial Sea where no EEZ has been declared (aka the High Seas); plus the seabed which lies beyond the limits of the continental shelf.	

1.2 APPLYING THE DESIGN PRINCIPLES: SYSTEMATIC PLANNING AND DEALING WITH UNCERTAINTY

Systematic spatial planning refers to a multi-step process that often includes the application of design principles, use of decision-support tools, stakeholder consultation, strategies to incorporate uncertainty and adaptive management systems (e.g. Cabral et al., 2015). Biophysical and socio-economic, cultural and management feasibility design principles can guide the placement and extent of no-take and other types of MPAs (Fernandes et al., 2012). Decision support tools can be used to help identify sites that achieve pre-specified design principles. Systematic MPA design can be supported by algorithm-based decision support tools such as Marxan, Marzone or Marine Map; however, users need to be aware of the drawbacks associated with such analytical planning tools (e.g. Day, 2016).

Uncertainty is a pervasive problem in marine resource management both inshore and offshore, because many areas are still data-poor. Observed patterns are often governed by multiple interacting factors at various spatial and temporal scales, many of which are poorly understood. Modelling can reflect this element of uncertainty, and take it into account during the planning of MPAs and MPA networks. For example, areas in which certain features or species are likely to occur can be predicted by the modelling of suitable habitats (PAME, 2015), and models of population connectivity can assist with MPA placement (Treml and Halpin, 2012). Alternatively, surrogates (for example, physical environmental information) can be used to infer patterns in biodiversity, particularly if used in marine spatial planning (Mellin et al., 2011; Reygondeau et al., 2012). Another way in which the limited information and uncertainty is acknowledged and accounted for is with an adaptive management approach. If MPAs and MPA networks have explicitly stated and achievable objectives, these can be broken down into targets that can inform the planning stages from design through to ongoing management and monitoring. As ecological, cultural and socio-economic conditions change, an adaptive approach involves an iterative cycle of planning, management, monitoring, reporting, and the provision for any change deemed necessary to continue to achieve the goals (e.g. Dunn et al., in press). This is becoming especially important, as climate change is leading to changes in species' distributions and changes to the regime of threats with which organisms are living (Wassmann et al., 2011).

Offshore systematic spatial planning has the same framework as in coastal ecosystems, but with larger areas, higher uncertainty, and sometimes international collaboration (O'Leary et al., 2012). Decision support tools such as Marxan may not work in this context, due to a lack of comprehensive or reliable data or computational limitations. Following a set of robust design principles that inherently addresses uncertainty is especially important in such circumstances (Fernandes et al., 2012). Sites for MPAs, for example, may need to be selected based on fragmented knowledge, or scientific inference based on similar sites (O'Leary et al., 2012). MPA network design principles can, for example, be constructed to hardwire the fact of the limited information and uncertainty by ensuring principles, such as those regarding repetition, minimum sizes and percentage protection, are robust to potential knowledge failures (Langford et al., 2009) Further, to achieve most marine resource management goals in data-poor systems, it is prudent to be more reliant on the precautionary principle, where the burden of proof is shifted towards protection first, followed by the proof of no environmental damage by human activities (Clark, 1996; Hooker et al., 2011).

The adaptive management cycle allows for flexibility and responsiveness to new and improved information where there is less certainty during the site selection and MPA design process. Monitoring may rely more heavily on proxies, since data collection in the open ocean can be difficult and expensive. Monitoring populations of wide-ranging species in offshore MPAs will require a combination of technologies, such as satellite technology, drifting baited stereo-videography, spotter planes, drones, horizontal acoustics and boat-based sampling (Bouchet and Meeuwig, 2015; Letessier et al., 2017). Physical and chemical data can be easier to obtain, and can be a good indicator for the distribution of some open ocean species (Reygondeau et al., 2012). The tracking of migratory or wide-ranging animals has also proven useful for identifying areas to protect (Lascelles et al., 2016; Thaxter et al., 2012), especially for species that can form aggregations (Maxwell et al., 2011).

The following section describes, in detail, the existing biophysical design principles as they currently apply to coastal seas.

2 DESIGN PRINCIPLES FOR COASTAL MPAS AND THEIR APPLICATION TO OPEN OCEAN

In coastal areas, biophysical design principles for MPAs and MPA networks have been developed based on knowledge about coastal habitats and species, while allowing for a degree of uncertainty to acknowledge the information gaps (Ballantine, 2014; Botsford et al., 2003; Fernandes et al., 2005). Using bioregions, biophysical features or habitats as surrogates during spatial planning allows for MPAs to capture as close to 100% of the diversity of ocean life despite imperfect knowledge and much less than 100% MPA coverage (Bridge et al., 2015).

BOX 1. Summary of biophysical design principles currently in use for coastal MPAs and MPA networks.

SUMMARY OF BIOPHYSICAL DESIGN PRINCIPLES

1. Represent at least 20–30% of bioregions in no-take MPAs.
2. Represent at least 10–30% of each known habitat type.
3. Represent whole features / habitats, wherever possible.
4. Have at least three replicate no-take MPAs within bioregions and include at least one example of each habitat or feature.
5. Ensure that no-take MPAs include critical habitats and biologically or physically special or unique sites.
6. Make no-take MPAs larger rather than smaller.
7. Use simple MPA shapes that maximize area to edge ratios.
8. Maximise connectivity between no-take MPAs in an MPA network.
9. Choose permanent over temporary protection.
10. Reduce or eliminate threats across the area that the entire no-take MPA network lies within by applying other types of Marine Protected Areas or spatial management areas throughout it.

PRINCIPLE 1: REPRESENT ALL BIOREGIONS

A network of MPAs should include representative examples of each bioregion within no-take MPAs: Overall, at least 20–30% of each bioregion should be included in no-take MPAs (Day et al., 2012; Fernandes et al., 2012; Green et al., 2013). The percentage should be at the higher end of the range in areas experiencing less management of activities outside the no-take MPA, or subject to more destructive activities.

This principle helps ensure that adequate examples of all species and populations of species are protected (Gilman et al., 2011). Protecting a reasonably large proportion of bioregions within no-take MPAs helps to manage for the uncertainty associated with habitat heterogeneity, and reduces the risk of overexploitation of marine populations in areas that remain open to extraction (Ballantine, 2014; Botsford et al., 2003; Day et al., 2012; Fernandes et al., 2012; Gaines et al., 2010; Green et al., 2013; Wilson et al., 2011).

PRINCIPLE 2: REPRESENT ALL HABITATS

A network of no-take MPAs should include representation of every known habitat type. This ensures that as many species as possible are protected (Day et al., 2012; Fernandes et al., 2012; Gilman et al., 2011). This requires the identification of habitats to be protected, and the specification of "minimum amounts" of protection per habitat (see, for example, Great Barrier Reef Marine Park Authority, 2002). This percentage may be higher in areas with less management of activities outside the no-take MPA, or subject to more destructive activities.

PRINCIPLE 3: REPRESENT WHOLE FEATURES

Individual habitats and features tend to function as complete entities and have a level of ecological integrity. The functioning of a habitat or feature depends on linked processes that may occur in different areas, but are connected across the entire habitat or feature. Using a coral reef example, primary production and nutrient cycling on coral reefs are often highest in the high-energy environment of the reef crest (Long et al., 2013), and are distributed to other parts of the reef (e.g. the back reef, reef flat and deeper parts of the slope). Sheltered areas of the reef may experience less damage from storms and provide larvae for the re-seeding of exposed, more readily damaged parts (Shedrawi et al., 2017). Also, "splitting" a habitat or feature and protecting only part of it means that human impacts would still be affecting ecological communities adjacent to the no-take MPA, subjecting it to potential flow-on or indirect effects such as changes in the behaviour of larger species. It is therefore important to represent entire habitats or features within the same level of protection and avoid split zoning (Day et al., 2012; Fernandes et al., 2012).

PRINCIPLE 4: REPLICATE PROTECTION OF A BIOREGION AND/OR HABITAT AT LEAST THREE TIMES

Ideally, each habitat or process should be represented at least three times within an MPA network (ANZECC, 1996; Great Barrier Reef Marine Park Authority, 2002). If there are several spatially separated examples of the features selected for protection (e.g. sites important for a population of a threatened species, patches of similar habitat, breeding sites), this reduces the risk of losing the entire feature(s) of interest to disturbance, poaching or even random temporal variability (e.g. recruitment failure, cyclones) (Gilman et al., 2011). Most destructive events are spatially patchy, allowing some areas or individuals to escape damage and provide a source of regeneration for damaged areas or depleted populations (Salm et al., 2006). In the face of climate change especially, replication across environmental gradients increases the probability of survival, regeneration or even adaptation of community assemblages and the species within them.. Furthermore, representation of latitudinal or longitudinal gradients is important for capturing the range of habitat types and species compositions (Ministry of Fisheries and Department of Conservation, 2008), which are not usually organised into discrete areas, but blend into each other along such gradients.

PRINCIPLE 5: INCLUDE SPECIAL, UNIQUE OR RARE FEATURES AND/OR SPECIES

In addition to representing examples of each habitat, sites may be selected for inclusion within an MPA according to criteria such as uniqueness, rarity or special characteristics such as importance for particular life stages of species, importance for threatened, endangered or declining species or habitats, biological productivity or diversity (Brock et al., 2012; Salomon et al., 2006; Secretariat of the Convention on Biological Diversity, 2014). Frameworks for identifying such areas have been developed in the form of Ecologically and Biologically Significant Areas (EBSAs) (e.g. CBD, 2009) and Key Biodiversity Areas (IUCN, 2016). Furthermore, all countries signed up to the Convention of Biological Diversity are required to develop a National Biodiversity Strategies and Action Plan (NBSAP), which list areas of interest for protection. Such special, unique or critical sites can be assessed based upon the amount, detail and nature of the justification for their selection (Fernandes et al., 2010).

Sites may be unique, rare or special due to habitat types, oceanographic or geological features, or species occurring there. For example, a site may be unique because there is a single population occurring there that is not found anywhere else. Special characteristics can be attributed to keystone species or sites where key processes take place (e.g. spawning and feeding grounds, nurseries, migratory corridors, hotspots, etc.). Sites can also be selected on the basis of hosting higher productivity than the surrounding areas; these 'hotspots' can support high biodiversity, which is often also used as a criterion for selecting sites for inclusion into MPAs or MPA networks (Briscoe et al., 2016; Possingham and Wilson, 2005; Sydeman et al., 2006). Areas that host a large variety of species are important for the maintenance of resilience, evolutionary potential and ecosystem services (Worm et al., 2006).

The existence of natural disturbance regimes is a component of ecosystems that should also be considered in MPA design (Harris, 2014). Resistance and resilience to disturbance, or the ability to either absorb disturbance without change or to return to pre-disturbance conditions, are becoming more important as large-scale environmental impacts become more pervasive (Game et al., 2008; Palumbi et al., 2008). Identification of such areas can be difficult in data-poor systems, because ascertaining these qualities typically requires an understanding of temporal dynamics in space. However, where they have been identified, they should be included within an MPA.

The value of unique and/or special features or areas stems from the fact that they are not usually replicated elsewhere and therefore not replaceable (Salomon et al., 2006). Their loss usually results in a reduction in overall biodiversity or abundance of important species (Halpern et al., 2007; Palumbi et al., 2008). Uniqueness, rarity and special characteristics can be assessed at the level of genes, populations, species, habitat types, special biological function or process, or the presence of threatened species and habitats (Jessen et al., 2011).

For special and/or unique sites or features that may be subject to particular stressors, it is important to understand the spatial distribution of potential stressors or impacts (Brock et al., 2012; Halpern et al., 2007). Any destructive activities taking place within the area should be prohibited (see also Principle 10).

PRINCIPLE 6: MAKE MPAS LARGER RATHER THAN SMALLER

Size is one of the most important design considerations when implementing MPAs (Gilman et al., 2011; Halpern, 2003). For nearshore areas, as a general rule, 20 km should be considered the minimum distance across a no-take area to ensure the integrity of the habitat (Fernandes et al., 2009; McLeod et al., 2008). Although generally the ethos of "bigger is better" applies (Edgar et al., 2014), very small permanent no-take MPAs are also effective in certain circumstances, especially when designed for the replenishment of fisheries target species, through 'spillover', in coastal environments (Fernandes et al., 2012; Harrison et al., 2012; Jones et al., 2007; Russ, 2002). Coastal and sedentary species can benefit from smaller MPAs, but larger, more mobile and migratory species require larger MPAs.

Larger areas hold larger parts of (or entire) populations, and have a greater chance of including the recommended 30% of representative bioregions or features of interest and of having a degree of biological integrity. By this, it is meant that larger areas are more likely to be self-sustaining and therefore will persist over time (Gaines et al., 2010). Larger MPAs also reduce the edge effect, where human activities at the edges of an MPA, including illegal entry and take within boundaries, can be intensive enough to undermine the MPA's overall effectiveness (Lester et al., 2009).

The movement distance of marine organisms poses one of the greatest challenges to MPAs (See also Principle 8). The dispersive larval stage and sometimes far-ranging movements or migrations of juveniles or adults mean that it is not possible for individual MPAs to protect all life history stages of any one species, let alone all species (Gruss et al., 2011). However, recent research has provided design guidelines for no-take MPAs based on known home ranges of species of interest. For instance, a no-take MPA designed to protect coral reef invertebrates and site-attached fishes could be as small as 400m to 1000m across, while an MPA of more than 20 km would be required for pelagic species such as silvertip sharks or trevallies (Fernandes et al 2012, Green et al., 2014). The mobility of the pelagic component relative to the size of the MPA and the home range sizes of organisms within the MPA should also be considered during MPA design (Grober-Dunsmore et al., 2008).

PRINCIPLE 7: MAKE MPAS SIMPLE SHAPES AND MAXIMISE THE AREA TO BOUNDARY RATIO

The boundaries of an MPA need to be determined according to the extent and location of the species, features, bioregions and ecological processes they are intended to protect. Edges of MPAs can be subject to intense fishing pressure and fishing incursions, and therefore offer a weaker degree of refuge than the core interior of protected areas (Halpern, 2003; Halpern and Warner, 2003). Recent interest in using marine reserves for marine resource management and conservation has largely been driven by the hope that reserves might counteract declines in fish populations and protect the biodiversity of the seas. However, the creation of reserves has led to dissension from some interested groups, such as fishermen, who fear that reserves will do more harm than good. These perceived differences in the effect of marine reserves on various stakeholder interests has led to a contentious debate over their merit.

We argue here that recent findings in marine ecology suggest that this debate is largely unnecessary, and that a single general design of a network of reserves of moderate size and variable spacing can meet the needs and goals of most stakeholders interested in marine resources. Given the high fecundity of most marine organisms and recent evidence for limited distance of larval dispersal, it is likely that reserves can both maintain their own biodiversity and service nearby non-reserve areas. In particular, spillover of larger organisms and dispersal of larvae to areas outside reserves can lead to reserves sustaining or even increasing local fisheries.

Ultimately, the success of any reserve network requires attention to the uncertainty and variability in dispersal patterns of marine organisms, clear statements of goals by all stakeholder groups and proper evaluation of reserve performance. Therefore, the ideal MPA shape minimises the edge effect by maximising the protected area to boundary ratio (Roberts et al., 2010; Rodríguez-Rodríguez et al., 2016). Squares or circles are considered to be the most favourable shapes to protect biodiversity, although the former would be preferable from a compliance point of view (Fernandes et al., 2012; White et al., 2012). Also from a compliance point of view, the boundaries of no-take MPAs are best placed according to landmarks, or using simple coordinates.

PRINCIPLE 8: SPACE MPAS TO MAXIMISE CONNECTIVITY BETWEEN THEM

In a functioning marine ecosystem, populations or patches of similar habitat that are geographically separate are linked through the movement of organic and inorganic matter and larvae, juveniles and adults (Brock et al., 2012; Cowen et al., 2007; Worboys et al., 2016). Larval connectivity within an MPA network can occur between MPAs that are from 1 to 200 km apart, depending on the species, with inshore species being connected over smaller scales than offshore species (Gilman et al., 2011; Green et al., 2014; Harrison et al., 2012; Jones et al., 2007; Shanks, 2009)Connectivity within a network of MPAs is also important because it ensures that if a population vanishes or a habitat is damaged in one MPA, it can be restored through the movement of larvae or adults from another MPA, or an undamaged habitat (Jones et al., 2007). From a genetic standpoint, connectivity ensures genetic diversity within populations, which ensures population persistence and evolutionary potential (Jones et al., 2007).

Genetic connectivity (genetic exchange among individuals within and between populations) depends on the absolute number of dispersers among populations, whereas demographic connectivity (exchange of individuals between spatially separate populations) depends on the relative contributions to population growth rates of dispersal vs. local recruitment (i.e. survival and reproduction of residents) (Lowe and Allendorf, 2010). Demographic connectivity, which influences recruitment levels, occurs over smaller scales than genetic connectivity.

Movement occurs either passively with currents or actively, through active dispersal, movement and migration. Within networks of MPAs, movement ideally occurs between protected areas (Roberts et al., 2010), and also between protected and unprotected areas (Gaines et al., 2010). Depending on dispersal strategy, release point, larval duration and motility, the direction and strength of currents, dispersal distance can range from a few metres to a few km to more than 150 km, even for some coastal species (Harrison et al., 2012; Jonsson et al., 2016; Shanks, 2009; Shanks et al., 2003. Benefits to the broader marine ecosystem are expected from MPAs that are self-replenishing, interconnected and/or important source areas for larvae (Krueck et al., 2017). The movement of larvae, juveniles and adults across MPA boundaries can be seen as negative because it implies a lower level of protection for individuals that move into areas where they can be exploited (e.g. Gruss et al., 2011). However, this “spillover” restores populations and target species and therefore benefit fisheries and the broader ecosystem alike (Gell and Roberts, 2002; Harrison et al., 2012).

Larval connectivity research on coastal coral reefs suggests that 50% of larvae originating from a population are likely to settle within 33 km of the origin, and 95% within 83 km, with a mean larval dispersal distance of 36.5 km (Abesamis et al., 2017). Similar research elsewhere concluded that 30% of larvae remained within 1–2km of their origin, with average dispersal distances of between 6 and 9 km (Harrison et al., 2012).

The spacing and positioning of MPAs within a network needs to take into account seasonal and net current speeds and direction, the presence of eddies and upwellings or downwellings, and the larval duration and swimming speeds, the migration pathways of important species and also the location of adjacent existing MPAs or even terrestrial protected areas (Jones et al., 2007; Shanks et al., 2003). Spacing also needs to take into account the local retention of larvae, and findings that suggest that dispersal distances may generally be lower than previously thought (Shanks, 2009) providing information on 67 species. PD and dispersal distance are correlated, but with many exceptions. The distribution of dispersal distances was bimodal. Many species with PDs longer than 1 day dispersed less than 1 km, while others dispersed tens to hundreds of kilometers. Organisms with short dispersal distances were pelagic briefly or remained close to the bottom while pelagic. Null models of passively dispersing propagules adequately predict dispersal distance for organisms with short PDs (<1 day.

PRINCIPLE 9: CHOOSE PERMANENT PROTECTION OVER TEMPORARY PROTECTION

The duration of no-take protection depends on the objectives of the MPA, but for biodiversity conservation objectives, permanent protection is recommended (Dudley, 2008), as it has been shown a number of times that the benefits of MPAs increase measurably with MPA age (Edgar et al., 2014).

While seasonal, rotational or temporary closures may be beneficial for no-take areas designed for fisheries benefits (Cinner, 2005; Kaplan et al., 2010; Sadovy et al., 2011) those benefits are quickly eroded upon opening the area to fishing (Friedlander and DeMartini, 2002; Russell et al., 1998). In addition, permanent protection provides time for the entire marine community to recover from human impacts as well as ensuring permanent benefits from “spillover” effects to be realised (IUCN-WCPA, 2008). Depending on the life cycle of protected species, it can take many years for populations to recover from exploitation (Russ, 2002); the re-establishment of balance and stability within a whole ecosystem, such as a coral reef, can take ten years or more (Johns et al., 2014).

PRINCIPLE 10: ONLY APPLY OTHER MPA CATEGORIES THAT ALLOW FOR EXTRACTIVE ACTIVITIES, ONCE 20–30% OF BIOREGIONS/HABITATS ARE ADEQUATELY PROTECTED IN NO-TAKE MPAS

MPA networks that include areas managed for different purposes or uses, beyond no-take zones, allow for existing human uses and cultural values of the seascape, and aim to integrate conservation with sustainable use (Day et al., 2012, Table 2). MPA guidelines therefore usually consider socioeconomic and cultural values and pressures as well as biophysical values (Agostini et al., 2010; Fernandes et al., 2009; Jessen et al., 2011), but this is beyond the scope of this report.

When designing other categories of MPAs, understanding the spatial distribution of potential stressors or impacts can provide additional guidance for the placement and design of MPAs and MPA networks (Halpern et al., 2007). The severity of the stressors may also inform the percentage of area to be included within MPAs of all categories, including no-take. This should include an understanding of cumulative impacts, which relies on the availability of both spatial and temporal data. This can also help to assess the potential threats to future and existing MPAs, as well as the threats to unprotected areas. Any destructive activities taking place within the area should be prohibited (Fernandes et al., 2012); ultimately, compliance with MPA regulations will be the most important contributor to MPA success (Arias et al., 2016; Edgar et al., 2014).

TABLE 2. Matrix of activities that may be appropriate for each IUCN category of MPA. N: No; N*: Generally no, unless special circumstances apply; Y: Yes; Y*: Yes because no alternative is possible, but special approval is essential; *: Variable, depends on whether this activity can be managed in such a way that it is compatible with the MPA's objectives. From Day et al. (2012).[1]

Activities	Ia	Ib	II	III	IV	V	VI
Research, non-extractive	Y*	Y	Y	Y	Y	Y	Y
Non-extractive traditional use	Y*	Y	Y	Y	Y	Y	Y
Restoration/enhancement for conservation (e.g. invasive species control, coral reintroduction)	Y*	*	Y	Y	Y	Y	Y
Traditional fishing/collecting according to cultural tradition and use	N	Y*	Y	Y	Y	Y	Y
Non-extractive recreation (e.g. diving)	N	*	Y	Y	Y	Y	Y
Large scale low intensity tourism	N	N	Y	Y	Y	Y	Y
Shipping (except as may be avoidable under international maritime law)	N	N	Y*	Y*	Y	Y	Y
Problem wildlife management (e.g. shark control program)	N	N	Y*	Y*	Y*	Y	Y
Research: extractive	N*	N*	N*	N*	Y	Y	Y
Renewable energy generation	N	N	N	N	Y	Y	Y
Restoration/enhancement for other reasons (e.g. beach replenishment, fish aggregation, artificial reefs)	N	N	N*	N*	Y	Y	Y
Fishing / collecting: recreational and/or subsistence	N	N	N	N	*	Y	Y
Fishing / collecting: long term sustainable local fishing practices	N	N	N	N	*	Y	Y
Aquaculture	N	N	N	N	*	Y	Y
Works (e.g. harbours, ports, dredging)	N	N	N	N	*	Y	Y
Untreated waste discharge	N	N	N	N	N	Y	Y
Mining (seafloor as well as sub-seafloor)	N	N	N	N	N	Y*	Y*
Habitation	N	N*	N*	N*	N*	Y	N*

Guides for identifying candidate areas for MPA placement have been developed specifically for individual offshore regions, such as Australia's extensive South-east Marine Region (Commonwealth of Australia, 2003). However, general and comprehensive MPA network design principles or guidelines for offshore ecosystems have yet to be formulated. There is a need to do this in a way that takes into account relevant information about open ocean habitats and species, about which there is increasing information, that can help determine attributes such as size, percentages, replication, location, shape, and so forth, to enhance the likelihood that offshore MPAs and MPA networks will deliver a positive ecological response in the ecosystem. The next section reviews relevant and current knowledge about offshore ecosystems, so that they may feed into Section 4 of the report, the development of biophysical design principles for offshore MPAs and MPA networks.

[1] This matrix is likely to change, because the 2012 guidelines about applying the IUCN categories in MPAs are currently being updated following a January 2018 workshop.

3 CHARACTERISTICS OF OFFSHORE HABITATS AND SPECIES

The authors have previously conducted a review of available literature describing the habitats, species, processes and connectivity associated with deep-water or open ocean environments (Ceccarelli and Fernandes, 2017). This section summarises that work.

3.1 OPEN OCEAN HABITATS

Open ocean habitats differ from coastal habitats in a variety of ways; most obviously, habitats and habitat features are organised at larger spatial scales. The extent and boundaries of biogeographic regions vary significantly by depth, and may or may not overlap with other regions in bathymetric layers above or below them (Ban et al., 2014). Habitat types range from highly ephemeral (e.g. surface frontal systems) to hyper-stable (e.g. the deep sea) (Ban et al., 2014), with a gradient that includes seasonal or recurring patterns. Connectivity across habitats occurs on a larger scale as well, most notably through highly mobile species, of which some individuals can travel 1,000s of km.

Connectivity also occurs vertically, through deep-diving species, marine snow, and the multitude of deep-dwelling pelagic species that undertake vertical migrations. Benthic-pelagic coupling can occur at several scales and in both directions; for instance, pelagic species that use seamounts also contribute to the benthic and demersal ecology of seamounts (Grober-Dunsmore et al., 2008).

Offshore habitats are organised across a much wider depth range than those over continental shelves, with five recognised broad bathymetric layers, each comprising a pelagic habitat and, where bathymetry allows, a benthic component (Figure 1). Offshore waters offer a variety of dynamic and stable habitats and processes; water masses may move through an offshore area, but some dynamic (e.g. upwelling zone, etc.) and benthic habitat components are spatially fixed.

1. **Photic zone.** From the ocean surface, down to a depth of 200m, planktonic primary producers receive enough light for photosynthesis and thus form the basis of pelagic food webs. Benthic habitats within this zone are dominated by organisms that rely on photosynthesis, such as algae and corals, and those they interact with.
2. **Mesophotic zone.** From 200m to 1,000m, primary production is replaced by sinking organic matter (marine snow), including plankton, as the primary food source for benthic and pelagic species. Consumers either scavenge marine snow or sinking carcasses, or prey on each other. There is still enough light for organisms to distinguish cycles of night and day, and the main thermocline occurs here (Sutton et al., 2008, 2017).

   Vertical connectivity between the photic and mesophotic zones is bidirectional, meaning that many species, including those of commercial value and conservation interest, that frequent the photic zone (manta rays, sharks, toothed whales, tunas), regularly dive to the mesophotic zone to feed. Concurrently, mesopelagic assemblages undertake vertical migrations to feed at the surface at night (Howey et al., 2016; Jaine et al., 2014; Papastamatiou et al., 2015; Perez et al., 2017; Rodríguez-Cabello et al., 2016). Benthic assemblages in the mesophotic zone can be highly diverse and provide resources for benthic, demersal and pelagic species from zones above and below, driving vertical connectivity.
3. **Bathyal zone.** From 1,000m to 4,000m there is no sunlight penetration, and conditions in any one location are relatively stable and uniform (Baker et al., 2007). Hydrostatic pressure continues to increase with depth. Organisms are adapted to the pressure and darkness, and pelagic diversity can be very high and include taxa such as fish (e.g. anglerfish, hatchetfish and dragonfish), crustaceans, mollusks and jellies (Davoren, 2013). The primary food source in this layer, and those below, is organic matter sinking downwards from the upper layers, often termed "marine snow" (Bochdansky et al., 2017). Benthic communities tend to be sparse and assemblages are structured according to the availability of hard substrata and chemosynthetic sources such as hydrothermal vents.
4. **Abyssal zone.** From 4,000m to 6,000m is an area of immense pressure and very low temperatures. The zone is primarily inhabited by decapods (such as deep-water swimming crabs and squat lobsters) and, in the deepest waters, by mysid shrimp. Hydrothermal vents can be found on the seafloor in this zone. Benthic communities in this zone tend

to be sparse and concentrated around fallen whale carcasses and other food sources, vents and seeps, polymetallic nodules, seamount slopes and a large variety of other biogenic and topographic features (Smith et al., 2008).

5. **Hadal zone**. This habitat occurs in ocean trenches and troughs, below 6,000m, to a maximum depth of ~11,000m in the deepest parts of the ocean such as in the Marianas and Tonga Trenches. Jellyfish and viperfish are typical pelagic organisms, and benthic habitats can support patchy but rich assemblages. The seafloor tends to be covered in fine mud. Benthic communities in this zone, as with other ocean zones, tend to be concentrated around fallen carcasses of large marine animals, vents and seeps, the sides of trenches and other topographic features.

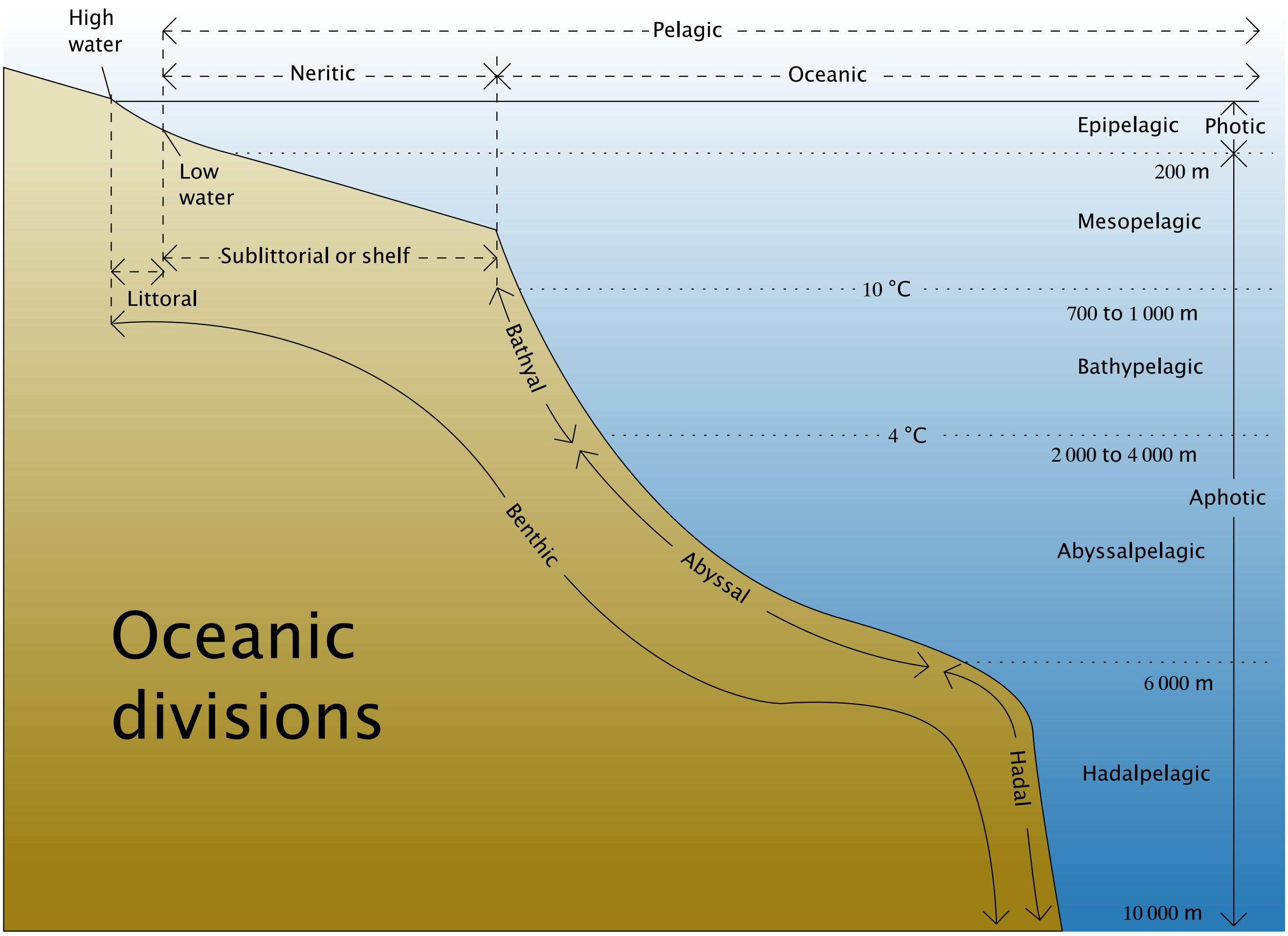


FIGURE 1. Bathymetry layers for pelagic and benthic habitats. From https://en.wikipedia.org/wiki/Oceanic_zone.

3.2 PELAGIC AND DEEP-SEA SPECIES

Pelagic species are often widely distributed (Read et al., 2013), and individuals of larger species at higher trophic levels are often wide-ranging or migratory (Ban et al., 2014). However, the bulk of pelagic biodiversity and abundance is made up of innumerable smaller pelagic species (plankton, micronekton and nekton) with relatively sedentary lifestyles and vertical, rather than horizontal, movement patterns (Afonso et al., 2014). In fact, it is estimated that the biomass of small deep-dwelling pelagic fishes (e.g. lanternfishes, ridgeheads, lightfishes) may be two to three orders of magnitude greater than the total global fisheries landings, which target higher-order predators such as tuna (Sutton et al., 2008). Broad diversity patterns of planktonic, nektonic and higher-order pelagic organisms tends to overlap, peaking at latitudes between 20 and 30° N or S (Trebilco et al., 2011). Diversity and biomass also vary vertically, and vertical connectivity occurs through most bathymetric layers (Sutton, 2013).

Communities of zooplankton and micronekton are fuelled either by phytoplankton at the surface or marine snow at depth and, in turn, sustain a food web of larger species that culminate in pelagic apex predators such as tunas, billfish, seabirds and sharks (Bochdansky et al., 2017; Herring, 2002; Howey et al., 2016; Verity et al., 2002). It is these species that are often the focus of conservation concerns as they:

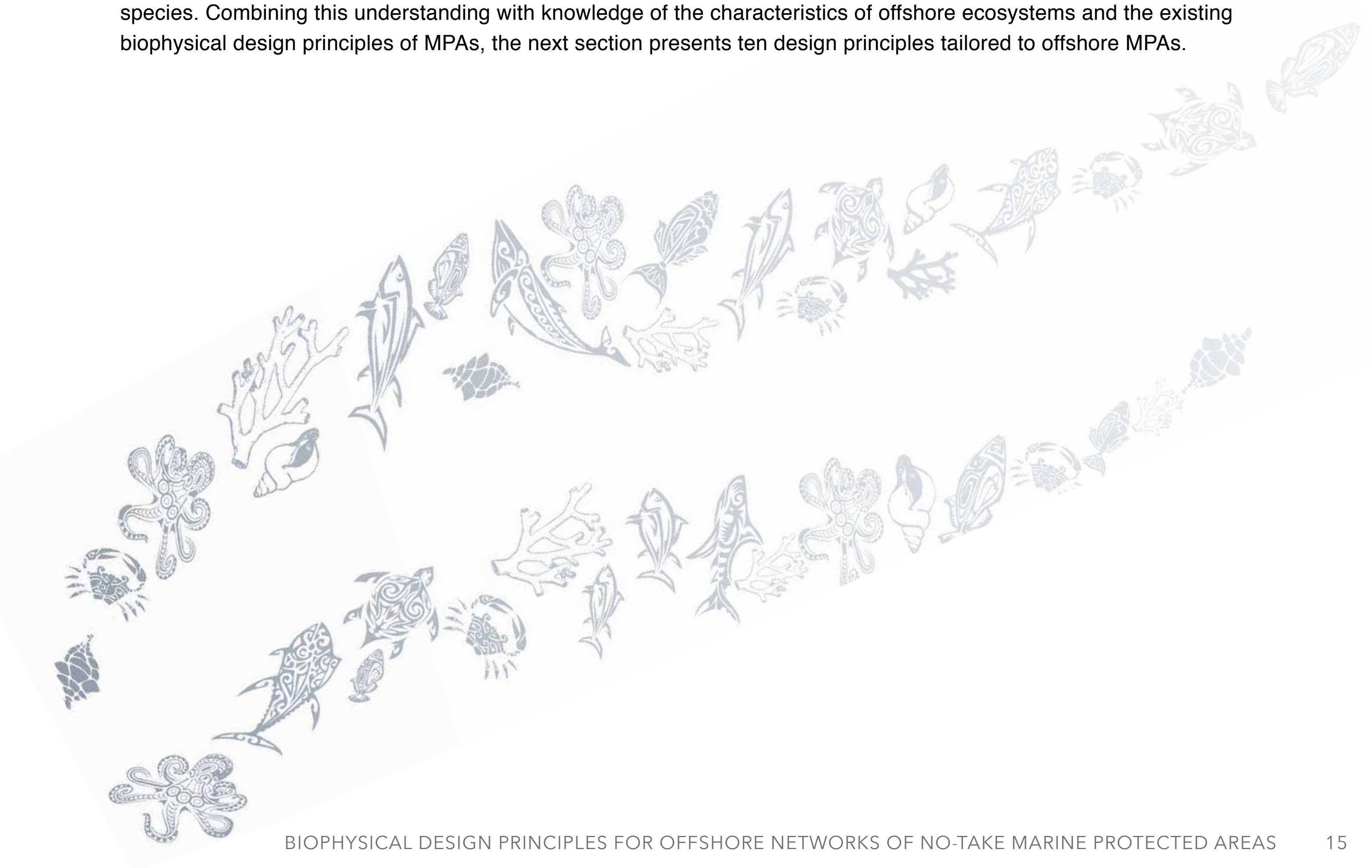
1. are often the target or bycatch of large-scale fisheries,
2. have disproportionate effects on marine communities by virtue of being high in the food web (Hobday et al., 2017; Ortuño Crespo and Dunn, 2017), or
3. are rare and / or threatened (Collette et al., 2011; Verity et al., 2002). In practical terms, larger species can act as “umbrella” species; protecting them can, by default, protect a wide suite of other species and their habitats (Trebilco et al., 2011). Larger species also contribute to connectivity between habitats and bioregions at scales of 100s to 1,000s of km (Block et al., 2011).

Benthic communities in the deep sea are either sparsely distributed over wide expanses of seafloor, or aggregated around sources of food (e.g. sunken whale carcasses, hydrothermal vents) or topographic features (e.g. seamounts, canyons). Near-surface seamounts, ridges and open ocean reefs and islands provide a direct link between the upper layers and deep-sea habitats, influencing the diversity, density and behaviour of benthic and pelagic organisms (Sutton et al., 2008).

3.3 PRESSURES AND THREATS

The anthropogenic pressures faced by the open ocean mirror those of coastal marine areas, but there is particular concern over the impact of industrial-scale fishing (including purse seine and long-line fishing) and activities such as deep sea mining and bottom trawling that damage seabeds (Huvenne et al., 2016; Merrie et al., 2014; OSCA, 2016). Habitat destruction, overfishing of target species and a high amount of bycatch are common problems resulting from these fishing practices (Boerder et al., 2017; Ortuño Crespo and Dunn, 2017; Partridge, 2009). A comprehensive summary is not within the scope of this report; pressures and threats to ocean ecosystems are reviewed in Harris (2012) and the UN Wold Ocean Assessment (Inniss et al., 2016). They highlight shifts and collapses, bycatch of vulnerable long-lived species such as albatrosses, leatherback and loggerhead sea turtles, sharks and marine mammals, and destruction of benthic habitats by bottom dragging gear (Gjerde, 2007; Ortuño Crespo and Dunn, 2017). Deep-sea biogenic habitats tend to be highly vulnerable to extractive human activities due to the slow growth rates and extreme longevity of many of their constituent species (Huvenne et al., 2016; Roberts, 2002).

Understanding the location, extent and specific nature of threats to pelagic and deep-sea environments is important when designing offshore MPAs. Prohibiting destructive activities is important due to the fragility of many deep-sea habitats, the long-lived, slow-growing, late-reproducing and low fecundity nature of many deep-dwelling and large pelagic species. Combining this understanding with knowledge of the characteristics of offshore ecosystems and the existing biophysical design principles of MPAs, the next section presents ten design principles tailored to offshore MPAs.



4 BIOPHYSICAL PRINCIPLES FOR DESIGNING NETWORKS OF OFFSHORE, NO-TAKE MARINE PROTECTED AREAS

Biophysical design principles for MPAs should apply offshore just as they do to coastal waters, and the MPAs should have defined boundaries that can be mapped, recognition by legal or other effective means, and distinct and unambiguous management objectives (Day et al., 2012). However, details of biophysical MPA design are likely to differ for open ocean areas compared to coastal areas, due to the different environmental aspects and pressures. This is discussed further below, and within the presentation of each principle.

Species ranges, the structure of communities and the scale over which ecological processes occur all vary between inshore, nearshore and offshore habitats (Syms and Kingsford, 2008), affecting the principles of, for example, MPA size (Honda et al., 2017). Here, we define inshore habitats as those extending from the coast to the edge of the shallowest adjacent marine habitats (e.g. the edge of the reef in the case of reef habitats). Ecological assemblages are subject to tidal fluctuations (sometimes to the extent of full exposure to air), large temperature fluctuations, the influence of land-based activities (run-off, pollution), wind-driven turbidity and wave energy changes and easy access for human exploitation of resources (Gruber et al., 2017). The environment can be harsh and often results in assemblages uniquely adapted to withstand these fluctuations, with relatively sedentary lifestyles and infrequent visits from wide-ranging predators.

Nearshore areas are those between the edge of shallow habitats where the seabed begins to slope down, and the edge of the shelf of continents or islands, or the 'shelf break'; often a significant change in habitat-forming benthos occurs at about 80m depth (Bridge et al., 2012; Brokovich et al., 2010; Slattery et al., 2011). This comprises what is generally considered "typical" marine habitats. It is relatively shallow, with slopes of varying steepness and structure which drive the assemblage composition and offers varying degrees of shelter (Darling et al., 2017) from environmental stresses that can severely damage shallow habitats (e.g. storm waves, heat anomalies) (Raymundo et al., 2017). In these shallower areas is a combination of species with site-attached lifestyles and those with larger home ranges, including large, highly mobile species that may occasionally feed in nearshore habitats (Green et al., 2014; Shanks, 2009) providing information on 67 species. Pelagic propagule duration (PD) and dispersal distance are correlated, but with many exceptions. The distribution of dispersal distances was bimodal. Many species with PDs longer than 1 day dispersed less than 1 km, while others dispersed tens to hundreds of kilometers. Organisms with short dispersal distances were pelagic briefly or remained close to the bottom while pelagic. Null models of passively dispersing propagules adequately predict dispersal distance for organisms with short PDs (<1 day).

Offshore habitats are beyond the shelf break, where coastal influences are much less. Oceanic assemblages prevail here, influenced by oceanographic and geomorphic features. Pelagic assemblages are typically oceanic (i.e. either widely distributed, specifically adapted to a fully pelagic lifestyle, associated with offshore geomorphic features, often having significant vertical movements and with some highly mobile or migratory individuals in some populations) (Kahng et al., 2010). Benthic assemblages are mostly aphotic (Kahng et al., 2010), unless associated with oceanic pinnacles rising directly from the deep sea to the surface, which support photic and mesophotic communities.

Much of our knowledge of species, especially offshore, is restricted to animals targeted by fisheries or of conservation concern; these are usually larger organisms which make up the minority of biodiversity in the open ocean. These organisms rely on physical habitat characteristics and on multitudes of smaller species about which knowledge is patchy at best.

Therefore, to ensure the long-term survival of these larger animals, significant examples of the system upon which they rely require protection; in addition, protecting significant portions of the ranges of these larger animals is also likely protect large tracts of the habitat of other species about which less is known. Ultimately, design principles that include representation of known habitats or bioregions, that have minimum requirements for replication, size and proportion of area covered can both using this existing knowledge and compensate for knowledge gaps.

PRINCIPLE 1: REPRESENT ALL BIOREGIONS

Represent at least 20–30% of offshore bioregions and offshore bioregional transition boundaries in no-take MPAs, within and outside the EEZs of maritime nations.

This principle is adapted directly from the literature, where it has been suggested MPAs should include representative examples of each bioregion within no-take protected areas (Box 1): Overall, at least 20–30% of each bioregion should be included in no-take MPAs (Day et al., 2012; Fernandes et al., 2012; Green et al., 2013).

This principle applies only to marine areas within which bioregions are described at a scale that is useful for management. This means, for example, where bioregions divide the area of interest into an adequate number of distinct areas for management purposes.

Biogeographic regions tend to be based on physical habitat variables that can often be measured only close to the surface or with seafloor features, but different spatial patterns exist at different depths, and biogeographies may or may not overlap vertically throughout bathymetric layers (Sayre et al., 2017; Sutton et al., 2017). At large scales, seafloor biogeographic provinces correspond to changes in oceanographic properties (Clark et al., 2011; Harris and Whiteway, 2011; Williams et al., 2010a). Boundaries and transition zones between biogeographic regions in the open ocean may be particularly productive, aggregating a high diversity and density of open ocean species (Block et al., 2011; Hyrenbach et al., 2000; Kanaji et al., 2017; Reygondeau et al., 2012).

At biogeographic scales, it is difficult to implement national representative networks of MPAs, because biogeographic regions are often very large in spatial extent, and do not describe biodiversity within national boundaries. To date, many bioregionalisations of offshore ecosystems are still too coarse, having been classified at the scales of ocean basins and often encompasses entire countries within one or two bioregions (Clark et al., 2011; O'Hara et al., 2011; Proud et al., 2017; Reygondeau et al., 2012; Sutton et al., 2017; UNESCO, 2009).

Therefore finer-scale marine bioregions should be described to support national planning processes (Etnoyer et al., 2004; Mannocci et al., 2015; Proud et al., 2017; Reygondeau et al., 2012). Recognising this, Wendt et al. (2018) have described marine bioregions for the SW Pacific at a scale useful for national management planning.

Because of the importance of both the centres of bioregions and the transition boundaries between them, the placement of no-take MPAs should encompass both areas within a bioregion and boundary or transitional areas between separate bioregions. The principle of representing 20–30% of each bioregion within no-take MPAs should apply both within and at the boundary of bioregions. Table 3 below summarises the two components of Principle 1.

TABLE 3. The two sub-principles of Principle 1.

Principle	Rationale	References
1a. Represent at least 20–30% of marine bioregions in no-take MPAs	Protection of all habitats, flora and fauna, ecosystem function, integrity and resilience requires that adequate examples of every bioregion are included in no-take areas. The best available science informs that at least 20–30% of each marine bioregion should be included in no-take areas, especially if aiming to protect species with lower reproductive output or delayed maturation (e.g. many large offshore and deep-water species), or in areas that host diverse, unassessed or poorly regulated fisheries, as is common offshore.	(Day et al., 2012; Fernandes et al., 2012; Worm et al., 2006)
1b. Represent at least 20–30% of marine bioregional transition boundaries in no-take MPAs	Boundaries and transition zones between bioregions in the open ocean tend to aggregate a high diversity and density of open ocean species. Bioregions in the open ocean are often much more extensive than in coastal marine habitats.	(Block et al., 2011; Clark et al., 2011; Hyrenbach et al., 2000; Kanaji et al., 2017; Reygondeau et al., 2012; UNESCO, 2009)

PRINCIPLE 2: REPRESENT ALL HABITATS

Represent at least 10–30% of each known habitat in no-take MPAs, with special considerations where bioregions are unknown.

This follows from established guidelines indicating that a network of no-take MPAs should include representation of every known habitat type, with a minimum representation for each (Box 1).

The open ocean, far from being featureless, has a multitude of static, recurring and ephemeral habitats, both benthic and pelagic, that can be mapped and used for spatial planning (Belkin et al., 2009; Harris et al., 2014; Hyrenbach et al., 2000; Miller and Christodoulou, 2014)2000; Miller and Christodoulou, 2014. These habitats may be identified by analysing the foraging distribution of higher predators (Hyrenbach et al., 2000), by making use of sophisticated real-time satellite imagery (Game et al., 2009), by using seabed geomorphology (Harris et al., 2014; Harris and Baker, 2012) or some combination of the above. In the context of spatial planning, lessons learned from general design principles can be applied to open ocean habitats defined in this way.

Given the data-poor status of most offshore habitats, and bioregions, if any, are not at a useful scale, (and therefore Principle 1 cannot be applied), research suggests that representing a higher level (35%) of each habitat feature in no-take MPAs enhances the likelihood of capturing unknown and therefore unmapped within-habitat variability, or even unknown features (Fernandes et al., 2012). Where there is some knowledge about bioregional boundaries (Principle 1), 10–30% of each habitat should be represented in no-take MPAs (Table 5).

Where a geomorphic feature (habitat) is known to be of special and/or unique value, the whole feature should be protected (Principle 3) and treated as a special and/or unique site (Principle 5). For example, seamounts are classed as habitats, but individual seamounts can be particularly important for aggregating pelagic assemblages, or hosting cold-water corals or endemic species (Morato et al., 2010; Richer de Forges et al., 2000); in this case individual seamounts would be treated not as habitats, but as special or unique features. In this sense, if the example of the feature listed in Table 5 is particularly special or unique in some way, it should be considered under Principle 5.

Table 4 below summarises the two sub-principles of Principle 2.

TABLE 4. Biophysical design principle for offshore MPAs relating to the representation of habitats.

Conditions	Principles	Rationale	References
2a. Defined bioregions: Principle 1 applies	Ensure that this includes a percentage of each habitat type or feature as indicated by Table 5 within no-take MPAs. Include adjacent habitats as buffer zones.	Mappable features of the open ocean include known areas of high productivity, diversity or significant ecological processes. To ensure future sustainability of offshore marine environments, examples of the full range of known and mapped biophysical habitats should be in no-take MPAs.	(Alpine and Hobday, 2007; Day et al., 2012; Fernandes et al., 2012; Hyrenbach et al., 2000; Sibert and Hampton, 2002)2000; Sibert and Hampton, 2002
2b. No bioregions defined	Include a percentage of each habitat type or feature as indicated by Table 5, plus 5%, within no-take MPAs. Include adjacent habitats as buffer zones.	When there is no definition of bioregional boundaries, there is often still at least an approximate understanding of habitats present. When Principle 1 cannot be applied, capturing a larger proportion of each habitat enhances the likelihood of capturing unknown and therefore unmapped with-in habitat variability.	(Great Barrier Reef Marine Park Authority, 2002)

TABLE 5. Major habitats of open ocean environments and suggested minimum proportions for inclusion in no-take MPAs. See Appendix 1 for definitions. Habitats adapted from Harris et al. (2014), definitions from Harris et al. (2014) and IHO (2008).

Habitat	Suggested minimum % for no-take MPAs
Shelf valleys	10%
Coral reefs (emerging from > 80m)	25%
Oceanic islands (emerging from > 80m)	25%
Basins (of various sizes, of seas and oceans, perched on the continental shelf, plateau or slope)	10%
Shelf, slope, abyssal and hadal sills	20%
Slope terraces	10%
Slope, abyssal and hadal escarpments	10%
Seamounts (of various types, rising from all depths)*	20% of each seamount type*
Canyons (shelf incising, connected to river systems)	10%
Canyons (shelf incising)	10%
Canyons (blind)	10%
Ridges	10%
Troughs	10%
Trenches	15%
Bridges	10%
Fans	10%
Plateaus	15%
Epipelagic	20–30%
Mesopelagic	20–30%
Bathypelagic	20–30%
Abyssopelagic	20–30%
Hadopelagic	20–30%
Any other habitats	20–30%

**Seamount types further classified as per Macmillan-Lawler and Harris (2016). See Appendix 1.*

PRINCIPLE 3: REPRESENT WHOLE FEATURES

Represent whole features / habitats, wherever possible.

This is an important consideration within existing design principles of MPAs and MPA networks, where placing a cohesive habitat under different forms of protection is to be avoided (Box 1).

While this follows from an established principle, the features on which whole habitats are delineated are likely to be different. In the open ocean, habitats and features can be isolated by large expanses of deep open water (e.g. seamounts) or areas with hydrologically different characteristics (e.g. upwelling, fronts), and protecting them in their entirety becomes even more important for safeguarding ecological functions and processes. Vertical zoning (applying different management rules to benthic and pelagic habitats of the same area) is generally not recommended (Grober-Dunsmore et al., 2008; Lausche, 2011); there are still knowledge gaps around benthic-pelagic coupling (Day et al., 2012), but emerging evidence suggests that it is stronger than previously thought (Grober-Dunsmore et al., 2008). Vertical zoning would disturb this ecological coupling.

In the open ocean, the representation of entire interlinked features includes both horizontal and vertical dimensions. For example, the effects of benthic communities (especially around prominent undersea features) on pelagic species are intrinsically accepted (Garrigue et al., 2015; Morato et al., 2010). Conversely, pelagic species may also directly or indirectly regulate benthic communities. Passfield and Gilman (2010) show that the feeding of predators around seamounts does, in fact, affect seamount ecology.

Some tuna aggregations may be present at an individual seamount for up to a period of weeks or months (Sibert et al., 2000). Similarly, bathypelagic fish assemblages have been found directly associated with ridge systems; trophic linkages are likely to be bi-directional (Sutton et al., 2008). The trophic influence of pelagic species on demersal and benthic communities may be largely indirect, such as large, mobile pelagic species preying on the predators of benthic prey, or preying on bentho-pelagic species (Allain et al., 2006). There is also an ontogenetic link between pelagic and benthic seamount habitats: most seamount benthic species have a pelagic stage, usually as juveniles (Allain et al., 2006).

Depletion of pelagic predators may therefore, indirectly affect benthic communities through release from predation of certain functional groups, increasing prey species abundance and subsequently affecting their interactions with benthic species, such as occurs in trophic cascades (Estes et al., 2011). It could be argued that benthic communities become ever more dependent on pelagic species with increasing depth, as organisms in deeper waters become almost entirely dependent on marine snow and sinking carcasses of large pelagic animals for food. Therefore, no-take MPAs should encompass protected features in their entirety, without vertical zoning.

Table 6 below summarises Principle 3.

TABLE 6. Biophysical design principle for offshore MPAs relating to the representation of whole features.

Principle	Rationale	References
3. Include whole features within no-take MPAs.	Mappable features (hydrographic or topographic) of the open ocean include known areas of high productivity, diversity or significant ecological processes, and need to be protected in their entirety to allow for the full range of ecological processes to take place (See also Principle 4 below).	(Alpine and Hobday, 2007; Day et al., 2012; Fernandes et al., 2012; Grober-Dunsmore et al., 2008; Hyrenbach et al., 2000; Sibert and Hampton, 2002)2000; Sibert and Hampton, 2002

PRINCIPLE 4: REPLICATE PROTECTION OF A BIOREGION AND/OR HABITAT AT LEAST THREE TIMES

Have at least three replicate no-take MPAs within bioregions, and include at least one example of each habitat or feature (e.g. hydrodynamic front, seamount, hydrothermal vent, migration bottleneck, resting areas, nesting, breeding or spawning area, other aggregation area, etc.).

This follows from the existing design principle of establishing replicate no-take MPAs to maximise the protection of known and unknown biodiversity and spreading risk (Box 1).

Representing multiple examples of features in MPAs can be both easier and more problematic in the open ocean. Easier, because the spatially broad nature of this environment means that larger MPAs are more feasible, which in turn increases the likelihood of encompassing multiple examples of a feature (e.g. multiple seamounts, canyons, hydrothermal vents, islands, etc.). Also, bioregions tend to be so large (e.g. O'Hara et al., 2011; Reygondeau et al., 2012) that it should easily allow for replicate no-take MPAs within a bioregion. But it can also be more challenging, because many features of interest in the open ocean are very large and unique (e.g. the Tonga Trench, individual seamounts); in some cases, there are, effectively, no other such features with exactly the same attributes in existence. For example, there are species endemic to individual seamounts (Richer de Forges et al., 2000).

Further, the replication principle can be used to protect populations of protected species along movement, including migratory, pathways. Many protected species can be very wide-ranging, and migration pathways can cover entire ocean regions, even though they may focus their routes over areas of higher productivity and aggregate at particular locations (Block et al., 2011). Many populations of migratory species, however, have only one main migration pathway (e.g. migratory seabirds, turtles that move between the western and eastern Pacific, etc.). MPA networks can therefore be designed to include at least three replicate no-take MPAs which protect several points along each population's known migration route (Table 7).

TABLE 7. Biophysical design principles for offshore MPAs relating to the replication of protected features.

Principles	Rationale	References
4a. Have at least three replicate no-take MPAs: within bioregions; of very large features (e.g. trenches or hydrodynamic fronts); and of known habitats and ecological processes.	Replication of protection minimizes the risk of losing all examples of a habitat, population or assemblage in the case of disturbance. Areas that remain intact or healthy may act as a refuge, and a source of larvae for the recovery of damaged areas. Replication also helps enhance representation of biological heterogeneity within poorly known habitats, as is commonly the case in the open ocean.	(Day et al., 2012; Fernandes et al., 2012; Great Barrier Reef Marine Park Authority, 2002)
4b. Include at least three points (ideally aggregation sites) along the migration path of migratory species or within the range of other highly mobile species in no-take MPAs.	Where it is not possible to protect an entire migration pathway, placing several replicate no-take MPAs at critical points along the migration route can disproportionately benefit the whole population. Replication of protection minimizes the risk of encountering damaging agents (e.g. purse seiners, longliners) along the entire route.	(Briscoe et al., 2017; Day et al., 2012; Fernandes et al., 2012; Gell and Roberts, 2002; Great Barrier Reef Marine Park Authority, 2002; Roberts and Sargant, 2002)

PRINCIPLE 5: INCLUDE SPECIAL, UNIQUE OR RARE FEATURES AND/OR SPECIES

Ensure that no-take MPAs include critical habitats and biologically or physically special or unique sites.

This follows from existing design principles that apply protection to known areas of high conservation value (Box 1).

In the open ocean, sites can also be and are, in fact, also selected according to criteria such as uniqueness, rarity or special characteristics (Maxwell et al., 2014). Sites may be unique, rare or special due to habitat types, oceanographic or geological features, or to species occurrences specific to particular open ocean environments, such as current systems and fronts, upwellings, seamounts or trenches, hydrothermal vents or populations of pelagic species (Ban et al., 2014; Hooker et al., 2011; Hyrenbach et al., 2000). These features are usually unique to a certain area and isolated from other similar features or populations by sheer distance. The larger the spatial scale at which the special or unique characteristics of open ocean habitats typically occur, the greater the effect of their loss. Criteria for selecting EBSAs in offshore environments have been developed for some regions, for example the Azores (CBD, 2009); these criteria could also be applied elsewhere and have been applied in the SW Pacific (CBD, 2014).

Unique or special species and populations in the open ocean have life histories and adaptations specific to the pelagic or deep benthic habitats they inhabit. Some large pelagic species may range very widely, while deep-dwelling species may have populations that are genetically disjointed due to the distance between suitable benthic habitats (e.g. seamounts or hydrothermal vents separated by large expanses of seafloor). Despite their wide-ranging nature, large pelagic species of conservation interest regularly use particular sites and migration corridors that can be mapped, monitored and even predicted (Etnoyer et al., 2004; Hooker et al., 2011; Morreale et al., 1996; Zainuddin et al., 2006).

Habitat types, features and processes unique to the open ocean include seamounts, deep trenches, canyons, cold water coral communities, hydrothermal vents and hydrodynamic processes such as eddies, fronts or upwellings (Appendix 3). Many such features are critical to species that migrate or range over wide distances, as feeding, breeding or migratory stop-over points (Garrigue et al., 2015; Hooker et al., 2011). The species that we know of that use these features are often of conservation concern, such as marine mammals, seabirds and turtles, or serve as prey for protected or commercially important species (Hobday et al., 2011).

Geomorphic features that are known to aggregate life could all be seen as special; mid-ocean ridges, seamounts and submarine canyons, cover only four percent of the seafloor, making them rare biodiversity hotspots within the vast extent of abyssal plains, hills, plateaus, basins, terraces, troughs, valleys, escarpments and sedimented slopes that, according to current knowledge, tend to be more sparsely populated (Glover and Smith, 2003; Garrigue et all, 2015). Many of these features are considered individual habitats or habitat types, and may be seen as covered by Principle 2 (representation of habitats), which is useful when very little or nothing is known about a particular feature or habitat. However, when a specific feature is known to be of critical importance, it should be protected according to Principles 3 (protection of whole features) and 5 (this Principle, special, unique or rare). For example, if a series of ridges are known to exist within an offshore area, with little or no information about their particular attributes, they would be protected under Principle 2.

In summary, offshore MPAs and MPA networks should be designed to conserve and / or restore special, unique or rare features and / or species, covering a spatial extent relevant to the feature or species as described in Table 8.

TABLE 8. Biophysical design principles for offshore MPA networks that capture critical habitats and biologically or physically special or unique sites.

Principle	Rationale	References
5. Ensure that no-take MPAs include critical habitats and biologically or physically special and/or unique sites. This may include, for example, unique geomorphologic or hydrodynamic features, areas important for aggregation, nurseries, spawning, foraging, offshore nesting sites, migratory staging points, mammal calving areas, areas with high biodiversity, endemism, productivity or with threatened, isolated or rare species or habitats.	For an MPA network to comprehensively and adequately protect biodiversity, known special or unique areas must be included in no-take MPAs. Productive areas are important due to their contribution to ecosystem functioning and potential for high biodiversity; they are usually "hotspots" for multiple species. Areas that are critical to large species are often automatically important for a large variety of other, smaller, more sedentary pelagic or benthic species. It is important to note that for threatened or endangered species, protecting 30% of their habitat niche may be insufficient to prevent extinction. Thus some habitats may require 100% protection while others can endure with less.	(Day et al., 2012; Fernandes et al., 2012; Glover and Smith, 2003; Great Barrier Reef Marine Park Authority, 2002; Hooker et al., 2011; Maxwell et al., 2014)

PRINCIPLE 6: MAKE MPAS LARGER RATHER THAN SMALLER

Wherever possible, make MPAs larger rather than smaller. This is especially important for offshore MPAs, where habitats can be larger or more diffuse, and many species of conservation interest are highly mobile.

This principle follows the universal guideline that "bigger is better" when applying spatial protection (Box 1).

The boundaries of an MPA need to be determined according to the extent and location of the species, features, bioregions and ecological processes they are intended to protect. The 0.2 km^2 "minimum size" guideline for more coastal no-take MPAs (Fernandes et al., 2012, 2009) is not suited for more offshore features or highly mobile pelagic species (Table 9). Huvenne et al. (2016) found that a deep-water (~1,000 m) no-take MPA approximately 30 by 40 km in diameter adequately protected deep-water coral communities, but where these corals were heavily damaged, even these protected areas could not mediate recovery. The effects of the size of MPA on fish communities themselves were not measured by Huvenne (2016). Roberts et al. (2010) suggest that in English EEZ waters beyond 12 nm, MPAs that are intended to protect commercial species should be at least 30 to 60 km in their minimum dimension, but this relates to waters over a continental shelf. Metcalfe et al. (2015) argued that even having no-take MPAs of 100 km^2 inshore and 900 km^2 offshore would not protect species with a dispersal distance of 1000–10000 km (the analysis included two species in this dispersal category, a mackerel and a scad).

Coastal and sedentary species, and oceanic benthic or more static pelagic assemblages, can benefit from smaller MPAs, but larger, more mobile and migratory species may require much larger MPAs and networks of MPAs. One benefit of larger MPAs are that in protecting the range, or part thereof, of a migratory or highly mobile species, they automatically protect a large array of other features (Wilhelm et al., 2014).

The challenges posed by larval and post-larval dispersal, movement and migration of marine species are amplified in oceanic environments, where larger pelagic species of interest tend to have larger home ranges and movement patterns or migratory pathways than coastal or inshore species (Gruss et al., 2011). In this case, several of the guidelines may best be considered together, whereby if size constraints make it impossible to contain a species' entire range, connectivity guidelines together with replication and minimum percentage guidelines can be combined to protect as much of the species' critical areas as possible, thereby achieving the best possible outcome for a species or population. Recent genetic work has shown that even for highly mobile species (e.g. tuna), there are proportions of the population that are much less mobile (Mee et al., 2017). Genetic modelling research has consequently shown an evolution of decreased movement for highly mobile tuna species after the establishment of MPAs, as less mobile individuals pass on their genes to successive generations more frequently than those that move beyond MPA boundaries into fishing grounds (Mee et al., 2017). In a practical sense, this means that the benefits of offshore MPAs will grow over time, including over generations of the target species of interest.

The size of open ocean no-take MPAs needs to reflect the species, habitats or features being protected. The guideline also needs to take into account oceanic island archipelagos that may be inhabited by people; the inshore, nearshore and offshore definitions given above (see Introduction: MPA Design Principles) therefore also apply here. In Table 9 below, minimum size limits are given for each part of the marine environment, based on known or modelled larval dispersal distances and average movement distances from tagging studies of large oceanic animals, considering the value of using these animals as "umbrella species" for the vast variety of smaller, more sedentary ocean inhabitants and the consideration of including the whole water column and seafloor as defined in Principle 3.

TABLE 9. Biophysical design principles for MPAs relating to size.

Location	Principle	Rationale	References
6a. Inshore (coast to edge of shallowest adjacent habitats)	Make no-take MPAs 400m-2km in diameter.	This guideline is for inshore areas and matches the range, distribution and dispersal patterns associated with many inshore habitats and species.	(Fernandes et al., 2012; Russ, 2002)
6b. Nearshore (outer edge of coastal habitat e.g. outer edge of reef to shelf break / 80m contour)	Make no-take MPAs 2–10 km in diameter.	Further offshore, habitat features and species ranges and dispersal patterns tend to be larger. There are various transition zones between pelagic and benthic habitats, and communities at various depths. Larger no-take MPAs are more likely to capture this.	(Green et al., 2013, 2014)
6c. Offshore (beyond shelf break / 80m contour)	Make no-take MPAs 50–200 km in diameter.	Tagging studies show that large pelagic predators (tunas, billfish, blue and shortfin mako sharks, dolphinfish, wahoo, penguins) can move 1000s of kms, but that the majority of the populations remain within 250 to 1000 km of their release location. Modelling studies show that protecting 50% of the range of wide-ranging species, especially if critical habitat is included, can benefit the entire population. Additionally, these species can act as "umbrella species"; protecting enough area for them will automatically benefit a large diversity of more sedentary pelagic species and the seafloor below.	(Alpine and Hobday, 2007; Bromhead et al., 2004; Clark, 1996; Clear et al., 2005; Cosgrove et al., 2010; Della Pella et al., 2017; Hampton and Gunn, 1998; Holdsworth et al., 2009; Huvenne et al., 2016; Kingsford and Defries, 1999; Kohler et al., 2002; Lauck et al., 1998; Micheli et al., 2004; Robinson et al., 2016; Schaefer et al., 2014; Sedberry and Loefer, 2001; Sepulveda et al., 2010; Sibert and Hampton, 2003, 2002; Theisen et al., 2008; Worm et al., 2003)

PRINCIPLE 7: MAKE MPAS SIMPLE SHAPES AND MAXIMISE THE AREA TO BOUNDARY RATIO

Use simple shapes and boundary lines, to maximise the area to boundary ratio. Where possible, set boundaries to coincide with prominent landmarks and even-numbered coordinates.

This follows the design principles that have shown to produce better compliance when simple shapes, landmarks or coordinates are used to define MPA boundaries (Box 1).

Edge effects in the open ocean are expected to occur in the same way as in inshore systems, especially as pertains to fishing. Existing literature on the effects of MPA shape on, for example, breeding seabirds also suggests that simple MPA designs are the most effective (Perrow et al., 2015). Also from a compliance point of view, the boundaries of no-take MPAs are best placed according to landmarks, or using simple coordinates. Inshore, landmarks may be possible, but offshore there will be a greater reliance on choosing simple latitude-longitude combinations.

TABLE 10. Biophysical design principles for MPAs relating to shape.

Guideline	Rationale	References
7. Use simple shapes such as squares that maximize area to edge ratios. Use simple lat-long combinations.	Areas at the edge of an MPA can be subject to human activities at and within the edges, and therefore offer less protection than areas at the core of an MPA. Simple shapes such as squares maximize the area at the centre of an MPA, reduce the complexity of boundaries and reduces boundary length, thus simplifying compliance regimes.	(Fernandes et al., 2012; Gaines et al., 2010; Russ, 2002)

PRINCIPLE 8: SPACE MPAS TO MAXIMISE CONNECTIVITY BETWEEN THEM

Ensure that the spacing between offshore MPAs allows for adequate larval and adult connectivity, taking into account available knowledge about movement patterns and hydrodynamics.

This principle is adapted from the literature, which shows that good connectivity between MPAs, taking into account relevant spatial scales, is important for achieving ecological objectives (Box 1).

In the open ocean, larger distances between populations or patches of similar habitat make connectivity more diffuse. Migratory and wide-ranging species provide connectivity over small scales as well as over 100s, and sometimes 1,000s of km (Lam et al., 2016). It has been shown that designing MPAs with a focus on connectivity, rather than species or habitats on their own, is especially important and has a greater chance of success in pelagic ecosystems (Moffitt et al., 2011). The scales of dispersal and connectivity for MPA design in the deep sea have been suggested to be slightly larger than those in shallow water, as suitable habitats tend to be more isolated (Baco et al., 2016). As for coastal MPAs, offshore MPAs are likely to benefit from placement that takes into account adjacent coastal MPAs, or of areas with existing protection, such as areas in which tuna fishing is banned (Jones et al., 2007).

In the open ocean, vertical connectivity is as important as horizontal connectivity, and occurs through the downward drift of organic matter (marine snow), deep-diving ocean predators, and the vertical migration of deep-dwelling species that move towards the surface to feed at night. MPA design needs to take into account that surface features of interest (e.g. hotspots of productivity, feeding or spawning aggregations) may or may not align with deeper hotspots. Also, MPA design needs to take into account potential connectivity pathways along benthic and demersal depth gradients (Papastamatiou et al., 2015).

The propensity for some larger open ocean species to range across large distances, and for the larval stages of marine species to occupy pelagic habitats during the dispersal phase, makes connectivity and movement an especially important consideration when designing offshore MPAs (Moffitt et al., 2011). Such information can be difficult to acquire and is ideally available over long timeframes (Berglund et al., 2012).

When designing MPAs in large-scale marine areas, it may be necessary to include “stepping stones”, or smaller areas that play key roles in dispersal or migration, by providing resting or feeding points (e.g. the staging areas known in bird migrations). These may be otherwise unremarkable habitats, but crucial to the persistence of species of interest. In their assessment of United Kingdom EEZ waters, Roberts et al. (2010) determined that MPAs within a network should be no more than 40–80km apart in order to ensure sufficient ecological connectivity.

This recommendation can also be applied to open ocean environments of the Pacific Islands region, especially within island archipelagos where a diversity of habitats and assemblages need to be protected. When protecting particular migratory species, this distance may be extended out to 200km, so that protected staging, feeding or breeding areas are no further than 200km apart. Table 11 below summarises the design principles of connectively and spacing.

TABLE 11. Biophysical design principles for offshore MPAs relating to connectivity and spacing.

Location	Distance Principle	Rationale	References
8a. Inshore (coast to edge of adjacent shallow habitats)	Distance between no-take MPAs should be between 500m and 5km.	This guideline is for inshore areas and matches the range, distribution and dispersal patterns associated with many inshore habitats and species.	(Fernandes et al., 2012; Green et al., 2014; Harrison et al., 2012)
8b. Nearshore (edge of slope to 80m contour)	Distance between no-take MPAs should be between 5 and 20km.	Connectivity beyond the reef edge tends to be naturally lower, and can occur over larger distances. Propagules from benthic biota are less likely to be entrained by inshore hydrodynamics and may disperse more widely. These areas are also frequented periodically by pelagic species that are demographically and genetically connected over larger distances.	(Baco et al., 2016; Green et al., 2014; Jones et al., 2007; Sibert and Hampton, 2003, 2002)
8c. Offshore (beyond 80m contour)	Distance between no-take MPAs should be between 20 and 200 km.	Because of the wide-ranging or widely distributed nature of offshore populations, genetic connectivity is possible across very large areas. However, as the bulk of the population is usually less mobile, MPAs, to ensure demographic connectivity, will need to take into account the mean or median distances found in tagging studies (see size and shape section above).	(Alpine and Hobday, 2007; Bromhead et al., 2004; Clark, 1996; Clear et al., 2005; Cosgrove et al., 2010; Hampton and Gunn, 1998; Holdsworth et al., 2009; Kingsford and Defries, 1999; Kohler et al., 2002; Lauck et al., 1998; Maxwell et al., 2014; Micheli et al., 2004; Schaefer et al., 2014; Sedberry and Loefer, 2001; Sepulveda et al., 2010; Sibert and Hampton, 2003, 2002; Theisen et al., 2008; Worm et al., 2003)

PRINCIPLE 9: CHOOSE PERMANENT PROTECTION OVER TEMPORARY PROTECTION

Choose permanent protection over temporary protection, to allow for the recovery of typically long-lived and slow-maturing open ocean species.

This principle follows from the understanding that species and populations require adequate amounts of time to recover, and therefore permanent protection is preferable to temporary protection (Box 1).

Open ocean ecosystems would also benefit most from permanent protection (Mee et al., 2017). The large pelagic species of conservation interest and deep-water species tend to be longer-lived, slower-growing and late-reproducing (K-selected life histories) compared to many of their inshore or nearshore counterparts; these species take longer to recover than more short-lived species (Alcala et al., 2005; Hart, 2006). For example, the orange roughy (*Hoplostethus atlanticus*), is highly sought after by commercial deep-trawl fisheries, but its extraordinary lifespan (up to 149 years) makes it extremely vulnerable to overexploitation (Doonan et al., 2015).

Recovery is possible, as seen, for example, in the case of the humpback whale populations after the cessation of widespread whaling, over the scale of decades (Pavanato et al., 2017). The slower rate of recovery measured in deep-sea benthic habitats also necessitates more permanent protection; in some cases, the lack of recovery measured over decades suggests that the timeframes required by oceanic populations or deep-sea assemblages are much longer than those necessary in coastal areas (Williams et al., 2010b). However, it may be necessary to adapt to an uncertain future governed by climate change, shifting distributions, home ranges or migration pathways necessitates revision of MPA boundaries over time (Gruss et al., 2011).

TABLE 12. Biophysical design principles for MPAs relating to duration.

Principle	Rationale	References
9. Choose permanent protection over temporary protection.	Permanent protection enhances the likelihood of recovery of populations and habitats, even if they are very long-lived, slow-growing or heavily damaged. However, MPAs should be subject to review over time.	(Abesamis et al., 2014; Fernandes et al., 2012; IUCN-WCPA, 2008; Williams et al., 2010b)

PRINCIPLE 10: ONLY APPLY OTHER MPA CATEGORIES, WHICH ALLOW FOR EXTRACTIVE ACTIVITIES, ONCE 20–30% OF BIOREGION/HABITATS IS ADEQUATELY PROTECTED IN NO-TAKE MPAS

Once adequate areas have been placed in no-take MPAs, apply other categories of MPAs to minimise human impacts.

This principle is applied more often in coastal ecosystems where human interests may be more concentrated, but other levels of protection should only be applied once the principles have been adequately applied to the establishment of no-take MPAs (Box 1).

For the design of offshore MPA networks, a simplified version of the IUCN categories is preferable, as this will make it less confusing for stakeholders and easier for compliance monitoring and enforcement. The rationale and principles applied to no-take MPAs should also apply, as much as possible, to other categories (see Table 1). Reducing threats to other categories of MPAs and to surrounding areas will enhance the effectiveness of no-take MPAs and the area as a whole. Given the data-poor nature of the open ocean, threat reduction in general can protect areas, features or species not yet identified as requiring protection (Jessen et al., 2011).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5 CONCLUSIONS

The purpose of this report was to specifically review biophysical information applicable to offshore ecosystems and synthesize this knowledge with existing design principles for offshore no-take MPAs. Many of the principles developed in this report are specifically adapted from existing principles guiding the design and placement of inshore or coastal MPAs. Whilst detailed offshore MPA biophysical design principles have never been proposed before, the science about offshore marine environments and MPA network design has advanced enough for an initial set of principles to be developed. The offshore MPA biophysical design principles in this report have been prepared for the use of practitioners but need to be applied within a larger process (Lewis et al., 2017). And although the biophysical design principles are presented in alignment with the best current science, they will need to be applied through the lens of specific cultural, social, economic and practical contexts (Lewis et al., 2017).

Designing MPAs and MPA networks in the open ocean requires a broader perspective than coastal seas. The main differences between protecting inshore and oceanic areas are related to scale and distance, and that there is less knowledge and larger uncertainties associated with the open ocean. Many of the same design principles used to protect coastal regions apply in the open ocean (e.g. size, shape, distance, replication, percentages; Table 13), with specific tailoring for the specific characteristics of oceanic ecosystems and species. Fortunately, there is a global willingness to move towards effective ocean conservation as indicated by the increasing number of very large MPAs.

The challenge of applying these principles in poorly understood offshore environments can be more easily met by prioritising at least some principles (Fernandes et al., 2009; Gilman et al., 2011; IUCN WCPA, 2018). We recommend prioritising the “top four” principles as follows:

1. Principle 1 where bioregions are defined, Principle 2 where there are no defined bioregions (Fernandes et al., 2009). This maximises the potential for representativeness, and consequently maximises the biodiversity and ecological processes that can be captured within no-take MPAs (Harris, 2007).
2. Principle 4, because replication spreads the risk of ecosystems within an MPA becoming degraded, and because bioregions, and habitats within bioregions, are not homogeneous (Salm et al., 2006). Similarly, staging points along migration routes are not identical, and replicating them will increase the likelihood that areas that may be used by the same migratory species in slightly different ways are captured (Block et al., 2011).
3. Principle 6, because maximising the size of MPAs increases the likelihood of other principles being applied automatically. In data-poor systems, it also provides insurance against missing important, but as yet unknown, features (Rodrigues et al., 2004).
4. Principle 8, because although applying the other principles might yield a network where connectivity is already high, in the open ocean MPAs are likely to be placed further from each other than is ideal (Baco et al., 2016). Therefore, this principle can help correct any placement issues not already addressed.

In an uncertain future governed by climate change, shifting distributions, home ranges or migration pathways MPA boundaries may require revision over time (Brock et al., 2012; Gruss et al., 2011). Allowing for different levels of activity to continue within a network of MPAs should still take into account existing threats and endeavour to minimise them across the entire network (Day et al., 2012). Ultimately, no-take MPAs can only stop extractive use, and must be used in conjunction with sectoral resource management, pollution controls and actions to reduce greenhouse gas emissions (Hilborn, 2016).

To allay future doubts and arguments about their effectiveness, effort must go into innovative monitoring solutions. Information from monitoring can then feed into an adaptive management cycle for existing MPAs (e.g. Dunn et al., in press), and help refine design guidelines for new offshore MPAs.

TABLE 13. Summary of biophysical principles to aid the design of no-take offshore MPA networks.

Design Principle	Conditions	Rationale	References
1a. Represent at least 20–30% of marine bioregions in no-take MPAs		Protection of all habitats, flora and fauna, ecosystem function, integrity and resilience requires that adequate examples of every bioregion are included in no-take areas. The best available science informs that at least 20–30% of each marine bioregion should be included in no-take areas, especially if aiming to protect species with lower reproductive output or delayed maturation (e.g. many large offshore and deep-water species), or in areas that host diverse, unassessed or poorly regulated fisheries, as is common offshore.	(Day et al., 2012; Fernandes et al., 2012; Worm et al., 2006)
1b. Represent at least 20–30% of marine bioregional transition boundaries in no-take MPAs		Boundaries and transition zones between bioregions in the open ocean tend to aggregate a high diversity and density of open ocean species. Bioregions in the open ocean are often much more extensive than in coastal marine habitats.	(Block et al., 2011; Clark et al., 2011; Hyrenbach et al., 2000; Kanaji et al., 2017; Reygondeau et al., 2012; UNESCO, 2009)
2a. Ensure that this includes a percentage of each habitat type or feature as indicated by Table 5 within no-take MPAs. Include adjacent habitats as buffer zones.	Defined bioregions: Principle 1 applies	Mappable features of the open ocean include known areas of high productivity, diversity or significant ecological processes. To ensure future sustainability of offshore marine environments, examples of the full range of known and mapped biophysical habitats should be included in no-take MPAs.	(Alpine and Hobday, 2007; Day et al., 2012; Fernandes et al., 2012; Hyrenbach et al., 2000; Sibert and Hampton, 2002)2000; Sibert and Hampton, 2002
2b. Include a percentage of each habitat type or feature as indicated by Table 5, plus 5%, within no-take MPAs. Include adjacent habitats as buffer zones.	No bioregions defined	When there is no definition of bioregional boundaries, there is often still at least an approximate understanding of habitats present. When Principle 1 cannot be applied, capturing a larger proportion of each habitat enhances the likelihood of capturing unknown and therefore unmapped with-in habitat variability.	(Great Barrier Reef Marine Park Authority, 2002)
3. Include whole features within no-take MPAs.		Mappable features of the open ocean include known areas of high productivity, diversity or significant ecological processes, and need to be protected in their entirety to allow for the full range of ecological processes to take place (See also Principle 4 below).	(Alpine and Hobday, 2007; Day et al., 2012; Fernandes et al., 2012; Grober-Dunsmore et al., 2008; Hyrenbach et al., 2000; Sibert and Hampton, 2002)2000; Sibert and Hampton, 2002
4a. Have at least three replicate no-take MPAs: within bioregions; of very large features (e.g. topographic or hydrodynamic features); and of known habitats and ecological processes.		Replication of protection minimizes the risk of losing all examples of a habitat, population or assemblage in the case of disturbance. Areas that remain intact or healthy may act as a refuge, and a source of larvae for the recovery of damaged areas. Replication also helps enhance representation of biological heterogeneity within poorly known habitats, as is commonly the case in the open ocean.	(Day et al., 2012; Fernandes et al., 2012; Great Barrier Reef Marine Park Authority, 2002)
4b. Include at least three points (ideally aggregation sites) along the migration path of migratory species or within the range of other highly mobile species in no-take MPAs.		Where it is not possible to protect an entire migration pathway, placing several replicate no-take MPAs at critical points along the migration route can disproportionately benefit the whole population. Replication of protection minimizes the risk of encountering damaging agents (e.g. purse seiners, longliners) along the entire route.	(Briscoe et al., 2017; Day et al., 2012; Fernandes et al., 2012; Gell and Roberts, 2002; Great Barrier Reef Marine Park Authority, 2002; Roberts and Sargant, 2002)

Design Principle	Conditions	Rationale	References
5. Ensure that no-take MPAs include critical habitats and biologically or physically special and/or unique sites. This may include, for example, unique geomorphologic or hydrodynamic features, areas important for aggregation, nurseries, spawning, foraging, offshore nesting sites, migratory staging points, mammal calving areas, areas with high biodiversity, endemism, productivity or with threatened, isolated or rare species or habitats.		For an MPA network to comprehensively and adequately protect biodiversity, known special or unique areas must be included in no-take MPAs. Productive areas are important due to their contribution to ecosystem functioning and potential for high biodiversity; they are usually "hotspots" for multiple species. Areas that are critical to large species are often automatically important for a large variety of other, smaller, more sedentary pelagic or benthic species. It is important to note that for threatened or endangered species, protecting 30% of their habitat niche may be insufficient to prevent extinction. Thus some habitats may require 100% protection while others can endure with less.	(Day et al., 2012; Fernandes et al., 2012; Glover and Smith, 2003; Great Barrier Reef Marine Park Authority, 2002; Hooker et al., 2011; Maxwell et al., 2014)
6a. Make no-take MPAs 400m-2km in diameter.	Inshore (coast to edge of shallowest adjacent habitats)	This guideline is for inshore areas and matches the range, distribution and dispersal patterns associated with many inshore habitats and species.	(Fernandes et al., 2012; Russ, 2002)
6b. Make no-take MPAs 2–10 km in diameter.	Nearshore (outer edge of coastal habitat e.g. outer edge of reef to shelf break / 80m contour)	Further offshore, habitat features and species ranges and dispersal patterns tend to be larger. There are various transition zones between pelagic and benthic habitats, and communities at various depths. Larger no-take MPAs are more likely to capture this.	(Green et al., 2013, 2014)
6c. Make no-take MPAs 50–200 km in diameter.	Offshore (beyond shelf break / 80m contour)	Tagging studies show that large pelagic predators (tunas, billfish, blue and shortfin mako sharks, dolphinfish, wahoo, penguins) can move 1000s of kms, but that the majority of the populations remain within 250 to 1000 km of their release location. Modelling studies show that protecting 50% of the range of wide-ranging species, especially if critical habitat is included, can benefit the entire population. Additionally, these species can act as "umbrella species"; protecting enough area for them will automatically benefit a large diversity of more sedentary pelagic species and the seafloor below.	(Alpine and Hobday, 2007; Bromhead et al., 2004; Clark, 1996; Clear et al., 2005; Cosgrove et al., 2010; Della Pella et al., 2017; Hampton and Gunn, 1998; Holdsworth et al., 2009; Huvenne et al., 2016; Kingsford and Defries, 1999; Kohler et al., 2002; Lauck et al., 1998; Micheli et al., 2004; Robinson et al., 2016; Schaefer et al., 2014; Sedberry and Loefer, 2001; Sepulveda et al., 2010; Sibert and Hampton, 2003, 2002; Theisen et al., 2008; Worm et al.,
7. Use simple shapes such as squares that maximize area to edge ratios. Use simple lat-long combinations.		Areas at the edge of an MPA can be subject to human activities at and within the edges, and therefore offer less protection than areas at the core of an MPA. Simple shapes such as squares maximize the area at the centre of an MPA, reduce the complexity of boundaries and reduces boundary length, thus simplifying compliance regimes.	(Fernandes et al., 2012; Gaines et al., 2010; Russ, 2002)
8a. Distance between no-take MPAs should be between 500m and 5km.	Inshore (coast to edge of shallowest adjacent habitats)	This guideline is for inshore areas and matches the range, distribution and dispersal patterns associated with many inshore habitats and species.	(Fernandes et al., 2012; Green et al., 2014; Harrison et al., 2012)

Design Principle	Conditions	Rationale	References
8b. Distance between no-take MPAs should be between 5 and 20km.	Nearshore (outer edge of coastal habitat e.g. outer edge of reef to shelf break / 80m contour)	Connectivity beyond the reef edge tends to be naturally lower, and can occur over larger distances. Propagules from benthic biota are less likely to be entrained by inshore hydrodynamics and may disperse more widely. These areas are also frequented periodically by pelagic species that are demographically and genetically connected over larger distances.	(Baco et al., 2016; Green et al., 2014; Jones et al., 2007; Sibert and Hampton, 2003, 2002)
8c. Distance between no-take MPAs should be between 20 and 200 km.	Offshore (beyond shelf break / 80m contour)	Because of the wide-ranging or widely distributed nature of offshore populations, genetic connectivity is possible across very large areas. However, as the bulk of the population is usually less mobile, MPAs to ensure demographic connectivity will need to take into account the mean or median distances found in tagging studies (see size and shape section above).	(Alpine and Hobday, 2007; Bromhead et al., 2004; Clark, 1996; Clear et al., 2005; Cosgrove et al., 2010; Hampton and Gunn, 1998; Holdsworth et al., 2009; Kingsford and Defries, 1999; Kohler et al., 2002; Lauck et al., 1998; Maxwell et al., 2014; Micheli et al., 2004; Schaefer et al., 2014; Sedberry and Loefer, 2001; Sepulveda et al., 2010; Sibert and Hampton, 2003, 2002; Theisen et al., 2008; Worm et al.
9. Choose permanent protection over temporary protection.		Permanent protection enhances the likelihood of recovery of populations and habitats, even if they are very long-lived, slow-growing or heavily damaged. However, MPAs should be subject to review over time.	(Abesamis et al., 2014; Fernandes et al., 2012; IUCN-WCPA, 2008; Williams et al., 2010b)
10. Reduce or eliminate threats across the entire MPA network area.		Reducing threats to other categories of MPAs and to surrounding areas will enhance the effectiveness of no-take MPAs and the area as a whole. Given the data-poor nature of the open ocean, threat reduction in general can protect areas, features or species not yet identified as requiring protection.	(Jessen et al., 2011)

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APPENDIX 1

MAJOR HABITATS OF OPEN OCEAN ENVIRONMENTS AND SUGGESTED PROPORTIONS FOR INCLUSION IN NO-TAKE MPAS

Habitats adapted from Harris et al. (2014), definitions from Harris et al. (2014), Harris and Whiteway (2011) and IHO (2008).

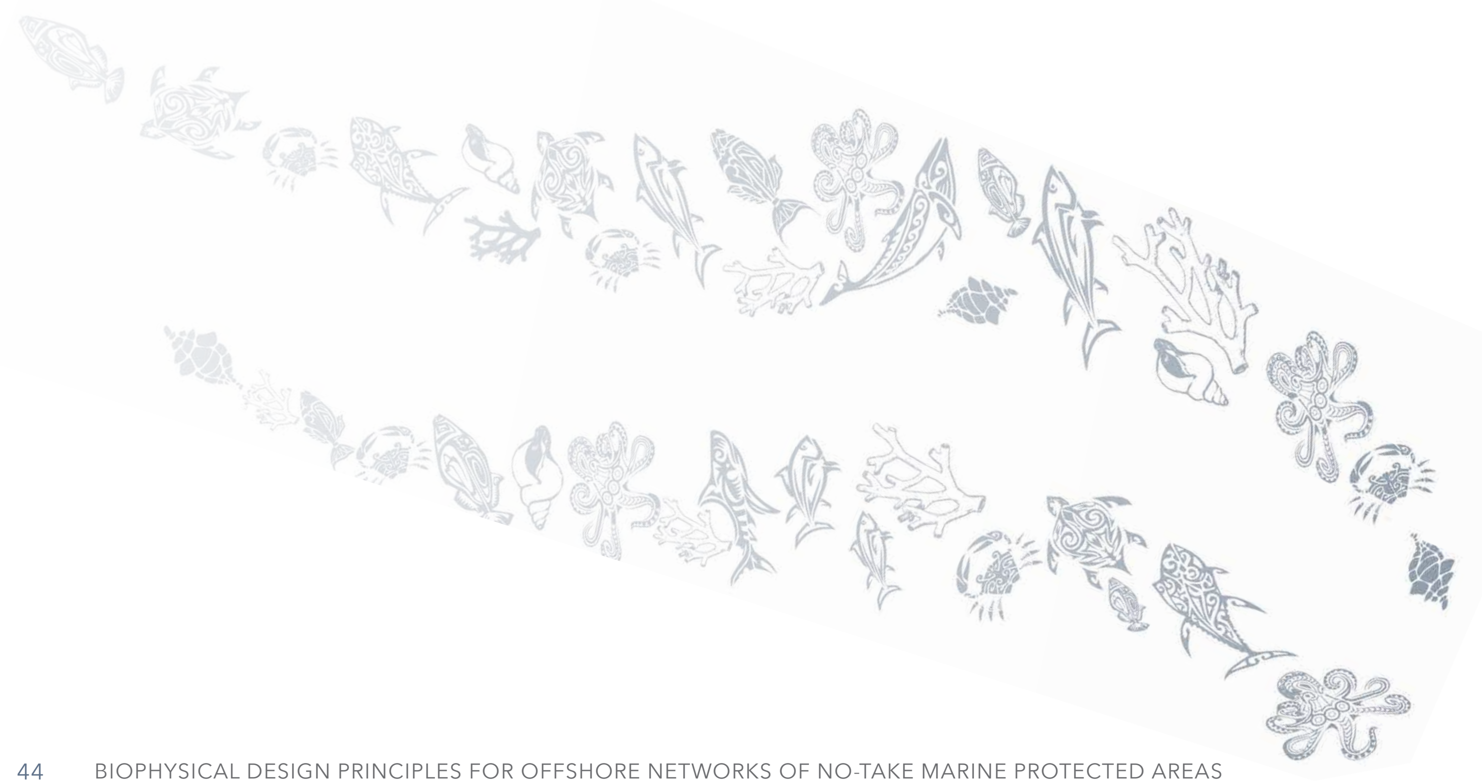
Habitat	Definition	Suggested minimum % for no-take MPAs
Shelf valleys	Valleys incised more than 10 m into the continental shelf, greater than 10 km in length.	10%
Coral reefs (emerging from > 80m)	(Oceanic context) A ridge of calcium carbonate rock in the sea formed by the growth and deposit of coral, surmounted by a living coral reef and rising directly from deep water.	25%
Oceanic islands (emerging from > 80m)	(Oceanic context) A ridge of rock in the sea, rising directly from deep water, usually at the apex of a seamount or pinnacle.	25%
Basins (of various sizes, of seas and oceans, perched on the continental shelf, plateau or slope)	A depression in the sea floor of variable extent.	10%
Shelf, slope, abyssal and hadal sills	A sea floor barrier restricting water movement between basins.	20%
Slope terraces	An isolated (or group of) relatively flat horizontal or gently inclined surface(s), sometimes long and narrow, which is (are) bounded by a steeper ascending slope on one side and by a steeper descending slope on the opposite side.	10%
slope, abyssal and hadal escarpments	An elongated, characteristically linear, steep slope separating horizontal or gently sloping sectors of the sea floor in non-shelf areas.	10%
Seamounts (of various types, rising from all depths)*	A discrete (or group of) large isolated elevation(s), greater than 1,000 m in relief above the sea floor, characteristically of conical form.	20% of each seamount type*
Canyons (shelf incising, connecting to rivers on land)	Steep-walled, sinuous valleys with V-shaped cross sections, axes sloping outwards as continuously as river-cut land canyons and relief comparable to even the largest of land canyons. Shelf incising canyons have heads that cut across the shelf break, and in which there are landward-deflected isobaths on the continental shelf, and there is a clear bathymetric connection to a major river system.	10%
Canyons (shelf incising)	Steep-walled, sinuous valleys with V-shaped cross sections, axes sloping outwards as continuously as river-cut land canyons and relief comparable to even the largest of land canyons. Shelf incising canyons have heads that cut across the shelf break, and in which there are landward-deflected isobaths on the continental shelf, without a bathymetric connection to a major river system.	10%
Canyons (blind)	Steep-walled, sinuous valleys with V-shaped cross sections, axes sloping outwards as continuously as river-cut land canyons and relief comparable to even the largest of land canyons. Blind canyons are those which have heads that are wholly confined to the slope, below the depth of the shelf break.	10%
Ridges	An isolated (or group of) elongated narrow elevation(s) of varying complexity having steep sides, often separating basin features.	10%
Troughs	A long depression of the sea floor characteristically flat bottomed and steep sided and normally shallower than a trench.	10%
Trenches	A long narrow, characteristically very deep and asymmetrical depression of the sea floor, with relatively steep sides.	15%
Bridges	Bridge geomorphic form a “bridge” across troughs or trenches; they may partially infill trenches and troughs.	10%
Fans	A relatively smooth, fan-like, depositional feature normally sloping away from the outer termination of a canyon or canyon system	10%
Plateaus	Flat or nearly flat elevations of considerable areal extent, dropping off abruptly on one or more sides.	15%
Epipelagic	The first 200m of open ocean, where planktonic primary producers receive enough light for photosynthesis, and therefore form the basis of the food web.	20–30%
Mesopelagic	From 200 to 1,000m, primary production is replaced by sinking organic matter (marine snow), including plankton, as the primary food source.	20–30%
Bathypelagic	Between 1,000 and 4,000m there is no sunlight penetration, and conditions in any one location are relatively stable and uniform.	20–30%
Abyssopelagic	From 4,000 to 6,000m is an area of immense pressure and very low temperature.	20–30%
Hadopelagic	This habitat occurs in ocean trenches, below 6,000m, to a maximum depth of ~11,000m in the deepest parts of the ocean, the Marianas and Tonga Trenches.	20–30%

** See Appendix 2*

APPENDIX 2
SEAMOUNT MORPHOTYPE CLASSIFICATION

Morphotypes used for the classification of seamounts, according to Macmillan-Lawler and Harris (2016).

Number	Morphotype	Description
1	Small, deep peak	Small, short seamounts with moderately deep peak depths, second smallest area and second shortest height
2	Small, deep peak	Most common morphotype. Second smallest morphotype with deep peak depth and moderate height. Highest amount of escarpment and second closest proximity to other seamounts or shelf break.
3	Intermediate	Larger, taller and with a deeper peak depth compared to morphotype 5. Greatest percentage of escarpment of all morphotypes.
4	Small, deep peak	Most isolated morphotype.
5	Intermediate	Small, moderately tall and with the shallowest peak depths of the intermediate seamounts, high percentage of escarpment. Closest proximity to other seamounts or shelf break.
6	Very large, tall, low escarpment	Very large and tall, with generally shallow peak depths, proportionally large summit plateaus and a low amount of escarpment. Many guyots fall into this category.
7	Small, short, very deep peak	Second most isolated, shortest morphotype, lowest proportion of escarpment
8	Small, short, very deep peak	Smallest mean area, deepest peak depth.
9	Large, tall, shallow peak	Large and tall with shallow peak depth, larger basal area, smaller escarpment. Second largest height and area of all morphotypes, second shallowest peak depth. Includes many guyots.
10	Large, tall, shallow peak	Large and tall with shallow peak depth, smaller basal area, greater escarpment. Shallowest peak depth of all morphotypes. Relatively close to other seamounts or shelf break.
11	Intermediate	Largest mean area and deepest peak depth of the three intermediate morphotypes (see 3 and 5).



APPENDIX 3
SOME POTENTIALLY TOPOGRAPHICALLY OR HYDROGRAPHICALLY UNIQUE, SPECIAL OR RARE FEATURES OF THE OPEN OCEAN

Type	Feature	Characteristics	Key sources
Topographic	Seamounts, knolls, hills, guyots, ridges	Seamounts are "large isolated elevation(s), greater than 1,000m in relief above the sea floor, characteristically of conical form"; knolls, hills and guyots are slightly lower elevations of different shapes. Ridges are defined as "elongated narrow elevation(s) of varying complexity having steep sides, often separating basin features". Seamounts and ridges have steep slopes which can cause the upward movement of nutrients from the deep ocean (upwellings) and create hotspots of pelagic productivity and biodiversity, attracting deepwater and pelagic species such as tuna, deep-water snapper, sharks, whales and dolphins.	(Harris et al., 2014; IHO, 2008; Morato and Clark, 2007)
	Canyons, trenches	Submarine canyons are steep-walled valleys with V-shaped cross sections. A trench is a long, narrow, usually very deep and asymmetrical depression of the sea floor, with relatively steep sides. Ocean trenches are the deepest parts of the ocean, commonly 6 to 10 km in depth. The steep walls of these features tend to create upwellings that support high productivity and biodiversity. Deep-diving pelagic species tend to congregate in the waters above these depressions to feed.	(IHO, 2008; Shephard, 1964)
	Shelf breaks	The shelf break is "the line along which there is a marked increase of slope at the seaward margin of a shelf". Shelf breaks can form fronts in the waters above them, and tend to be highly productive pelagic habitats.	Belkin et al. (2009); (Harris et al., 2014)
	Reefs, islands	Oceanic reefs and isolated islands can form as rises and pinnacles from the deep seabed and break the ocean surface. In their wake, there are often turbulent areas and eddies that entrain plankton and attract larger pelagic species. The deep slopes off the islands and reefs support rich benthic communities that are often habitat for feeding and breeding.	(Rissik and Suthers, 2000)
Hydrographic	Eddies	Eddies are vortex-like circulations of water, usually spinning off major currents, and can occur at various scales. Mesoscale eddies (typically less than 100 km across) tend to be predictable, and can revolve in cyclonic or anti-cyclonic directions, depending on hemisphere. Anticyclonic eddies accumulate organic matter within their cores and exhibit elevated microbial respiration and heterotrophic production. Cyclonic eddies enhance nutrient inputs to the surface ocean increasing new production and chlorophyll concentration. Current estimates suggest that ~50% of the global new primary production may be caused by eddy-induced nutrient fluxes.	Baltar et al. (2010)
	Fronts	A front is a narrow zone of abrupt change in water properties (salinity, temperature, nutrients, etc.) that separates broader areas with different water masses or different vertical structure. They can be a few metres or many thousands of km long. Most fronts are almost stationary and seasonally persistent. The vertical extent varies from a few meters to more than 1 km, with major fronts reaching depths exceeding 4 km. Major thermohaline fronts are associated with fronts in other properties, such as nutrients, ocean colour, chlorophyll, and turbidity. Convergences of surface waters towards fronts contribute to elevated primary production known as "hot spots" of marine life, from phytoplankton to apex predators, and serve as spawning, nursing and feeding areas for fish, sea birds, and marine mammals, with high biodiversity. The surface convergence can also lead to concentrations of pollutants, thus endangering species frequenting the fronts.	Belkin et al. (2009)
	Upwellings and downwellings	Upwelling is a process in which deep, cold water rises toward the surface, usually bringing nutrients from deeper pelagic layers and from the benthos to the upper layers. Downwelling is sinking of accumulated high-density material beneath lower density material, such as colder or saline water beneath warmer or fresher water. Downwelling occurs warm surface water spins clockwise, creating surface convergence and pushing surface water downwards.	Saldivar-Lucio et al. (2016)

APPENDIX 4 GLOSSARY

(Adapted from Lewis et al. (2017))

Abundance (of species): The number of individuals of a particular species occurring within a defined area.

Adaptive management: The cyclical process of systematically testing assumptions, generating learning by evaluating the results of such testing, and further revising and improving management practices. The goal of adaptive management in a protected area context is improved effectiveness and increased progress towards the achievement of goals and objectives.

Anthropogenic: Caused or produced by humans. Used in relation to environmental pollution and pollutants originating from human activity.

Assemblage: (see Community)

Baseline: Information collected about a specific target (e.g. condition of a resource, knowledge, population of a particular species, etc.) at the initial stages of a project, thereby providing a basis for measuring progress or change over time.

Benthic: Relating to or occurring at the bottom of the ocean or seafloor.

Biodiversity: The variability among living organisms and the living complexes of which they are a part. It is expressed in the genetic variability within a species, the number of different species, and the variety of different ecosystems and habitats.

Biomass: The total mass of all organisms of a given type or in a given area.

Boundary: A limiting or bounding line; a geographic area with a discrete perimeter (e.g. the boundaries of a piece of real estate or a country). In terms of an MPA a boundary delineates the area that has been designated to enhance the conservation of marine resources.

Commercial fishery: One where fish are harvested under the authority of a license for the purpose of sale, trade or barter.

Community (biological definition): A collection of different and interacting populations of organisms found living together in a defined area.

Connectivity (biological): The degree to which local production results in recruitment to other populations. For any local population, connectivity could be characterised by: (1) the proportion of recruitment into the local population that is self–sustaining; (2) the proportional contributions of other populations to recruitment into the local population, in a spatially explicit manner; and (3) the spatial distribution and proportional representation of the contributions of local production to externally–based recruitment of other populations.

Conservation: The maintenance or sustainable use of the Earth's resources in order to maintain ecosystem, species and genetic diversity and the evolutionary and other processes which shape them. In the context of the IUCN definition of an MPA, conservation refers to the *in situ* maintenance of ecosystems and natural and semi–natural habitats and of viable populations of species in their natural surroundings.

Climate change: A long–term change in the statistical distribution of weather patterns over periods of time that range from decades to millions of years. It is a change in the average weather conditions or a change in the distribution of weather events with respect to an average; for example, greater or fewer extreme weather events. Climate change may be limited to a specific region, or may occur across the whole Earth.

Cultural value: The value attributed to a human work or place that holds spiritual or historic meaning for a group of people.

Declaration: The act of making an official statement of the intent to create an MPA; a potential first step in a longer process to legally establish an MPA through formal legislative action.

Ecologically important: A community, process, area or species that provides a biological or ecological function, which contributes relatively more value to the greater system.

Ecosystem: A geographically specified system of organisms (including humans), the environment and the processes that control its dynamics.

Edge effect: Ecological changes in population or community structure that occur at the boundary of two or more areas with distinctive characteristics.

Endangered species: A species at risk of extinction due to any number of factors, including human activity, changes in climate, changes in predator–prey ratios, etc.

Enforcement: The act of compelling observance of or compliance with a law, rule or obligation. Enforcement can occur in situ by catching those who may be breaking the regulations or laws of an MPA or by taking civil or criminal enforcement action.

Exclusive economic zone (EEZ): Sea area in which a nation has special rights over the exploration and use of all marine resources, including energy production, fishing and mining, as prescribed by the United Nations Convention on the Law of the Sea. It usually stretches from the baseline out to 200 nautical miles from a nation's coast but can include offshore islands.

Habitat: The living space of an organism, population or community, as characterised by both its biological and physical properties. Habitat types are distinguished from one another by their distinct composition and structure that forms the living space.

High seas (international waters): All parts of the sea not included in the EEZ, in the territorial sea or in the internal waters of a state.

Intertidal: Area located between the elevations of the lowest and highest yearly tides.

Keystone species: A species that has a disproportionately large effect on its environment relative to its abundance. Such species are described as playing a critical role in maintaining the structure of an ecological community affecting many other organisms in an ecosystem and helping to determine the types and numbers of various other species in the community. Loss of keystone species would often precipitate the loss of many ecologically–linked species. As such, keystone species often warrant special conservation attention.

Large–scale MPA (LSMPA): Currently, there is no official definition for what constitutes a large–scale MPA but some NGOs, and the managers of Big Ocean member sites, have chosen to use a working definition that defines these sites as marine conservation areas larger than 150,000 km^2.

Marine protected area (MPA): Any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna and historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment. MPA is used as a generic term to cover all sites that meet the IUCN definition, regardless of purpose, design, management approach or name (e.g. marine reserve, sanctuary, marine park). As well, MPAs are but one of the more general category of protected area which, under the current official IUCN definition, is "A clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long–term conservation of nature with associated ecosystem services and cultural values."

Marine snow: A shower of organic material falling from upper waters to the deep ocean.

Monitoring: The process of observing and checking the progress or quality of something (a resource) through an intermittent (regular or irregular) series of observations in time to show the extent of compliance with a formulated standard or degree of deviation from an expected norm.

MPA Network: A collection of individual MPAs or reserves operating cooperatively and synergistically, at various spatial scales and with a range of protection levels that are designed to meet objectives that a single reserve cannot achieve.

No–take zone: An area that is completely (or seasonally) free of all extractive or non–extractive uses that have an impact on the area.

Objective: A specific statement of what must be accomplished to attain a related goal.

Outcomes: The consequences, effects or real impacts of management actions. Similar to outputs, outcomes help assess the extent to which management objectives are achieved.

Outputs: Resulting products, services or achievements of a planned work programme that arise from a management activity.

Pelagic: Living in the water column of the open oceans or seas.

Permanence: The state or quality of being perpetual; existing or remaining unchanged indefinitely.

Precautionary principle: When there is a lack of full scientific certainty to aid in the decision–making process, one should not use this situation to postpone taking action where the threat is serious or irreversible environmental damage may occur. Additionally, when consequences are uncertain, managers err on the side of caution, thereby giving the benefit of the doubt to nature, public health and community well–being.

Protected species: A species (animal or plant) which is forbidden by law to harm or destroy.

Protection: Any regulatory or other provision to reduce the risk of negative human impacts on an area or species.

Recruitment (biological): The addition of a new cohort to a population. The magnitude of recruitment depends on the time and life history stage at which it occurred.

Remote sensing: The science of gathering data on an object or area from a considerable distance. Standard technologies often include satellites, radar and infrared photography. For the marine environment, additional technologies can also include visual identification, echo–sounders and sonar, as well as LIDAR (Light Detection and Ranging) and similar laser technologies mounted to UAVs (unmanned aircraft or drones).

Replication: The process of duplicating or replicating a process, procedure or outcome, such as in scientific experiments.

Representative (sample): A selected subset of a group whose characteristics reflect those of the population from which it is drawn.

Reserve (or marine reserve): No-take marine protected area.

Resilience: The ability of a system to maintain key functions and processes in the face of stresses or pressures by either resisting or adapting to change. Resilience can be applied to both ecological systems and social systems.

Shifting baselines: Refers to the fact that people measure ocean health against the best they have experienced in their own lifetimes – even if those measures fall far short of historical ones. One generation sets a baseline for what is healthy and natural, based on its own experience. Successive generations see even more degraded ecosystems as healthy and therefore set their standards for ecosystem health even lower.

Species: A group of organisms differing from other groups of organisms and that can breed and produce fertile offspring.

Species richness: The number of different species that exist within a given area or community.

Stakeholder: An individual, group or organisation that has a vested interest in, can influence or may be directly affected by the establishment of an MPA or a particular management strategy.

Subtidal: Area below the low–tide level.

Threat: A factor with immediate negative impacts on the natural or cultural resources of an MPA, such as biodiversity, food security or livelihoods.

Threatened species: A species likely to become endangered if limiting factors are not reversed.

Viability: The ability to live, especially under certain conditions; the capacity to operate or be sustained; the capability of becoming actual, useful or practicable, etc.

Vulnerable: Particularly sensitive to impacts from human activities or natural events.

Zoning: A process in which marine areas, including marine protected areas, are divided into discrete zones, each permitting and regulating specific human activities through conditions such as gear limitations in fishing and waste discharge prohibitions in tourism.

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