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Existing global marine protected area network is not representative or comprehensive measured against seafloor geomorphic features and benthic habitats

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ABSTRACT

The Aichi targets of the Convention on Biological Diversity leverage the use of protected areas to halt the loss of global biodiversity. Target 11 recommends that ecologically representative portions (10%) of important coastal and marine areas be set aside within MPAs. Despite global progress in attaining the 10% target, few areas are set aside with consideration of ecological representation (area and diversity of features) as a conservation goal. Using publicly available datasets of marine geomorphic features and benthic habitats, we assessed the relative representativeness of features, by assessing feature coverage and diversity, within existing protected areas of both Large Marine Ecosystem (LMEs) and Exclusive Economic Zones (EEZs). Only 18 of the 66 LMEs contained greater than 10% of their marine geomorphic features and benthic habitats within MPAs. The Caribbean, Pacific Central, Mediterranean and Canary Current LMEs were identified as areas that protected the most diversity, while the geomorphically diverse Arctic Ocean had the least area of features within MPAs. Less than one quarter of EEZs (46 out of 230) had more than 10% of their geomorphic features and benthic habitats within MPAs. The coral triangle and other warm water reef areas are clear priorities for conservation, exhibiting high diversity of geomorphic features and benthic habitats, yet, most LMEs and EEZs in these areas fail to achieve representativeness or 10% feature coverage. Australia, New Zealand and the United States and areas in Europe and the South Pacific achieve relative representativeness scoring highly in coverage and diversity of features protected. Assessing the coverage and diversity of protected features within EEZs and LMEs can assist nation states and ecosystem management regions to better assess representativeness in achieving the 2020 Aichi targets.

1. Introduction

1.1. Global targets for conservation of ocean biodiversity

Global concern over the declining condition of ocean species and habitats has prompted nations to develop international agreements such as the Convention on Biological Diversity (CBD). The CBD's Aichi targets are a series of twenty, time-bound, measurable targets set out as a strategic plan for marine biodiversity conservation. Target 11 leverages the use of protected areas as conservation tools and states that at least 17 per cent of terrestrial and inland waters, and 10 per cent of coastal and marine areas "… are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas …" To achieve this target, governments have established more and larger marine protected areas. Despite the rapid progress, many MPAs have not been placed in the best locations (Lubchenco and Grorud-Colvert, 2015) and have failed to meet thresholds for effective and equitable management processes (Gill, 2017; Worm, 2017). These conservation interventions, made to fulfil targets, have often given a false illusion of progress and have also presented opportunity costs that impede further conservation (Agardy et al., 2016). To address this, the Aichi Targets have been strengthened by the United Nations 2030 Agenda Sustainable Development Goals (SDGs). These include SDG-14, "Conserve and sustainably use the oceans, seas and marine resources for sustainable development," and SDG-14 Target 14.5, "By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information".

In 2008, CBD parties attempted to define further scientific guidance for establishing representative networks of MPAs. This included establishing, ecologically or biologically significant marine areas incorporating the principles of comprehensiveness, adequacy and representativeness together with elements of connectivity, replication of ecological features, as well as adequate and viable sites (Rees et al., 2017; Harris and Whiteway, 2009). Including representation as a conservation goal in trying to achieve such targets will require characterization of habitats and mapping of habitat distributions to develop an understanding of which MPAs, nations or ecosystems have the potential

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to conserve representative portions of global biodiversity (Agardy et al., 2016). Being ecologically representative means that protected areas should contain adequate samples of the full range, feature coverage and diversity of existing habitats.

Quantifying progress toward international environmental commitments and developing metrics that incorporate representation is critical for assessing protected area impact and efficacy (Tittensor et al., 2014) and can help prioritize where and how future MPA development occurs (Jenkins and Van Houtan, 2016). Building on extensive, publicly available datasets, the present study characterizes the global distribution and diversity of marine geomorphic features and benthic habitats within the existing global marine protected area network. Specifically, it looks at what features are represented in the globally established marine protected areas within national jurisdictions (exclusive economic zones) and bioregions (large marine ecosystems).

1.2. Seabed geomorphic features and benthic habitats are a proxy for biodiversity

The ocean contains a vast amount of biodiversity and this biodiversity depends on, among other things, the heterogeneity of geomorphic habitats. The variety of geomorphic features and its links to biodiversity on terrestrial environments were first inferred by Alfred Russel Wallace in "*A Narrative of Travels on the Amazon and Rio Negro*" published in 1889 (Wallace, 1889). Subsequent studies further illustrated links between the heterogeneity of geomorphic habitats (or geodiversity) and biodiversity. Schmidt (1998) demonstrated that diversity on Mediterranean Islands reflected their *physiographic complexity*, while Burnett et al. (1998) and Nichols et al. (1998) showed links between geomorphic heterogeneity and biotic diversity across small patches and landscapes. Many of these studies relate back to early discussions of the controls of dynamic equilibrium and associated turnover in island biogeography theory (Macarthur and Wilson, 1967) being ascribed to effects of a rigorous physical environment (Simberloff, 1976). The so-called "habitat heterogeneity hypothesis" is now largely accepted and explains why positive correlations between habitat heterogeneity/diversity and animal species diversity exists (Tews et al., 2004; Buhl-Mortensen et al., 2010; Williams et al., 2010). Examining the representativeness of geomorphic habitats within MPAs can therefore further guide biodiversity conservation measures.

In the marine environment, geomorphic habitats provide a heterogeneous and dynamic physical framework, supporting a high diversity of habitats and species across a range of scales (Harris and Baker, 2012b). For example, and despite scientific debate (McClain, 2007), seamounts have been shown to provide physiographic complexity supporting a greater variety of species. The diversity of life on seamounts is typically high across several taxa (Richer de Forges et al., 2000; Morato et al., 2010; Kvile et al., 2014) and seamounts create 'oases' with an abundance of species and high population densities (Samadi et al., 2006), elevating levels of biodiversity (Roberts, 2002). Within submarine canyons, multiple linked processes related to habitat heterogeneity, ecosystem engineering, and bottom-up dynamics are important to deep-sea biodiversity (McClain and Barry, 2010; Huang et al., 2017). As sites of enhanced organic-matter flux and deposition, dense shelf-water cascades, channelling of resuspended particulate material, and topographically induced internal wave pumping and upwelling, submarine canyons have been identified as potential hotspots of primary production and commercial fisheries yields (Ryan et al., 2005, 2010, De Leo et al., 2010, Cunha et al., 2011, Moors-Murphy, 2014).

For other geomorphic habitats, spreading ridges harbour distinctive microbial communities in relation to surrounding areas (Lysnes et al., 2004) and deep-sea vent communities display remarkable physiological and phylogenetic diversity (Sogin et al., 2006; Nakagawa and Takai, 2008). On abyssal hills, benthic assemblages and trophic composition are significantly different from the abyssal plain and are correlated with sediment size distribution (Durden et al., 2015). Likewise, faunal benthos can vary in relation to sediment distributions on continental shelves (Ellingsen, 2002) and shallow subtidal habitats (Schaffner, 1990). Trenches harbour a relatively high degree of endemism (Paterson et al., 2009) an important concept in biodiversity hotspot conservation (Myers et al., 2000). Small-scale habitat structure (e.g. sponges) on the deep-sea floor can also create heterogeneous environments that influence the diversity of surrounding communities (Hasemann and Soltwedel, 2011). Likewise, mangroves, seagrasses and coral reefs play key ecological roles in coastal ecosystems by forming extensive stretches of habitat supporting high biodiversity and providing a high level of ecosystem goods and services (Costanza et al., 1997; Hoeksema, 2017). Overall, marine landscapes in topographically complex seabed areas possess higher species diversity than areas with fewer seabed features (Kaskela et al., 2017).

The aims of the present study are to (1) develop a global map of benthic habitat diversity based on seafloor geomorphology, (2) examine the representativeness of the existing inventory of global marine protected areas; and (3) quantify national obligations, priorities and accomplishments in biodiversity conservation, especially with regards to the Aichi targets. We demonstrate how geomorphic heterogeneity is a valuable tool in assessing biodiversity conservation planning (Parks and Mulligan, 2010) and for the management and delivery of ecosystem services (Thomas, 2012). Furthermore, our assessment of representativeness and diversity within MPAs provides: 1) guidance in replacing underperforming protected areas (Fuller et al., 2010); 2) information for the design of deep-sea reserves in regions that are under consideration for submarine mining (Vrijenhoek, 2010); and 3) a better understanding of anthropogenic impacts on geomorphic ecosystems (Fernandez-Arcaya et al., 2017).

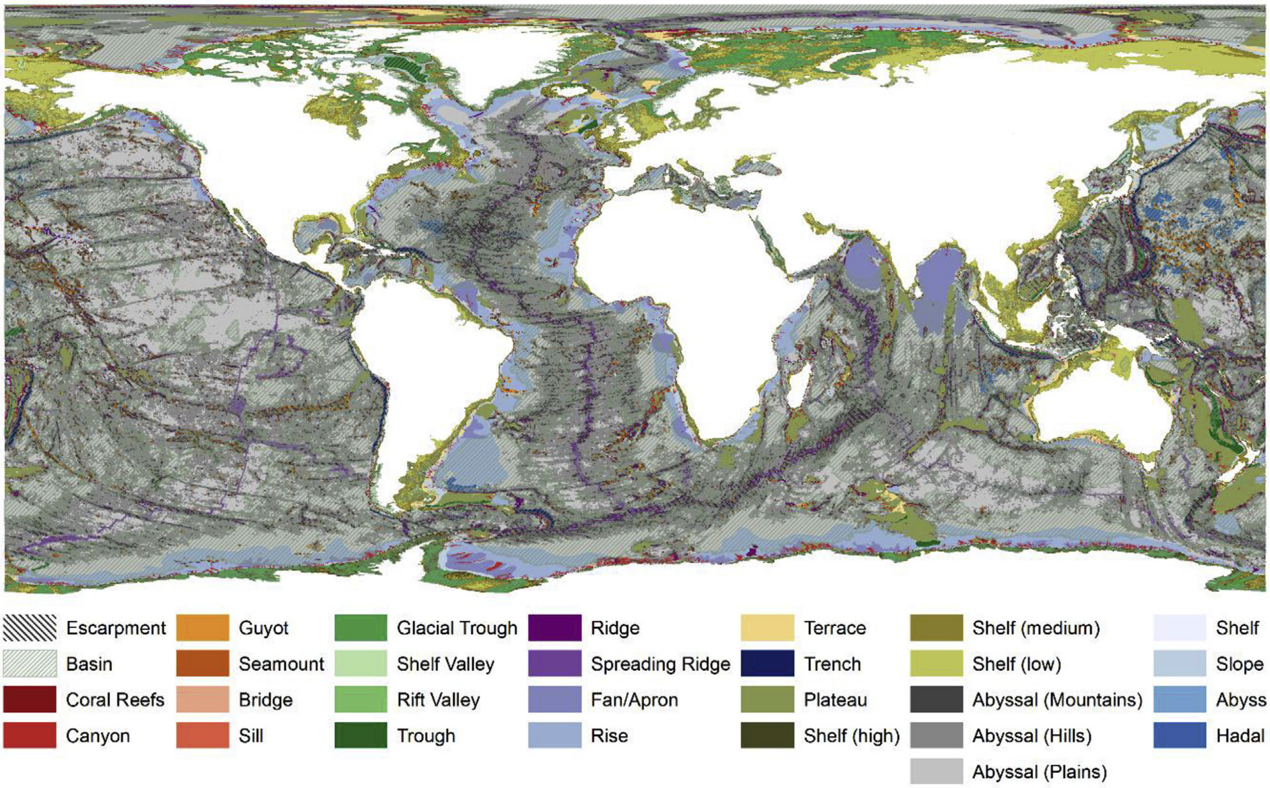
2. Methods

2.1. Data sources

Four primary data sources were utilized in this study, 1) Exclusive Economic Zones Boundaries, 2) the World Database on Protected Areas, 3) Large Marine Ecosystem Boundaries and 4) the Digital Global Seafloor Geomorphic Features map. The digital global seafloor geomorphic features map (GSFM) is a collaborative effort of Conservation International, GRID-Arendal and Geoscience Australia and is based on the analysis and interpretation of a modified version of the SRTM30_PLUS global bathymetry grid (Harris et al., 2014). Nineteen geomorphic features and benthic habitats were considered in this study (Fig. 1). The GSFM data set was supplemented with global coverage of seagrasses, mangroves and coral reefs data sets created by the World Conservation Monitoring Centre (Spalding et al., 1997; UNEP-WCMC et al., 2010; Short, 2016).

To estimate protected area coverage and representativeness of the GSFM, we used the January 2017 data from the World Database on Protected Areas (WDPA). The European Union Joint Research Commission, who uses this layer in the BlueBridge Virtual Research Environment platform (http://www.bluebridge-vres.eu), made several modifications to the dataset. First, only marine protected areas were extracted from the dataset. Protected areas for which only point locations and estimated extents are available, circular buffers were created with areas equal to the reported areas. Although this allowed for the inclusion of more protected areas, circular features do not reflect actual boundaries, potentially leading to some over- and under-estimation of geomorphic features and benthic habitats within MPAs. This is likely to have a minor effect at the global scale.

Further revisions included the removal of all polygons with STATUS = "not reported" and STATUS = "proposed," and the removal of MPAs with no reported area. No differentiation was made between varying levels of implementation or management within MPAs, because these data were not readily available. The additional site of the East



1. Shelf	2. Slope	3. Abyssal	4. Hadal
5. Mangroves*			
6. Seagrasses*			
7. Coral Reefs*			
8. Shelf valleys			
9. Glacial troughs		10. Ridges	
		11. Rift valley	
	12. Escarpments	12. Escarpments	12. Escarpments
	13. Seamounts	13. Seamounts	13. Seamounts
	14. Guyots	14. Guyots	
	15. Canyons	15. Canyons	
	16. Ridges	16. Ridges	16. Ridges
	17. Troughs	17. Troughs	17. Troughs
		18. Trenches	18. Trenches
	19. Plateaus	19. Plateaus	

Fig. 1. The marine geomorphic features map and the modified hierarchy of geomorphic features used in the present study (adapted from Harris et al., 2014). Mutually exclusive base layer features are the shelf, slope, abyss and hadal zones. Classification layers of the abyss (mountains, hills and plains) and shelf (low, medium and high) layers, as described Harris et al. (2014), are considered as only individual features (e.g. abyss and shelf). The occurrence of some features were confined to one of the base layers, whereas the occurrence of other features are confined to two or more base layers, as illustrated by shading; elsewhere the feature layers and classification layers may overlay each other (eg. escarpments on seamounts; ridges and seamounts on the abyss; etc.). * The mangrove, seagrass and coral reef layers were obtained from the World Conservation Monitoring Centre (Spalding et al., 1997; Short, 2016; UNEP-WCMC et al., 2010). These layers were not modified in any way.

Antarctica and Ross Sea MPA, not included in the January 2017 WDPA data set, was added. MPAs across all IUCN categories (I-VI), even those not designated under an IUCN category, were considered.

The Large Marine Ecosystem (LME) Boundary layer was obtained from the Large Marine Ecosystem Program NOAA-Fisheries (NOAA, 2017). Large Marine Ecosystems (LMEs) are large areas of ocean space typically greater than 200,000 km^2 and are adjacent to the continents in coastal waters where primary productivity is generally higher than in open ocean areas (Sherman, 1991). Currently there are 66 LMEs. Lastly, we used the Flanders Marine Institute Exclusive Economic Zone (EEZ) boundary layer (Flanders Marine Institute, 2016). Two hundred and thirty EEZs, which excluded disputed areas and joint regime areas, were

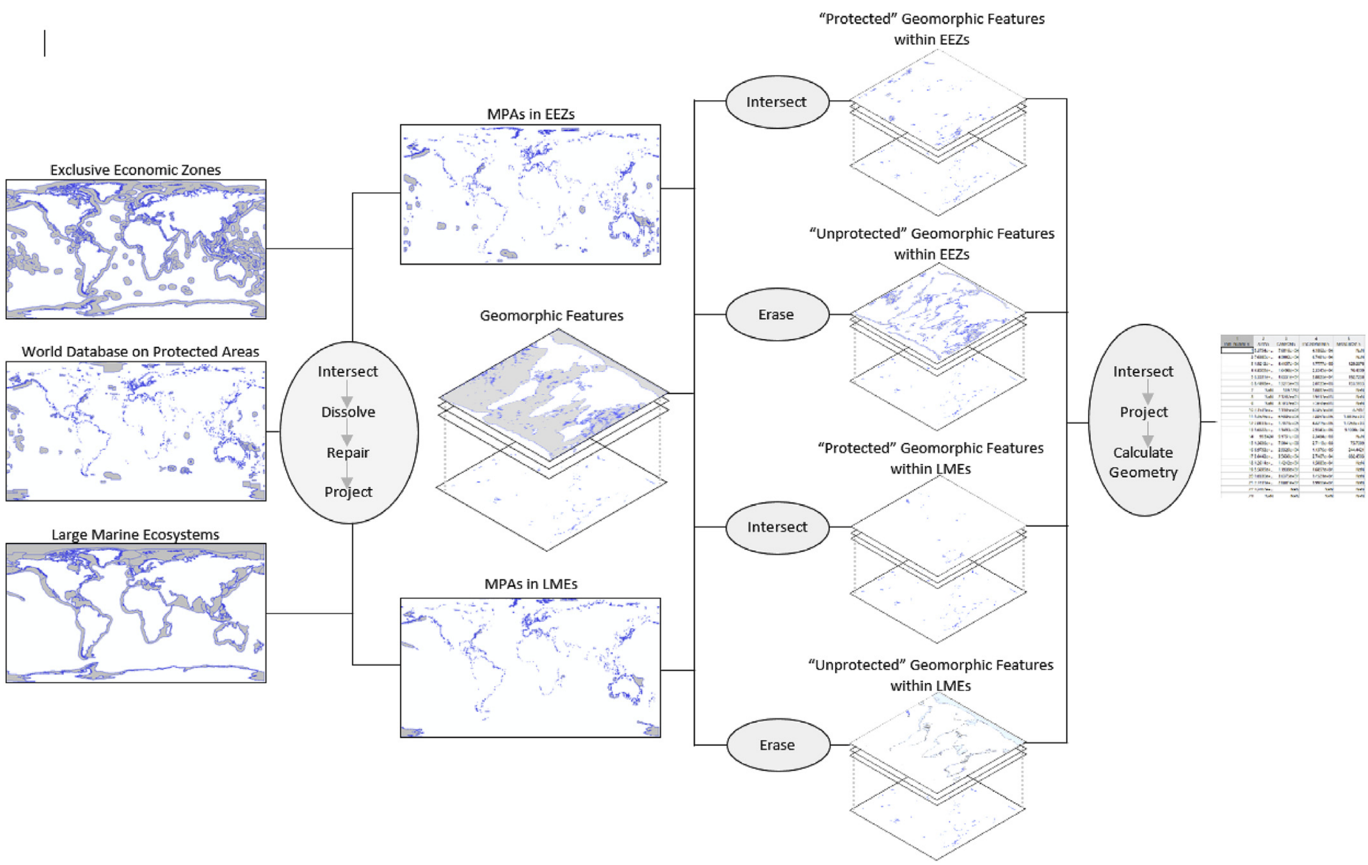


Fig. 2. A schematic of the geoprocessing workflow developed using ModelBuilder in ArcGIS 10.5 for Desktop.

considered in this analysis. Territorial claims of the Antarctic were not included, but rather the Antarctic was considered as a single entity EEZ with the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) as the managing body.

2.2. Data processing and analysis

To derive the representative coverage or area (km^2) of geomorphic features and benthic habitats within and outside of existing MPA boundaries, a geoprocessing workflow was developed using ModelBuilder in ArcGIS 10.5 for Desktop (Fig. 2). Initially, both the EEZ and LME layers were intersected with the modified WDPA layer to create two layers that represent marine protected areas (MPAs) within EEZs and MPAs within LMEs. Next, in each of these layers, overlapping features were dissolved to avoid calculating overlapping areas, geometries were validated and repaired, and the layers were projected into the common coordinate system (WGS84) of the geomorphic feature layers. The MPAs in EEZ layer and the MPAs in LME layers were then both passed through the Intersect and Erase tools with each of the 19 global geomorphic features and benthic habitats to isolate features and habitats that fall within MPAs in EEZs and LMEs. The same procedure was conducted using the Erase tool to find portions of the 19 geomorphic features and benthic habitats that fall outside MPAs in both EEZs and LMEs. The area (km^2) of features and habitats (within and outside of the MPA boundaries for EEZs and LMEs) was calculated based on three projected coordinate systems. For areas between 60 and 90° north, the North Pole Lambert Azimuthal Equal Area projection was used. For areas between 60° north and 60° south the World Eckert IV projection was used while, for areas between 60 and 90° south the South Pole Lambert Azimuthal Equal Area projection was used. The areas of mangroves and seagrasses were determined using a merged country boundary and EEZ/LME files with the coastline removed, to obtain a more accurate estimate of the protected extent of these features.

A region dominated by one or two geomorphic features and benthic habitats is less diverse than one that has several features and habitats. In order to provide a quantitative measure reflecting how many different types of features and habitats there are in each LME and EEZ, while simultaneously taking into account their relative abundance, the reciprocal Simpson index was calculated (Simpson, 1949; Primack and Sher, 2016).

$$1/D = \frac{\sum_{i=1}^{R} n_i(n_i - 1)}{N(N-1)} \tag{1}$$

where n_i is the number of entities belonging to the ith feature and N is the total number of entities for each individual LME and EEZ. In this study, we have calculated the reciprocal Simpson index for all portions of LME's and EEZ's within MPAs to assess the diversity or representativeness of geomorphic features and benthic habitats (entities) under protection in these administrative and bioregional boundaries. This index has been widely used to assess regional geodiversity and landscape complexity (Honnay et al., 2003; Benito-Calvo et al., 2009; Persson et al., 2010).

2.3. Focal variety analysis

To assess spatial patterns in the variety of geomorphic habitats at a global scale, a focal variety analysis was conducted using the focal statistics tool in ArcGIS 10.5. The focal statistic tool calculates, for each input cell location, a statistic of the values within a specified neighbourhood around it. In this analysis, the "variety" statistic was applied, which calculates the number of unique values of the cells in the specified neighbourhood. First, the geomorphology of the seafloor was viewed as a hierarchy of base layers for the shelf, slope, abyss and hadal

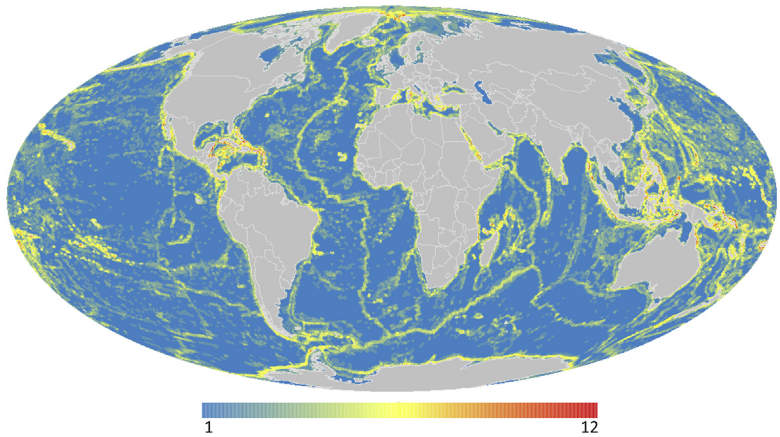


Fig. 3. Focal variety map showing the distribution of the spatial heterogeneity of global geomorphic features. The red color indicates that 12 different geomorphic features are represented in a (50 km radius) neighbourhood. The blue color indicates that only one feature is represented. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

zones overlaid with discrete feature layers (Fig. 1). The layers were flattened and rasterized to a one kilometer cell size. Focal variety analysis was then applied to the rasterized layer using a circular neighbourhood with a radius of 50 km. The ultimate output is a diversity map of geomorphic features and benthic habitats and a relative measure of global biodiversity.

3. Results

3.1. Focal variety

The focal variety map (Fig. 3) identifies global regions representing different levels of geomorphic heterogeneity. Each circular 50 km neighbourhood represents the number of unique features found within each cell. Higher values represent a higher variety in the number of features and therefore represent a more heterogeneous area. Regions with high diversity of geomorphology possess a greater diversity of benthic habitats and are thus predicted by the "habitat heterogeneity" hypothesis to possess greater biodiversity. These regions include the Coral Triangle area in the Western Pacific Ocean, the Caribbean, the Mediterranean, the Red Sea, areas in the Arctic Ocean (Greenland Sea), and areas of the western South Pacific, including the northeast Australian shelf. Geomorphologically diverse zones also occur along the juncture of the continental shelves/slopes and along the mid-ocean spreading ridges (Fig. 3).

3.2. Feature area and diversity within MPAs of LMEs

There are approximately 84 million km^2 of LMEs with an effective area of approximately 6.8 million km^2 (8%) within MPAs. A summary of geomorphic features and benthic habitats within MPAs is shown in Table 1. Features that have the greatest area within MPAs include the abyssal plain (2.5 million km^2), slope (1.2 million km^2), shelf (2.7 million km^2), escarpments (0.5 million km^2), and plateaus (0.7 million km^2). Features with the greatest proportion of area within the MPAs of LMEs include coral reefs (47%), guoyts (42%), mangroves (43%), seagrasses (32%). Trenches, spreading ridges, rift valleys and the hadal had < 0.1% within MPAs.

All 66 LMEs contained at least one MPA that protected a geomorphic feature or benthic habitat. The area (km^2) of features and habitats within MPAs of specific LMEs is shown in Fig. 4a. The four LME's having the greatest area within MPAs are the Northeast Australian Shelf (1.9 M sq km), Antarctica (0.97 M sq km), Insular Pacific-Hawaiian (0.93 M sq km) and the Gulf of Alaska (0.67 M sq km), protecting 13, 7, 11 and 11 out of 19 features, respectively.

Seventeen LMEs had < 1.0% coverage or area of features and habitats within MPAs. The Northeast Australian Shelf was the only LME with greater than 90% of its features within MPAs. Rift valleys and the hadal zone were represented in the protected areas of only 0 and 2 LMEs, respectively, while actually being present in 14 and 9 LME boundaries. The hadal zone was protected only in the Caribbean Sea and the South West Australian LMEs. The continental shelf had the highest representation, with 64 LMEs having some area of shelf within an MPA.

Table 1
Total square area (km^2) of the 19 geomorphic features that fall within and outside of protected area boundaries of Large Marine Ecosystems (LMEs), the percent of the geomorphic feature by LME that falls within a marine protected area (MPA) boundary and the number of LMEs that contain geomorphic features not included in any MPA. Features with **bold text** have the greatest area (not percentage) within MPAs. Features *in italics* are those with more than 30% within MPAs. Differences exist in statistics shown for LMEs and EEZs (Table 2) because there is not 100% overlap between the two (i.e. EEZs extend 200 nautical miles offshore in some places where LMEs do not).

	Feature area within MPAs (km^2)	Feature area outside MPAs (km^2)	% area within MPA	# of LMEs without features within MPAs
Abyss	**2,527,141**	34,760,062	7%	30
Canyons	234,430	2,519,310	8%	23
Escarpments	**503,119**	4,215,584	11%	22
Mangroves	64,486	84,827	*43%*	33
Coral Reefs	45,308	52,124	*47%*	42
Seagrass	218,417	469,867	*32%*	29
Glacial Troughs	387,513	3,242,296	5%	49
Guyots	62,425	86,447	*42%*	60
Hadal	255	311,413	0%	64
Plateaus	**781,705**	4,352,086	15%	50
Ridges	179,636	961,180	16%	43
Rift Valley	0	87,324	0%	66
Seamounts	93,251	565,684	14%	50
Shelf	**2,754,311**	27,683,713	9%	2
Shelf Valley	474,629	4,218,293	6%	12
Slope	**1,229,938**	12,746,488	9%	15
Spreading Ridges	97	564,455	0%	65
Trenches	575	579,762	0%	64
Troughs	114,219	953,114	11%	53

Of the 66 LMEs analysed, 18 have over 10% coverage features and habitats within MPAs, 12 had over 20%, and three LMEs had over 50% within MPAs. However, percent coverage did not necessarily correlate (Pearson's linear correlation coefficient) with the diversity of features ($r = 0.2814$, $p < 0.05$). As is evident in Fig. 4a, some zones and ecosystems protect large areas of a single feature (e.g. Yellow Sea, Bengula Current and Patagonian Shelf LMEs), while some protect a greater diversity of features (e.g. Aleutian Islands, Northwest Australian Shelf).

Maps of the overall percent cover of geomorphic features and benthic habitats within MPAs of LMEs and the corresponding diversity index (Fig. 5a and b) show that LMEs with the highest diversity index

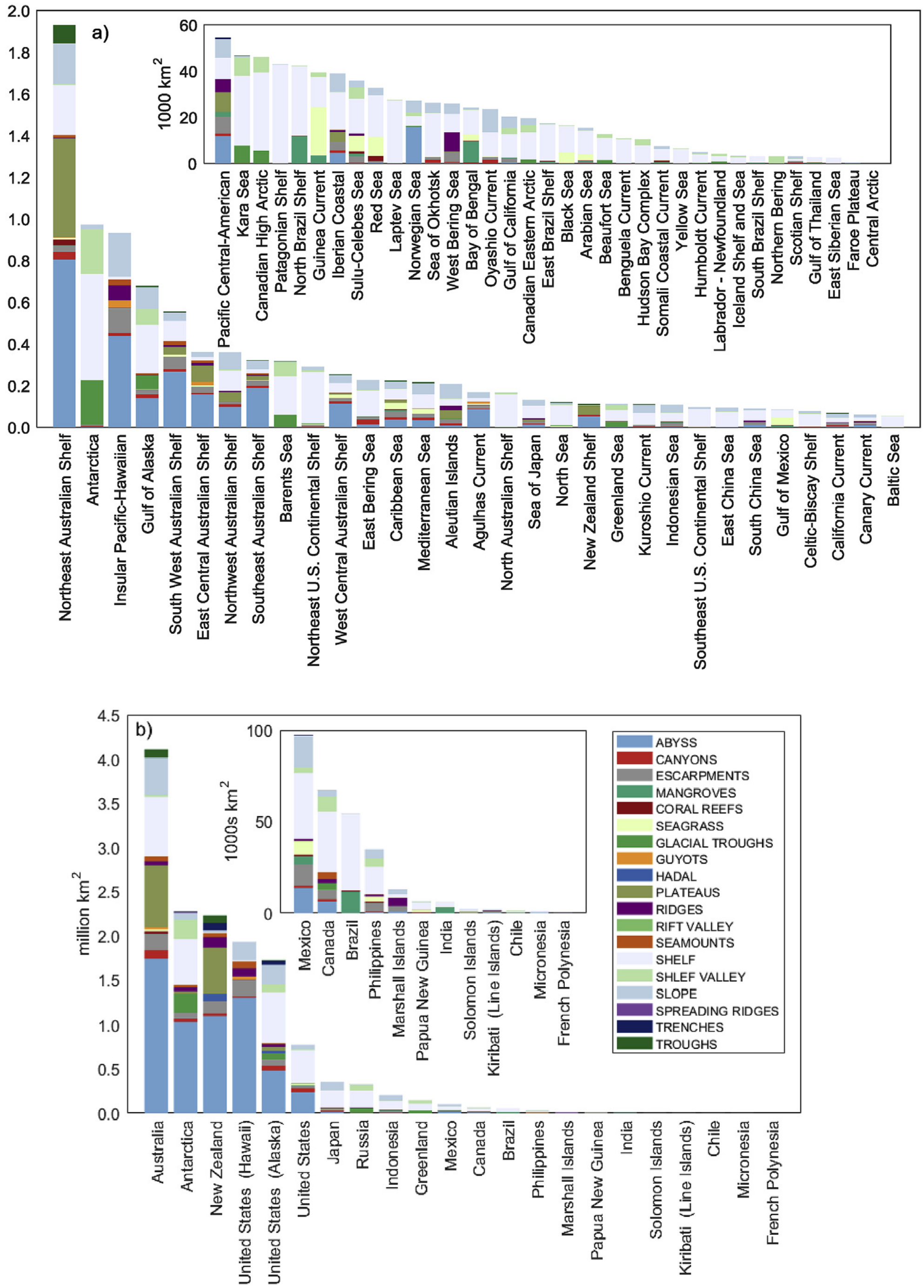


Fig. 4. Total area of geomorphic features occurring in marine protected areas: a) within Large Marine Ecosystems (LMEs); and b) within the 22 exclusive economic zones (EEZs) that hold over 50% of the global marine estate. The colors represent geomorphic feature types (same as Fig. 1). The inset panels show the data for smaller area LMEs and EEZs using a different vertical scale. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

include the Pacific Central-American Coast (diversity score of 6.14), Caribbean Sea (5.98), Canary Current (5.45), Aleutian Island (5.07) and the Gulf of Alaska (4.80). LMEs with the lowest diversity score include the Central Arctic, East Siberian Sea, North Bering – Chukchi Seas, Laptev Sea and the Patagonia Shelf. LMEs with a relatively high percent of features within MPAs (> 10%) but low diversity scores were the Baltic Sea (12.5% within MPAs/diversity score of 1.3), the North Australian Shelf (20.6/1.8) and the Southeast U.S. Continental Shelf (24/1.2), the Northeast U.S. Continental Shelf (79.1/1.36). Dividing all LMEs into quantiles by the percent area within MPAs and diversity scores shows that the top quantile is populated by LMEs that have over 10% of their features and habitats within MPAs (Fig. 5a). However, only the Gulf of Alaska LME is in the top quantile for both percent of features in MPAs and diversity score.

The focal variety analysis (Fig. 3) identifies major coral reef ecosystems as regions of high geomorphic variety and diversity. The majority of LMEs in these regions (e.g. South China Sea, Indonesian Archipelago and the Sulu-Celebes Seas) fail to achieve greater than 10% of identified geomorphic features and benthic habitats within MPAs (Fig. 5a). Other highly diverse regions, such as the Central Arctic/East Greenland Seas also fall into the lower quantiles of less than 10% of features within MPAs.

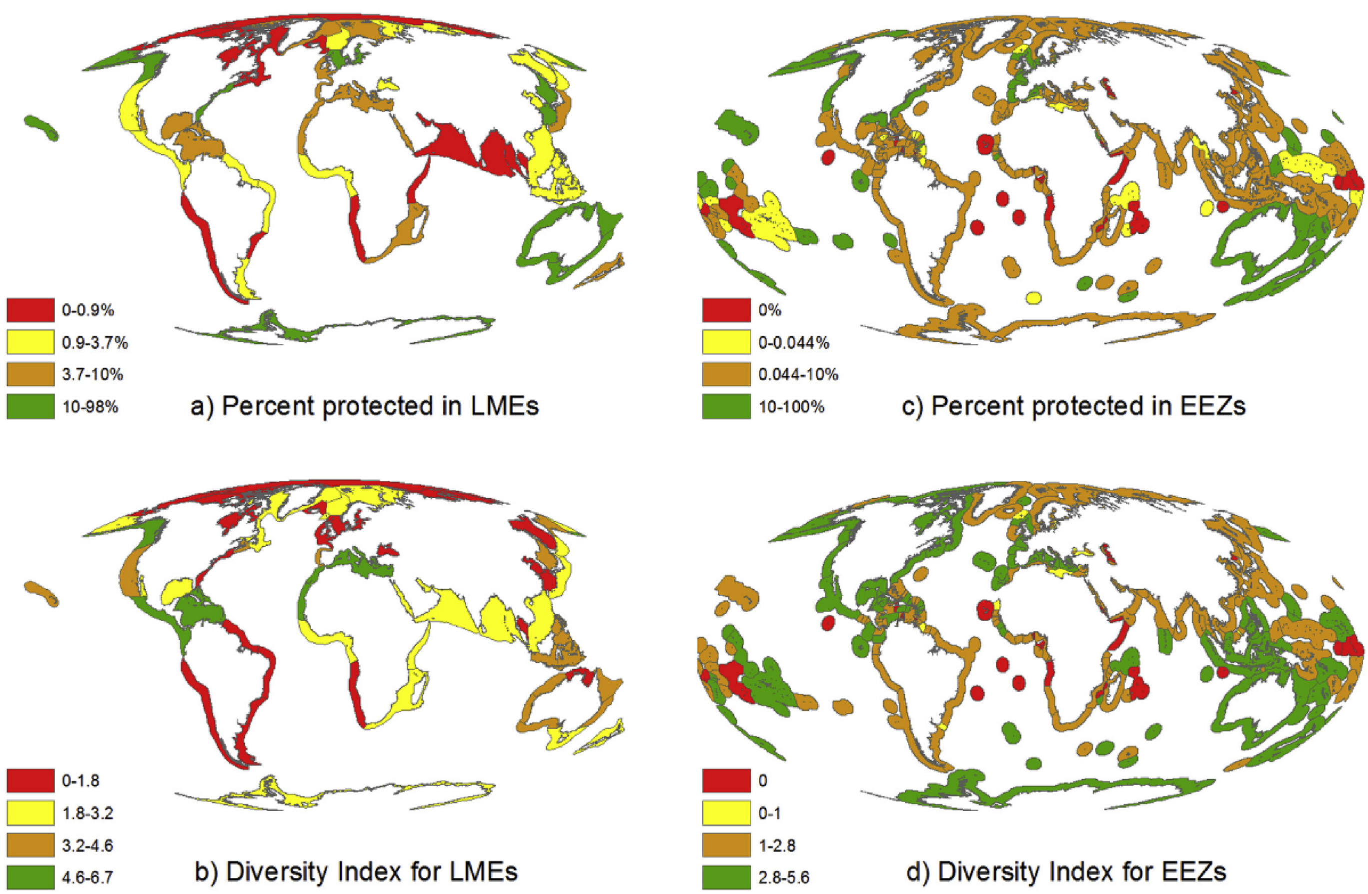


Fig. 5. Measurements of geomorphic heterogeneity to assess marine protected area (MPA) representativeness: a) percent of geomorphic features occurring in MPAs within Large Marine Ecosystems (LME); b) the Simpson's diversity index, taking into account the number and abundance of geomorphic features occurring in MPAs within LMEs; c) percent of geomorphic features occurring in MPAs within Exclusive Economic Zones (EEZ). The lowest quantile (red) represents EEZs with 0% of its area within MPAs. The top quantile (green) represents 10–99% of features within MPAs; and, d) Simpson's diversity index, taking into account the number and abundance of geomorphic features occurring in MPAs within EEZs. Measures of heterogeneity were divided into quantiles and assigned colors to each quantile: green = highest quantile, orange = second highest quantile, yellow = second lowest quantile, red = lowest quartile. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The Caribbean is a geomorphologically diverse region, containing 15 of the 19 features analysed, within MPAs. It is also one of the two regions having hadal features within MPAs. Though it attained a higher diversity score, only 4.3% of the geomorphic features and benthic habitats in the region are represented within MPAs. Likewise, the Pacific Central-American Coastal region also attained a high diversity score but only had 1.8% of its features within MPAs. Conversely, the Northeast U.S. Continental Shelf, which had over 79% of its features and habitats protected, was identified as an area of relatively low diversity. Other large marine ecosystems exhibiting a high proportion of percent protected, but low diversity scores include the area of the North Australian Shelf, the Baltic Sea and the Southeast and Northeast U.S. Continental Shelves. The Mediterranean, which contained nine of the 19 features analysed, was also identified as an area of high diversity in the focal variety map and with the Simpson's diversity index, yet had only 6.5% of features within MPAs.

While close to half (30) of all LMEs (66) appear to have > 10% of their physical boundaries within MPAs, several do not contain a representative portion (> 10%) or diversity of features and habitats (Fig. 6a). Ecosystems such as the Greenland Sea and the Canadian High Arctic – North Greenland appear to be highly heterogeneous regions, geomorphically, with large areas set aside as MPAs (Fig. 3), yet provide protection for only 6.2 and 4.5% of their features and habitats, respectively. These LMEs also set aside a relatively a low-level diversity, scoring 3.1 and 1.7, respectively (Figs. 5b and 6a), within their MPAs. These LMEs, while appearing to achieve the 10% Aichi target, have relatively low representation within MPAs. On the other hand, large marine ecosystems, such as the Aleutian Islands, the Gulf of Alaska and the Northwest Australian shelf appear to have representative portions, set aside in MPAs and maintain a higher-level diversity representation (Fig. 6a). Overall, the majority of LMEs lack sufficient coverage and diversity representation within protected areas.

3.3. Feature area and diversity within MPAs of EEZs

Globally, EEZs (excluding disputed and jointly managed areas) cover a total area of 146,254,021 million km^2 with approximately 19 million km^2 or 13%, falling within MPAs. Features that had the greatest area within MPAs include the abyssal plain (11 million km^2), shelf (3.5 million km^2), slope (1.7 million km^2), escarpments (1.5 million km^2), and plateaus (2.1 million km^2). Features with the greatest proportion of area occurring in MPAs include mangroves (41%), coral reefs (39%) and seagrasses (18%). Spreading ridges and rift valleys had the lowest percentage occurring in MPAs at less than 1% each (Table 2).

One hundred and forty-seven of the 230 EEZs had some area (> 1%) of features or habitats falling within MPAs, with 39 of the 230 EEZs have no (0%) feature coverage within MPAs (Fig. 5c). The shelf was well represented within MPAs, appearing in 181 EEZs. Features that occur in MPAs in the least number of EEZs are glacial troughs (11 EEZs), rift valleys (8), spreading ridges (13), deep ocean trenches (12) and deep ocean troughs (26 EEZs; Table 2).

Only 46 of the 230 EEZs examined in this study have greater than

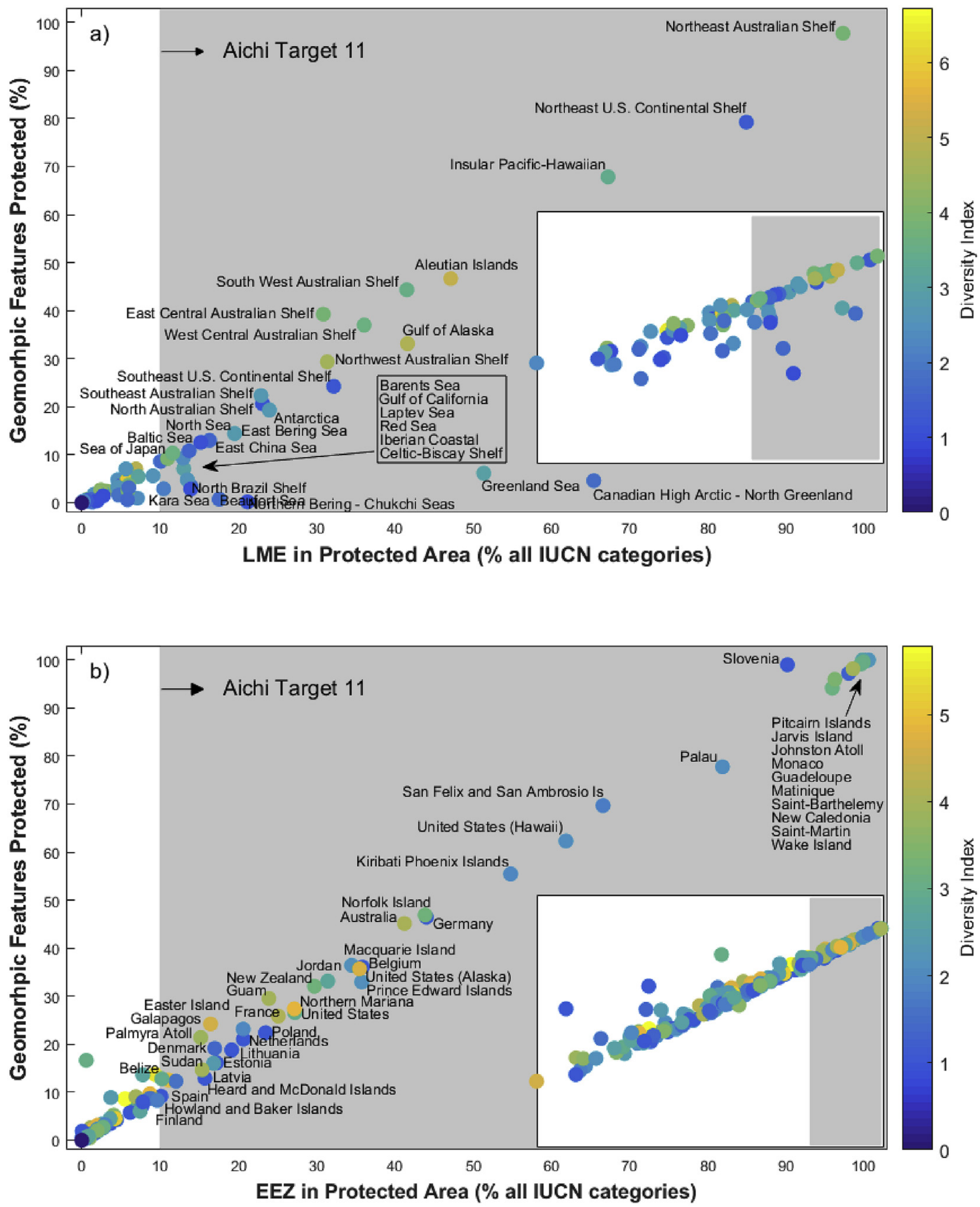


Fig. 6. a) The relationship between the percent of marine protected areas within LMEs, the percent area of geomorphic features within MPAs and the diversity of the geomorphic features within MPAs. The inset show the same data plotted on a log-log scale to highlight LMEs with less than 10% of their area within MPAs. b) The relationship between percent of marine protected areas within EEZs, the percent area of geomorphic features within MPAs and the diversity of the geomorphic features within MPAs. The inset show the same data plotted on a log-log scale to highlight the EEZs with less than 10% of their area within MPAs.

10% of their geomorphic features and benthic habitats within MPAs. Twenty-one of the 46 EEZs (46%) are considered overseas territories, collectivities and commonwealth areas, or special areas beyond continental boundaries. Examples include New Caledonia, a territory of France, and Heard and Macdonald Islands, a territory of Australia. Overseas regions, such as Saint Barthélemy, Martinique and Guadeloupe (France), in the Caribbean, and small islands, such as Macquarie Island (Australia) and Prince Edward Island (South Africa) are essentially managed as offshore special nature reserves. A further thirteen of the 46 EEZs (28%) are part of the European Union and the European Economic Area. Areas not considered overseas territories or regions or part of the EAA, include the United States (27%), Australia (45%) and New Zealand (32%), Palau (78%), Sudan (16%), Belize (13%), Jordan (33%), Guinea Bissau (14%) and Monaco (99%). These EEZs had large portions of their geomorphic features and benthic habitats within protected areas.

When considering EEZs that constitute 50% of the global marine estate (22 EEZs), the greatest area of features within MPAs occurs within Australia (4.1 million km^2), Antarctica (2.3 million km^2), New Zealand (2.2 million km^2), the United States – Alaska (1.7 million km^2), and United States – Hawaii (1.9 million km^2) (Fig. 4b). The Flanders Marine Institute divides the US EEZ into three zones (Hawaii, Alaska and the continental US). When combining these three zones, the US EEZ has the largest area of features within MPAs at 4.4 million km^2. New Caledonia had 2 million km^2 of its features within MPAs. The Australian EEZ has 15 out of the 19 examined features and habitats within MPAs

Table 2
Total square area (km^2) of the 19 geomorphic features that fall within and outside of marine protected area (MPA) boundaries of 230 exclusive economic zones (EEZs). The percent of the geomorphic features by EEZ that fall within a protected area boundary and the number of EEZs that contain geomorphic features not included in any MPA. Features with **bold text** have the greatest area (not percentage) within MPAs. Features *in italics* are those with more than 30% within MPAs. Differences exist in statistics shown for Large Marine Ecosystems (LMEs) (Table 1) and EEZs because there is not 100% overlap between the two (i.e. EEZs extend 200 nautical miles offshore in some places where LMEs do not).

	Feature area within MPAs (km^2)	Feature area outside MPAs (km^2)	% area within MPA	# of EEZs without features within MPAs
Abyss	**11,337,339**	383,425,114	3%	158
Canyons	371,161	7,436,405	5%	156
Escarpments	**1,507,129**	30,382,648	5%	114
Mangroves	65,679	92,920	*41%*	137
Coral Reefs	46,445	73,748	*39%*	142
Seagrass	112,644	509,415	18%	136
Glacial Troughs	387,865	5,807,947	6%	219
Guyots	94,815	1,235,346	7%	215
Hadal	257,096	4,438,888	5%	215
Plateaus	**2,177,085**	28,024,616	7%	192
Ridges	811,972	13,514,179	6%	167
Rift Valleys	7830	901,339	1%	222
Seamounts	610,786	10,329,459	6%	192
Shelf	**3,519,431**	56,971,744	6%	48
Shelf Valley	477,389	7,835,461	6%	173
Slope	**1,696,183**	35,394,885	5%	108
Spreading Ridges	80,747	8,192,924	1%	217
Trenches	279,283	3,483,115	7%	218
Troughs	358,942	4,601,933	7%	204

while Antarctica, New Zealand, United States - Alaska and the United States -Hawaii have 14, 13, 14 and 11 features within MPAs, respectively. New Caledonia has 10 features and habitats within MPAs.

EEZs with the highest diversity include the Spanish Canary Islands, the Kiribati (Line Islands), Portugal, Costa Rica, and Honduras with a reciprocal Simpson's diversity index score of > 5.0 (Figs. 5d and 6b). Those EEZs that had less than 1% of their features and habitats within MPAs and had the lowest diversity indices included Brunei, Sint-Maarten, Oecussi Ambeno (East Timor), Jersey, Guernsey, Uruguay, Guyana, Faeroe, Israel and Libya. Conversely, countries that have more than 10% in MPAs tend to have higher diversity scores. Australia has 45% of its features in MPAs and has a diversity score of 4.0. The United States (Alaska) has 35% of its features in MPAs and has a diversity score of 4.2. New Zealand has 32% of its features in MPAs and has a diversity score of 3.2. In some cases, smaller area MPAs have also captured a high diversity of features within their boundaries. For example, MPAs in the Kiribati Lines Islands have a high diversity (5.7) even though less than 1.0% of its features and habitats are within MPAs. The Mexican EEZ scored reasonably high in feature/habitat diversity (4.7), with only 2.4% of features within MPAs.

There are several EEZs that score in the top quantile for area within MPAs (> 10% of features and habitats within MPAs) and the diversity index (2.8–5.7), representing EEZ that are more successful in achieving representativeness (coverage and diversity) (Fig. 5c). Among those EEZs there are Australia, the United States, New Zealand, Portugal, France, and Spain. For those 22 EEZs that hold over 50% of the global marine estate (Fig. 4b), Indonesia, Greenland and Mexico are highly heterogeneous areas identified in the focal variety analysis (Fig. 3). These EEZs fall within the third quantile of percent features/habitats within MPAs (Fig. 5c) at 2.7, 4.5 and 2.4%, respectively. Indonesia and Mexico ranked in the top quantile of the diversity index, scoring 3.1 and 4.7, respectively (Fig. 5d), indicating that their configuration of MPAs is potentially representative of the occurring features and habitats. The Greenland EEZ scored a much lower diversity index (2.5) indicating that MPAs here are potentially lacking representativeness. There are also several high-diversity regions within the western Pacific Ocean (e.g. Cook Islands and Gilbert Islands (Kiribati)), without any MPAs.

While nations have moved toward increasing the area of MPAs within their EEZs and attaining the 10% target (Fig. 6b), feature/habitat coverage within MPAs does not always correlate (Pearson's linear correlation coefficient) with diversity ($r^2 = 0.16$, $p < 0.01$). Fig. 6b shows 46 EEZs that have achieved the 10% Aichi target, the associated area of geomorphic features and benthic habitats within MPAs, and the diversity of these features. As is evident in Fig. 6b, several EEZs have large portions (> 10%) of their area within MPAs. Whereas the general increase in MPA area coincides with greater inclusion of features and habitats, the actual diversity within MPAs varies greatly. Large, remote offshore regions or territories are useful in protecting large areas of features and habitats, but in many cases fail to capture feature diversity or representativeness within their MPA configuration.

4. Discussion

This is the first analysis of global patterns of diversity within the existing MPA network, using a publicly available data set of marine geomorphic features and benthic habitats. Assessing coverage and diversity of features, provides an opportunity for nations and global environment authorities to assess representativeness in achieving the Aichi Targets. Geomorphic features and benthic habitats (Harris and Baker, 2012a) play a critical role in maintaining marine biodiversity (Nakagawa and Takai, 2008, Paterson et al., 2009, McClain and Barry, 2010, Moors-Murphy, 2014), and knowledge of these diversity patterns is important for effective development of marine spatial plans (MSP) and conservation policies. They are also important for the effective development and management of protected areas (Lubchenco and Grorud-Colvert, 2015; Agardy et al., 2016; Worm, 2017; Gill, 2017).

Tropical coral reef regions play a large role in driving patterns of diversity on a global scale and are priority areas for conservation (Selig et al., 2014). A majority of the more highly geomorphic diverse regions found in this study contain coral reef ecosystems, such as the Caribbean, the Hawaiian Islands and the Great Barrier Reef and the coral triangle, an area known to be exceptional since the time of Wallace (1869). In addition, shelves and nearby areas with a collection of diverse features, including canyons, escarpments, trenches, shelf valleys and sometimes seamounts, ridges and guoyts, also represent regions of high geomorphic heterogeneity. These highly diverse regions tend to fall within ecosystem management boundaries and under the management of nation states through their EEZ (as opposed to occurring on the high-seas). This means that countries have the ability (and the responsibility) to manage and protect the most geomorphically diverse parts of the global ocean.

4.1. Ecosystem based management and large marine ecosystems

LME ecological planning units are useful for managing large regions of the coastal ocean exclusive of political boundary considerations (Sherman, 1991; Sherman et al., 2009; Sherman, 2014). The LME strategy was developed to measure changing conditions within global coastal ecosystems, assess the success or failure of actions to recover depleted fish stocks, restore degraded habitats, and reduce and control coastal pollution and nutrient over enrichment (Sherman, 1991). Understanding spatial patterns of diversity within LMEs is essential for prioritizing conservation actions and for designing MPAs so that they capture a representative cross section of habitats.

Our analysis shows how the existing suite of MPAs, exclusive of categorization (i.e. IUCN level) and stages of implementation, contain different levels and representativeness of geomorphic features and benthic habitats within MPAs around the globe. For example, MPAs around Australia generally capture a high (> 10%) percentage of geomorphic features and benthic habitats within the MPAs of their LME regions. However, the diversity within MPAs varies around the continent (Fig. 5). Notable LMEs that have a higher percentage of features within MPAs but protect a low diversity include the North Australian Shelf, the Baltic Sea, and the North East and South East U.S. continental shelves. These LMEs may simply not contain a high diversity of features. In any event, the outcomes of this analysis will allow managers to reprioritize and realign MPA (and MPA category) boundaries considering MSP exercises. Areas that fall in the lower quantiles of percent feature protection yet achieved higher diversity scores (e.g. Scotian Shelf LME) are examples of potentially representative MPAs. These examples demonstrate that it is possible to attain the 10% Aichi target, while simultaneously achieving representative feature coverage and diversity in of network of MPAs.

Looking at ecosystems from a holistic and integrated approach, such as LMEs, has been a beneficial alternative to sectoral and species-specific management approaches. However, existing fragmentation among and within management institutions across geopolitical boundaries, international agencies and a lack of resource sharing among nation states (including weakened national policies, legislation, and enforcement) may all challenge the successful implementation of this approach (Duda and Sherman, 2002; Coleman, 2008). The research presented here can be used to strengthen biodiversity conservation across ecosystem management boundaries by highlighting pathways, both successful and not, toward achieving representativeness in the Aichi targets. Currently, a Global Environment Facility initiative is working toward joint governance arrangements to assist this effort (Sherman, 2014), targeting mainly Africa, Asia, Latin American and Eastern Europe. An LME that could potentially benefit from this effort is the North Brazil shelf, a region with a low diversity of features within MPAs (mangroves, reefs, shelf and shelf valleys) (Fig. 5a, and b) and a low percent of area protected (Fig. 4). Yet the features and habitats for the North Brazil Shelf examined in this analysis indicate high levels of diversity and, include canyons, escarpments and terraces (Figs. 1 and 3) vast stretches of mangroves and reefs (Moura et al., 2016).

4.2. National obligations and exclusive economic zones

Many nations have made pledges to protect 10% of their marine area by 2020 through Aichi Target 11 of the United Nations Convention on Biological Diversity (CBD). This means that national-scale spatial conservation prioritisation is needed to help meet this target and guide broader conservation and MSP efforts. However, in pursuit of achieving the quantitative goal, many MPAs have been poorly planned and implemented (Lubchenco and Grorud-Colvert, 2015). Many are inefficient in meeting current conservation goals and their representativeness is questionable (House et al., 2017). Balancing the representativeness of geomorphic features and benthic habitats and related biodiversity, including threatened species habitats, is critical for improving protected area planning and management and achieving the CBD strategic goals (Polak et al., 2016). In addition, the objectives and design of MPAs should consider the peculiarities of each EEZ, as relatively small MPAs can be very effective and include a high diversity of habitats at their spatial scale (Pérez-Ruzafa et al., 2017). Unique local environmental features and processes (e.g. larval dispersal) in addition to geomorphic heterogeneity should also be considered in MPA design to assure the protection of unique global features and global-scale representativeness.

Of the 230 EEZs examined, 45 (20%) did not have any MPAs. Many of these, clustered around the African continent, including Somalia, Angola, Eritrea, Cameroon, Benin, Libya, Cape Verde and Mauritius. Countries where balancing conservation and socioeconomic objectives, particularly poverty alleviation needs, remains a challenge. This highlights the need to continue to develop innovative sustainable development programs and approaches that integrate biodiversity conservation with socioeconomic concerns (Jones et al., 2017) by focusing resources on information provision, training and education (Fairer-Wessels, 2017) and linking protected area management to health and well-being (Terraube et al., 2017). It will be important for governments in these areas, instead of focusing on targets, to develop appropriate conservation strategies that are incremental and improve information provision, information quality and capacity building through training and education. Low governance capacity remains a major barrier to conservation, especially for MPAs (Gill, 2017) and greater funding needs to be directed to administrative effectiveness.

Countries that have over 50% of the globally marine estate (Fig. 4b) and the resources to commit to biodiversity conservation have a strong obligation to increase their efforts toward achieving the Aichi targets and meaningful representativeness of habitats. Of these countries Australia, New Zealand, the United States, Japan, Russia and Canada have the greatest area in square kilometres of features and habitats within protected area boundaries. Australia, New Zealand and the EEZ regions of the United States scored in the top quantile for the percent area of features within MPAs and the diversity index (Fig. 4a and b). Outside of the countries holding greater than 50% of the marine estate, EEZs that showed a high percent of area within MPAs and a high diversity index were the Spanish, French, the United Kingdom and Northern Mariana EEZs.

The EEZ of Antarctica, jointly managed through the Convention on the Conservation of Antarctic Marine Living Resources and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), established the Ross Sea Region MPA in 2016. With this, CCAMLR has taken the first step in creating a network of Antarctic MPAs, which preserves connectivity and provides resilience for the many unique ecosystems of the Southern Ocean. Our analysis indicates that the features and habitats protected within the Ross Sea MPA scored in the top quantile (> 2.8) for the diversity index (Fig. 5d), indicating that it contains a high level of ecological representativeness for Antarctic biodiversity.

4.3. The role of environmental information

The Central Arctic LME and areas in the Greenland Sea LME are facing new environmental challenges in the wake of climate change. As a result of climate change, access to these areas will increase by opening the benthic habitat to fisheries exploitation and safer and easier shipping access (Harris et al., 2018; Nyman, 2018). A seasonally ice-free Arctic could result in a three-fold increase in primary productivity (Arrigo et al., 2008) and cause profound changes to the ranges and ecology of Arctic fish (Hollowed et al., 2013; Christiansen et al., 2014). The region is also rapidly turning into area of economic and geopolitical development, and a variety of industries are attempting to seize emerging opportunities (Lamers et al., 2016). The focal variety analysis conducted here has identified the Arctic/Greenland Sea area as a region of high diversity (Fig. 3) but having very little of its geomorphic features within MPAs (Fig. 5a and b). In the face of rapid climate change, the challenge for the Arctic will be to provide for adaptive governance approaches to conserve marine biodiversity to avoid over-fishing and habitat degradation (Harris et al., 2018).

Increased transparency through the disclosure of data, information, and knowledge can be beneficial for improving governance efforts (Lamers et al., 2016). BlueBridge and the Protected Area Impact Maps MPA Reporting Interface, on which the outcomes of this research are based, provides the users with tools to visualize, analyze and report on a range of ecologically important seafloor features within MPAs on a country by country basis. The outcomes of this global analysis and the BlueBridge interface can support capacity building in interdisciplinary research communities actively involved in increasing scientific knowledge about resource overexploitation and degraded environments and ecosystems, with the aim of providing a more solid ground for informed advice to competent authorities. More importantly, with the looming 2020 Aichi targets our analysis provides a status report of where nations and ecosystem planning regions sit in terms of achieving representativeness with their MPAs networks.

5. Conclusions

Overall, the global MPA network has made great strides toward achieving its 10% targets. However, MPAs areas are not targeting all LMEs equally. While of 54% of LMEs have set aside more than 10% only 27% contain a representative (> 10%) portion of their geomorphic features within MPAs. Similarly, only a small portion of EEZs (19%) have achieved the Aichi Target (greater than 10% of their areas within MPAs) as well as representativeness (> 10% geomorphic feature coverage and diversity). While increasing the area of MPAs within LMEs and EEZs generally shows an increase in the protection of the 19 geomorphic features, this trend does not relate to an increase in diversity or habitat representativeness. Globally, ecological representativeness within MPAs, does not correlate with the size of MPAs – large-scale MPAs do not always contain a more representative set of features (greater diversity) than small MPAs. Furthermore, we find several geomorphic features that have low representation in any MPA, including the hadal zone, rift valleys, spreading ridges and trenches. Though there remain challenges in achieving representativeness, this assessment provides the basis for re-examining what MPAs actually contain and indicates a pathway towards achieving better representation of known seafloor features in light of the approaching Aichi 2020 deadline.

Reserves in offshore regions or territories should be re-examined, as many of these EEZs, while covering large areas of geomorphic habitats within MPAs, generally contain low diversity. The lack of correlation between area and diversity could be explained by countries avoiding protecting areas that serve commercial interests and the politically complex process of protecting highly populated coastal areas. As human impacts continue to spread across the globe and touch hard to reach areas, perhaps consideration should be given to increasing protection in areas such as rift valleys and the hadal zone.

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