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LETTER

Mapping status and conservation of global at-risk marine biodiversity

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Abstract

To conserve marine biodiversity, we must first understand the spatial distribution and status of at-risk biodiversity. We combined range maps and conservation status for 5,291 marine species to map the global distribution of extinction risk of marine biodiversity. We find that for 83% of the ocean, >25% of assessed species are considered threatened, and 15% of the ocean shows >50% of assessed species threatened when weighting for range-limited species. By comparing mean extinction risk of marine biodiversity to no-take marine reserve placement, we identify regions where reserves preferentially afford proactive protection (i.e., preserving low-risk areas) or reactive protection (i.e., mitigating high-risk areas), indicating opportunities and needs for effective future protection at national and regional scales. In addition, elevated risk to high seas biodiversity highlights the need for credible protection and minimization of threatening activities in international waters.

KEYWORDS

conservation status, global, marine biodiversity, marine conservation, marine reserves, protected areas, Red List, species at risk, threatened species

1 | INTRODUCTION

Global oceans face increasing pressures from the direct and indirect consequences of human activities, including climate change (Poloczanska et al., 2016), fishing, pollution, and habitat destruction (Halpern et al., 2008, 2015). These stressors threaten the sustainability and existence of marine biodiversity (Dulvy, Sadovy, & Reynolds, 2003; Sala & Knowlton, 2006) and the suite of benefits these ecosystems provide (McCauley et al., 2015; Worm et al., 2006). Recognizing these threats, the Aichi Biodiversity Targets adopted by the United Nations Convention on Biodiversity (CBD) in 2010 incorporate strategic goals to counteract the decline in global biodiversity. In particular, Aichi Target 11 sets a target of effective protection of 10% of marine areas particularly important to biodiversity and ecosystem services by 2020 (Leadley et al., 2014). Determining whether actions taken to meet this target are effectively addressing conservation goals requires, at a minimum, identifying regions where biodiversity is at risk, and to what extent, relative to current protection and management. A baseline assessment of global marine biodiversity conservation status relative to existing marine protection will be critical to inform renegotiations of protection targets toward a post-2020 biodiversity framework.

Marine conservation prioritization literature critically relies on understanding the spatial distribution of biodiversity

(Klein et al., 2015; Roberts, 2002; Selig et al., 2014) to identify interventions that can effectively mitigate human impacts and slow or reverse the global decline of marine species. Two complementary strategies are often cited for prioritizing areas for marine protection: reactive approaches that protect highly impacted areas to mitigate stressors and allow for recovery, and proactive interventions that preserve areas of low current impact to prevent future degradation (Brooks et al., 2006). Extractive uses impose direct human impacts on the marine environment, and therefore reactive protection, in closing access to valuable resources, often faces political and economic opposition. Focusing on areas of low commercial value may minimize opportunity cost but will likely result in residual reserves that provide little protection for species and ecosystems most threatened by extractive activities (Devillers et al., 2015). However, prioritization approaches, particularly at the global scale, often rely on species richness measures that do not account for conservation status (i.e., risk of extinction in the near future) of marine biodiversity in the face of threats and impacts (e.g., Roberts, 2002; Selig et al., 2014). Understanding where to target conservation initiatives to improve the conservation status of at-risk marine biodiversity poses a particularly pressing and important challenge.

Here, we combine spatial range and extinction risk data for 5,291 marine species on the IUCN Red List of Threatened Species to map the mean conservation status of marine biodiversity (hereafter "biodiversity risk") at a resolution relevant to policy makers. We then compare biodiversity risk scores with existing marine reserve coverage and ecologically important habitats to highlight places that harbor few at-risk species and merit protection from future degradation (i.e., proactive protection), as well as areas of elevated risk that would benefit from protection to mitigate existing threats (i.e., reactive protection). This work provides a critical global map of marine biodiversity risk, improving our understanding of its spatial distribution and providing a necessary tool to highlight gaps and opportunities for effective marine conservation.

2 | METHODS

Global distributions of species were determined by rasterizing IUCN Red List range maps for 5,291 marine species, in 226 families within 25 comprehensively assessed taxa (IUCN, 2018; Table S1), to a 10 km × 10 km (100 km^2) global grid using a Gall-Peters equal area projection. Hereafter, all results are understood to be based on the set of species included in these comprehensively assessed taxa.

We calculated biodiversity risk scores for each ocean cell as the mean conservation status X of all N assessed species present in the cell: $X_{cell} = \frac{1}{N_{cell}} \sum_{i=1}^{N_{cell}} s_i$, where s_i is IUCN conservation status for each species i (IUCN, 2018), scaled linearly between 0 and 1, where 0 = Least Concern (LC), 0.2 = Near Threatened (NT), 0.4 = Vulnerable (VU), 0.6 = Endangered (EN), 0.8 = Critically Endangered (CR), and 1.0 = Extinct (EX) (Butchart et al., 2004; Selig et al., 2013). Generally, conservation status for each species present within a 100 km^2 cell was based on the global conservation status value. For spatially delineated subpopulations, subpopulation status was used. For species included in regional assessments, we identified appropriate marine ecoregions (Spalding et al., 2007) to approximate the regional extent, and then used regional conservation status.

We accounted for endemism by calculating range rarity–weighted biodiversity risk (Roberts, 2002; Selig et al., 2014), weighting conservation status for each species present by the reciprocal of its range extent. Additionally, we calculated the proportion of threatened species (i.e., those classified as VU, EN, or CR) in each cell, similar for range-rarity weighting, where counts were weighted by the reciprocal of range. Ranges for neritic species were clipped to 200 m bathymetry (Sandwell, Gille, & Smith, 2002) to reduce potential range overestimation (O'Hara, Afflerbach, Scarborough, Kaschner, & Halpern, 2017). We clipped ranges to cells with ocean presence, truncating total range for species who venture inland from the coast, particularly many birds. This ensures that only marine-specific range is counted for range-rarity purposes.

To determine the extent of marine protection, we identified marine protected areas (MPAs) classified as no take ("marine reserves") from the World Database on Protected Areas (WDPA; IUCN & UNEP-WCMC, 2018) meeting IUCN protected area categories Ia (strict nature reserve), Ib (wilderness), or II (national park), and/or designated no-take area at least 75% of total reported area. WDPA polygons were rasterized on a 500 m × 500 m (0.25 km^2) grid. These 0.25 km^2 cells were then used to calculate percent coverage for each analysis cell at the 100 km^2 resolution of the species range data. Resulting marine protected areas (MPA) raster data include values for earliest year of protection, category of protection, and percent of cell area protected. See Supporting Information for further details and sensitivity analysis of MPA calculations to raster resolution.

We identified ecologically important habitats based on spatial extents of 11 marine habitats previously used in an assessment of global cumulative human impacts (Halpern et al., 2015). Geopolitical regions are based on national Exclusive Economic Zones (EEZ), CCAMLR region (Antarctica), or FAO Major Fishing Areas (high seas) used previously (Halpern et al., 2015).

All analysis and figures were generated in R version 3.5.3 (R Core Team, 2019), using the tidyverse (Wickham, 2017), raster (Hijmans, 2017), and sf simple features (Pebesma, 2018) packages. All code and outputs are available at https://github.com/oharac/spp_risk_dists. Maps include landforms from Natural Earth 1:10 m land polygons (www.naturalearthdata.com).

3 | RESULTS

We find that the global mean of biodiversity risk significantly centers just below Near Threatened (0.184 ± 0.043; mean ± *SD*; Figure 1a). Barely 0.09% of the ocean is truly at Least Concern (all species at Least Concern), whereas 43% is at Near Threatened or higher. For a majority of the ocean (83%), at least 25% of species are listed as threatened (Figure 1b). As expected, biodiversity risk is spatially heterogeneous (Figure 1a), with similar patterns evident in the proportion of threatened species (Figure 1b). Risk to Antarctic and Arctic biodiversity tends to be relatively low, with the exception of the Norwegian Sea. Overall, the Mediterranean and Black Seas exhibit the highest biodiversity risk (mean = 0.260). Temperate regions and upwelling zones in the eastern Pacific evince higher marine biodiversity risk than tropical and polar oceans. Coastal and continental shelf regions generally display lower risk than open ocean basins, despite expectations of higher cumulative human impact (Halpern et al., 2008), notably in the South China Sea and the Coral Triangle; the presence of species at high threat levels is masked by a greater presence of coastal species assessed as Least Concern. This masking effect may be due to the set of taxa available for this analysis; for example, in the open ocean, assessed taxa (mammals, birds, turtles, sharks and rays, and large pelagic fish) are likely at a higher risk than those that have not been assessed (e.g., deep sea organisms). Although these taxa are also found closer to shore, the presence of many low-risk coastal bony fish species significantly reduces the average risk. For 96.1% of the oceans, our estimate of biodiversity risk is based on conservation status of 20 or more species (Figure S1).

Giving greater weight to endemic species results in a similar mean but wider spread of values as patterns of both high and low risk are accentuated (Figure 1c; 0.179 ± 0.093; mean ± *SD*), highlighting at-risk regions in the Mediterranean Sea, the Indian Ocean, the southwest and eastern Pacific, and the European Arctic. Similarly, when examining proportion of threatened species, weighting by range rarity accentuates areas with particularly high and low proportions of threatened endemics (Figure 1d); in 15% of the ocean, at least half of these species are threatened. Areas of high species richness in the Coral Triangle and Caribbean, which are known to harbor many at risk species (Carpenter et al., 2008; Comeros-Raynal et al., 2012), correspond to surprisingly low biodiversity risk, due to a high proportion of healthy small-range endemic species. The great variation in spatial patterns of biodiversity risk between taxonomic groups (Figure 2) can lead to considerable differences in understanding of distribution of threatened species depending on which taxonomic groups are included (Polidoro et al., 2012).

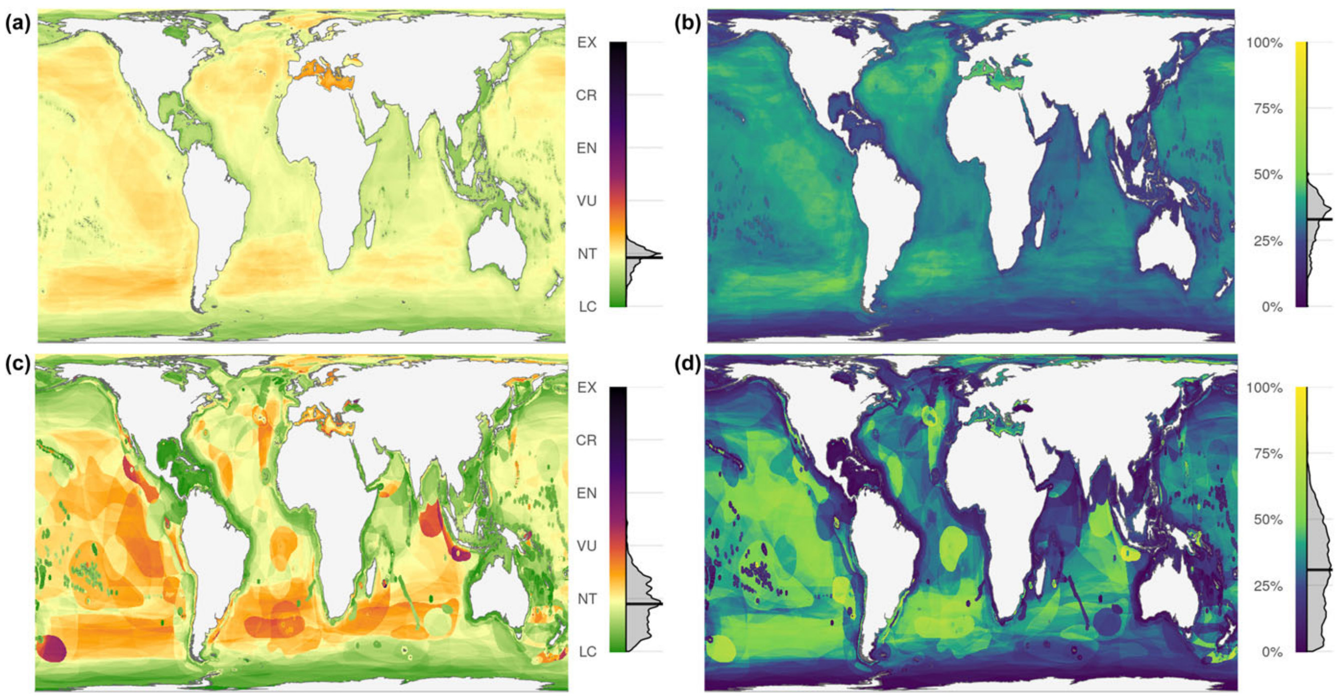

FIGURE 1 Spatial distribution of biodiversity risk and proportion of threatened species. (a) Biodiversity risk with uniform weighting of all species present. (b) Percent of local species classified as threatened (uniform weighting). (c) Biodiversity risk with species conservation status weighted by range rarity. (d) Percent of threatened species (range-rarity weighting). Sidebars in each panel show the distribution of global risk scores and proportion of threatened species

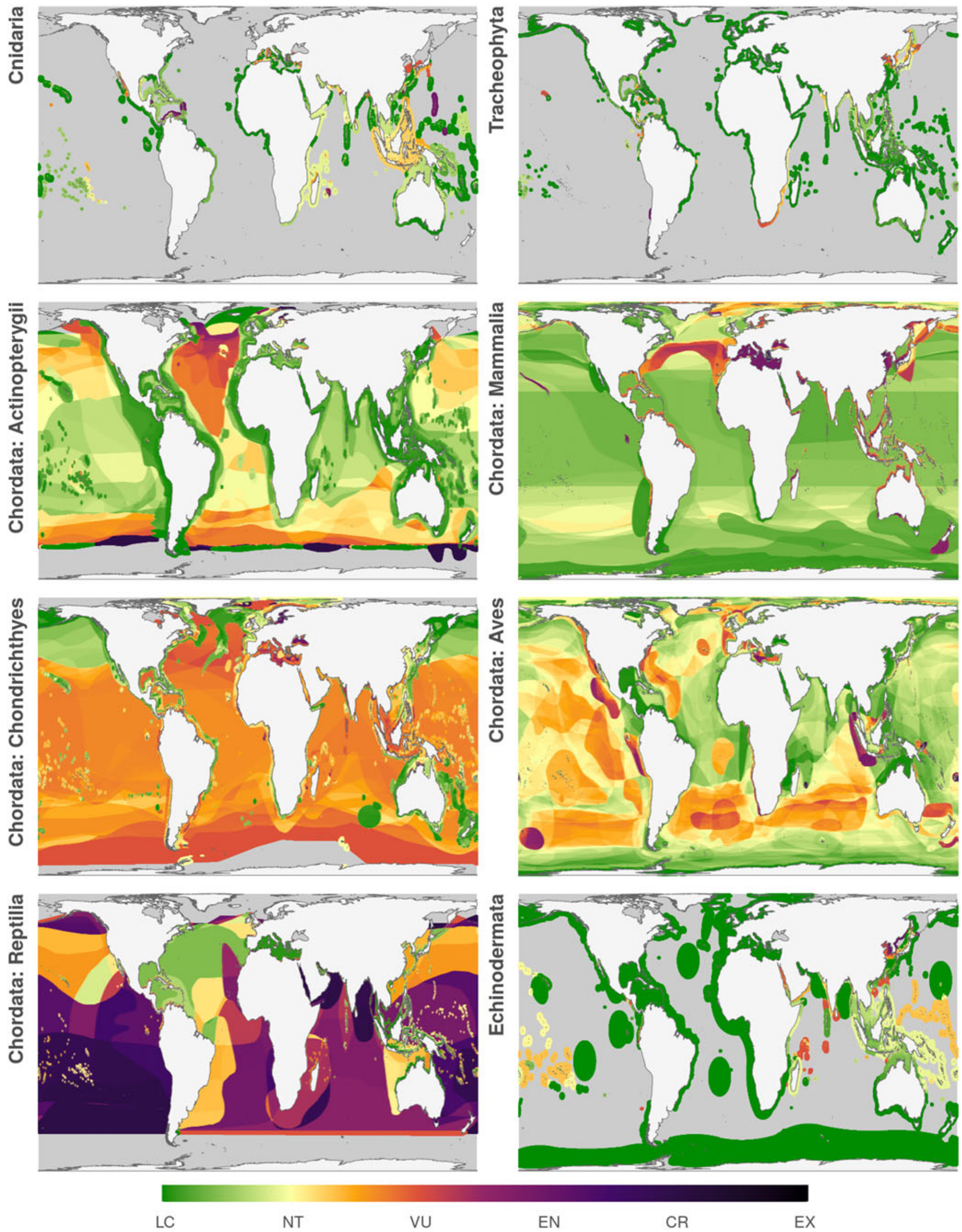

FIGURE 2 Biodiversity risk by select taxa, range-rarity-weighted. Biodiversity risk (range-rarity weighted) by comprehensively assessed taxonomic groups. Cnidaria comprises all warm-water corals. Tracheophyta comprises seagrasses and species that make up mangrove plant communities. Actinopterygii represents a subset of all ray-finned fishes. Mammalia, Chondrichthyes, and Aves represent all marine members of these classes. Reptilia comprises seasnakes, crocodiles, and sea turtles. Echinodermata comprises sea cucumbers

Fully or highly protected areas that exclude extractive activity, that is, marine reserves, are a particularly important conservation intervention (Edgar et al., 2014; Sala et al., 2018). We found that biodiversity risk within marine reserves, weighted by the proportional area of protection within each cell, was generally higher (+0.010, where +0.200 is an increase of one risk category) than in other national waters (Figure 3). Results are similar for endemism-weighted risk (Figure 3), with marine reserves on average providing more protection for high-risk endemics (+0.018). Marine reserves implemented since the creation of Aichi Target 11 (Figure 2; global post-Aichi) show a slight bias toward protection of higher risk endemic biodiversity relative to the overall global MPA estate (+0.010).

Marine reserve protection, examined through the lens of geopolitical regions (Figure 3) and national EEZs (Tables S2 and S3), shows great variation in emphasis relative to overall biodiversity risk. North and South American reserves, and

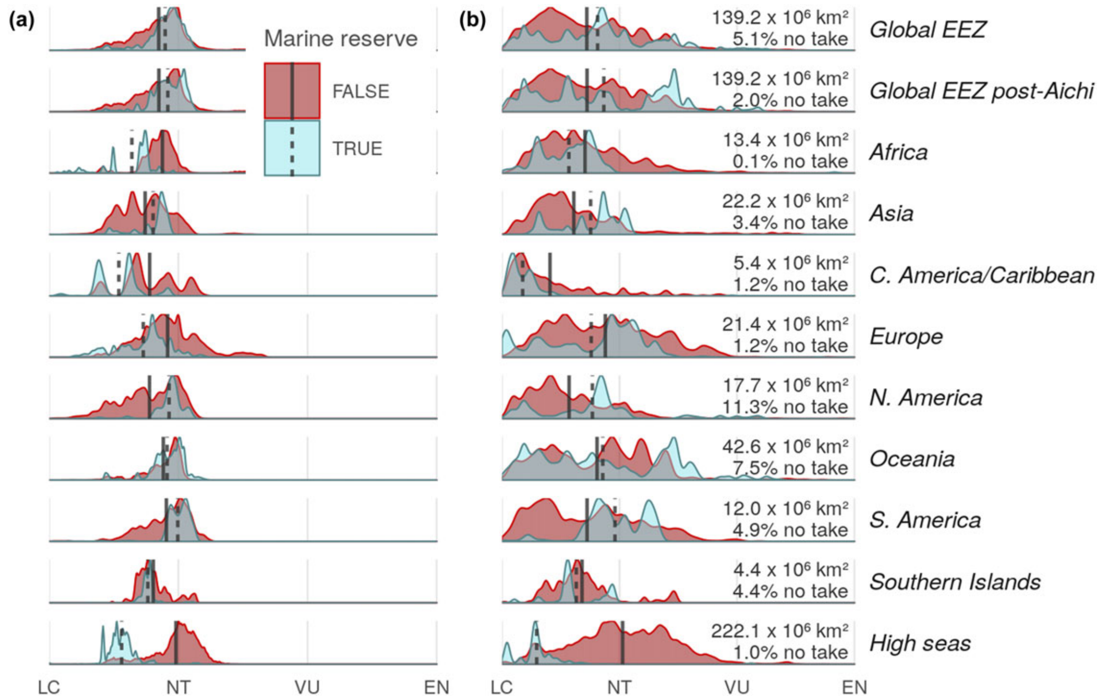

FIGURE 3 Biodiversity risk under marine reserve protection. (a) Risk to biodiversity protected within MPAs. (b) Range-rarity weighted biodiversity risk within MPAs. By either metric, global risk of biodiversity protected within MPAs is nearly indistinguishable from biodiversity outside MPAs. MPAs established since 2010′s Aichi targets seem to slightly favor high-risk biodiversity relative to the overall MPA estate. North and South American MPAs tend to focus on higher-risk areas while African, Central American, and European MPAs focus on lower-risk areas. High seas biodiversity is at higher risk than biodiversity within EEZs, whereas high seas reserves focus on healthy Antarctic waters

to a lesser extent Asian reserves, tend to protect biodiversity at greater risk than that outside of reserves (+0.040, +0.048, and +0.029, respectively, by endemism), whereas European reserves preferentially protect low-risk areas (–0.024; African reserves are negligible in coverage: only 0.10% of the total area of African EEZs). High seas biodiversity is at higher risk than that in national waters (+0.027 for uniform weighting and +0.061 for range-rarity weighting). Marine reserves protect only 1.0% of the high seas, driven entirely by Southern Ocean MPAs that protect areas of exceptionally low risk relative to other high seas areas (–0.084 for uniform weighting, and –0.146 for range-rarity weighting). When including all categories of marine protected areas, patterns of regional biodiversity risk under protection remain largely similar to those under no-take protection (Figure S2).

Examining distribution of biodiversity risk within important marine ecosystems (Figure 4), rather than geopolitical regions, we found that open oceanic marine ecosystems bear high biodiversity risk relative to coastal habitats (Figure 4), due to the greater proportional representation of high-risk pelagic taxa (2 sharks, sea turtles, pelagic birds, and commercially valuable large fish). Despite the presence of greater pressures and increasing impacts (Halpern et al., 2008, 2015), biodiversity in coastal ecosystems generally appears to be at relatively low risk. Species in kelp forest ecosystems display higher risk than those in other biogenic habitats (corals, mangroves, and sea grasses), corresponding with a generally higher risk seen in temperate coastal regions (Figure 1a,b), which typically have lower species richness (Figure S1).

For coastal habitats, biodiversity risk was similar inside and outside marine reserves. Notable exceptions are kelp forests and shallow sandy bottom habitats, in which unprotected biodiversity is at considerably higher risk (+0.047 and +0.053, range-rarity weighted). Marine reserve protection in the open ocean favors low-risk areas over high-risk areas (–0.037). Open ocean marine reserve protection includes high seas protection as noted earlier, but also includes reserves within national EEZs, much of which is provided by recently established large MPAs (Toonen et al., 2013).

4 | DISCUSSION

These results provide a detailed spatial understanding of the distribution of conservation status of global marine biodiversity. Comparing biodiversity risk against existing marine reserves highlights the balance within regional (Figure 3) and national waters (Tables S2 and S3) between reactive and proactive protection of marine ecosystems. Although a "correct" balance is a normative question not addressed here, understanding the distribution of biodiversity risk under

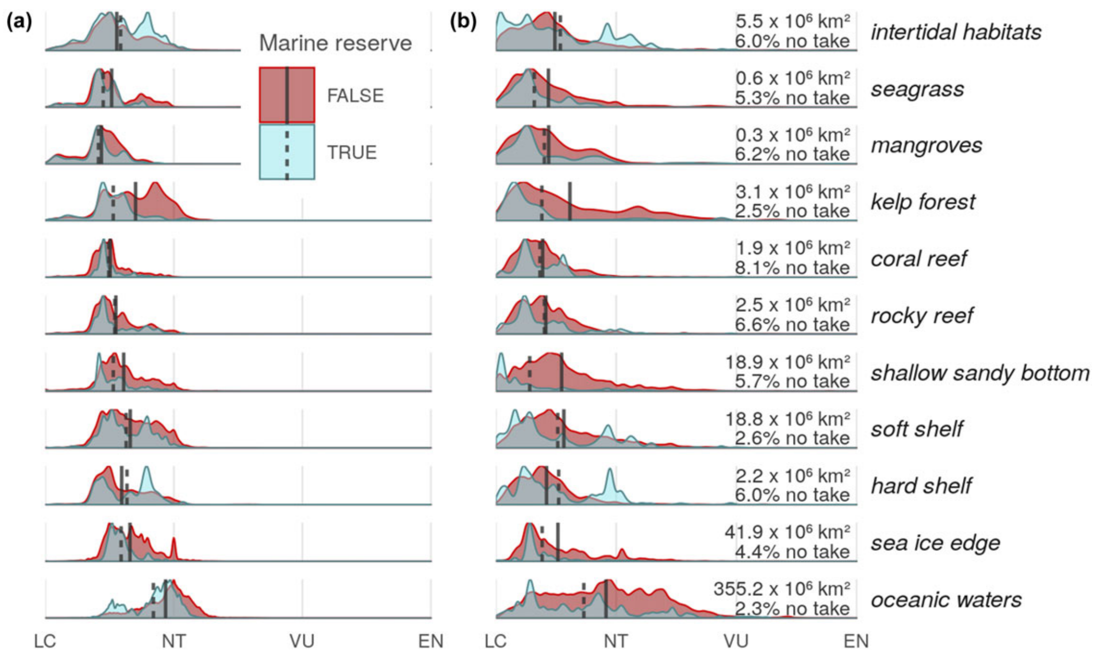

FIGURE 4 Biodiversity risk by marine habitat. (a) Risk to biodiversity within ecologically important marine habitats; mean risk shown in red. Biodiversity risk for oceanic waters is more heavily influenced by pelagic taxa at higher average risk (e.g., sea turtles, sharks, and pelagic birds) compared to coastal habitats. (b) Range-rarity weighting reveals a similar mean risk though greater range of risk to endemic species across all habitats

current protection stands to better inform development of targets for effective future protection.

Regions and nations in which existing marine reserves focus primarily on areas of higher biodiversity risk (e.g., 3 North and South America; Tables S2 and S3: United States, New Zealand, and Brazil), whether by design or by chance, may have an opportunity to develop proactive protection with minimal displacement of human activity. Conversely, regions and nations whose marine reserves disproportionately protect lower-risk biodiversity (e.g., 3 Europe and Central America/Caribbean; Tables S2 and S3: Egypt and Canada) may have to accept difficult tradeoffs in opportunity cost to increase reactive protection of heavily impacted areas.

The small apparent increase in protection of at-risk endemic biodiversity since establishment of the Aichi targets in 2010 (3 Global EEZ post-Aichi) may indicate a shift in recent marine policy to preferentially protect degraded areas, or may be evidence of greater effectiveness of long-established MPAs in promoting biodiversity health (Edgar et al., 2014). It may also result from recent trends toward establishing very large MPAs (Toonen et al., 2013), which frequently extend into oceanic waters with fewer species but higher mean risk.

Aichi Target 11 strives toward, among other things, "ecologically representative" systems of protected areas. Existing protection of most coastal ecosystems is well balanced, in that biodiversity risk under protection reasonably matches the overall distribution of biodiversity risk. In kelp forests and shallow sandy bottom habitats, however, mean risk under protection is far lower than unprotected mean risk, suggesting either proactive protection or, more likely, residual reserves. Both ecosystem types would benefit from efforts to identify and protect highly impacted areas to reduce risk to extant biodiversity. The same is true of open oceanic waters: unprotected open ocean falling within EEZ jurisdiction is at generally greater risk than waters falling within the large MPAs that make up much of the protected open ocean.

Our results show disproportionately high risk to high seas biodiversity relative to that within EEZs, with little in the way of protection from extractive activities. Currently established no-take reserves cover only 1% of the high seas, proactively protecting low-risk Southern Ocean biodiversity (IUCN & UNEP-WCMC, 2018). Among other stressors, fisheries are a significant economic activity impacting biodiversity across the high seas: between 48% and 57% of the high seas were fished in 2016 (Sala et al., 2018). High seas fishing effort provides only 4.2% of total wild capture production (Schiller, Bailey, Jacquet, & Sala, 2018), but is dominated by longline fisheries (Kroodsma et al., 2018b), known for high bycatch rates for marine mammals, seabirds, and sea turtles (Lewison et al., 2014). Although monitoring and enforcement would be a significant challenge, establishment of marine reserves in the high seas and improving ocean governance could protect high-risk biodiversity while imposing little impact on food security (Schiller et al., 2018) and likely increasing profitability of fisheries in EEZs (White & Costello, 2014).

Coordination and enforcement of policy at national and subnational levels is far more tractable than international coordination, and can more readily target localized threats to biodiversity and account for local contexts and values. Examining distributions of risk at the EEZ scale (Tables S2 and S3) may be useful to inform national or local marine conservation efforts. However, while our results provide a valuable heuristic for identifying conservation opportunities, this present analysis is primarily based on global extinction risk assessments and is not able to capture the heterogeneity of conservation status of local subpopulations. Additionally, the IUCN range maps used to describe species presence do not contain information on distribution within the outlined range; additional information on relative abundance, environmental suitability, or area of occupancy would be valuable in better identifying species presence. To better inform conservation planning initiatives at these finer spatial scales, the methods presented here can and should be adapted to incorporate scale-relevant species risk assessments and range maps at finer spatial resolution.

We emphasize that our results, though derived from aggregating a broad sample of species-level assessments, are intended to estimate system-level risk to the total biodiversity within an ecosystem. Although the species included in this analysis represent only a small fraction of marine life (Mora, Tittensor, Adl, Simpson, & Worm, 2011), the included taxa represent ecologically essential habitat-building species (corals, seagrasses, and mangroves), a wide cross section of bony fishes, a large proportion of other marine vertebrates—many of which serve as iconic species—and several commercially important invertebrate groups. Importantly, the included taxa contain most large marine predators, which are useful surrogates for ecosystem health as biodiversity indicators and sentinel species (Sergio et al., 2008); as such, their inclusion in this analysis of system-level risk is particularly valuable. Future analyses will benefit from continuing rapid addition of species to the Red List (Figure S3) in comprehensively assessed taxonomic groups.

Focusing on small-ranged endemics may provide a richer understanding of risk to local biodiversity, but may underestimate the ecological contribution of wide-ranging species, including large marine predators. The correlation between uniform-weighted and range rarity–weighted risk (adjusted $R^2 = .508$ for global maps) suggests that it may be counterproductive to use both measures simultaneously. The choice of weighting, as in any indicator exercise, largely depends on the goal of an assessment or conservation measure.

Although our analysis focused on species weightings analogous to two commonly applied biodiversity metrics, other weighting schemes, for example, by functional group or trophic level, may provide additional important insights for conservation (Vačkář, ten Brink, Loh, Baillie, & Reyers, 2012). The choice of an equal-steps numeric scale for conservation status is based on Red List Index methodology (Butchart et al., 2004), but other status-weighting scales may better capture extinction risk (Butchart et al., 2004) or perceptions of risk (Selig et al., 2013).

Variance of biodiversity risk, calculated as the variance of conservation status among all assessed species found in each cell (Figure S4), could have important implications for management decisions beyond the place-based conservation examined in this study. An area with systemic biodiversity risk (i.e., high mean, low variance) may benefit from broad protection or ecosystem-based management strategies, while high risk driven by a few outliers (i.e., high variance) may indicate an opportunity for targeted management (e.g., single species quotas and gear restrictions) while imposing little harm on other ocean uses.

Marine biodiversity risk is spatially heterogeneous and varies substantially according to geography and taxonomy. Well designed and targeted conservation measures are critical to maintaining the vitality of biodiverse ecosystems at low risk and allowing highly impacted ecosystems to recover. Spatial understanding of marine biodiversity extinction risk relative to existing marine protection can be a valuable tool to identify needs and opportunities for future conservation at national, regional, and global scales, especially when used in conjunction with spatial distributions of human impacts and systematic conservation planning tools. Matching marine biodiversity risk with areas of high and low human impact can illuminate cost-effective opportunities for balancing protection of at-risk and pristine ecosystems as we strive toward Aichi marine protection targets for 2020 and beyond.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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