Report

Current Biology

The Location and Protection Status of Earth's Diminishing Marine Wilderness

Highlights

- We classify 13.2% (~55 million km^2) of the world's ocean as marine wilderness
- Little wilderness remains in coastal areas (e.g., coral reefs)
- Only 4.9% of marine wilderness is currently within marine protected areas
- Targets to retain marine wilderness are needed in global conservation strategies

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In Brief

Jones et al. show that Earth's marine wilderness has been eroded by humanity, with 13.2% now remaining across the oceans. Despite holding high genetic diversity, unique functional traits, and endemic species, wilderness areas are ignored in global environmental agreements, highlighting the need for urgent policy attention.

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Report

The Location and Protection Status of Earth's Diminishing Marine Wilderness

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SUMMARY

As human activities increasingly threaten biodiversity [1, 2], areas devoid of intense human impacts are vital refugia [3]. These wilderness areas contain high genetic diversity, unique functional traits, and endemic species [4–7]; maintain high levels of ecological and evolutionary connectivity [8–10]; and may be well placed to resist and recover from the impacts of climate change [11–13]. On land, rapid declines in wilderness [3] have led to urgent calls for its protection [3, 14]. In contrast, little is known about the extent and protection of marine wilderness [4, 5]. Here we systematically map marine wilderness globally by identifying areas that have both very little impact (lowest 10%) from 15 anthropogenic stressors and also a very low combined cumulative impact from these stressors. We discover that ~13% of the ocean meets this definition of global wilderness, with most being located in the high seas. Recognizing that human influence differs across ocean regions, we repeat the analysis within each of the 16 ocean realms [15]. Realm-specific wilderness extent varies considerably, with >16 million km^2 (8.6%) in the Warm Indo-Pacific, down to <2,000 km^2 (0.5%) in Temperate Southern Africa. We also show that the marine protected area estate holds only 4.9% of global wilderness and 4.1% of realm-specific wilderness, very little of which is in biodiverse ecosystems such as coral reefs. Proactive retention of marine wilderness should now be incorporated into global strategies aimed at conserving biodiversity and ensuring that large-scale ecological and evolutionary processes continue.

RESULTS AND DISCUSSION

Global Marine Wilderness

Identifying marine wilderness requires finding biologically and ecologically intact seascapes that are mostly free of human disturbance [3, 16]. Here we do so by mapping those areas that have low impact across all human stressors and also have a low cumulative impact, as even low levels of human activity can significantly impact some critical aspects of biodiversity (e.g., mobile top predators [4]). To identify marine wilderness, we used the most comprehensive global data available for 19 human stressors to the ocean (detailed summary in Table S1) and the cumulative impact of these stressors [17]. We first identified areas within the bottom 10% for every separate human stressor (e.g., demersal fishing and fertilizer runoff; Table S1) and then applied a secondary classification to only include areas also within the bottom 10% of total cumulative impact at the global scale (see STAR Methods). Because the impacts of climate change are widespread and unmanageable at a local scale, there are significant variations in exposure and vulnerability across marine ecosystems (e.g., coral reefs versus deep sea), and including climate variables would result in no wilderness remaining (Figure S1), we excluded climate change variables (temperature and UV anomalies, ocean acidification, and sea level rise) from the individual stressor analysis but included them in the cumulative impact analysis (Table S1).

Our method identified 13.2% (~55 million km^2) of the world's ocean as global marine wilderness (Figure 1), primarily located in the high seas of the southern hemisphere and at extreme latitudes. Most wilderness within exclusive economic zones (EEZs) is found across the Arctic (6.9 million km^2) or Pacific island nations (2.7 million km^2; Figure 1), although there is substantial wilderness in the EEZs of some other nations, such as New Zealand (25% of EEZs, 1.1 million km^2), Chile (6% of EEZs, 120,000 km^2), and Australia (4.3% of EEZs, ~350,000 km^2). This is most likely due to low human populations in these areas and, in some cases,

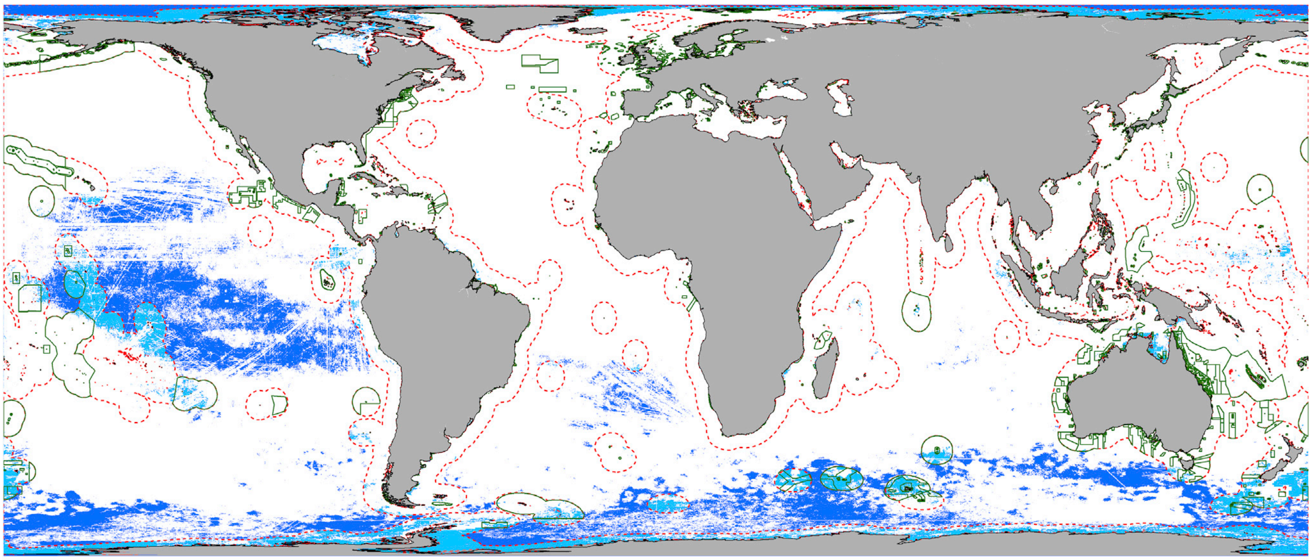

Figure 1. Global marine Wilderness Extent and Protection
Marine wilderness in exclusive economic zones (light blue), in areas outside national jurisdiction (dark blue), and marine protected areas (green). See also Tables S1–S3 and Figures S1–S4.

sea ice preventing human access to the ocean (Figure S2). However, with sea ice rapidly disappearing in the Arctic [18], some wilderness loss has already occurred in previously ice-covered areas (Figure S2), and this trend is likely to accelerate as sea ice continues to decline.

Global wilderness extent varies considerably across the ocean, with substantial wilderness in the southern high seas and very little in the northern hemisphere (Table 1). For example, 26.9% (25 million km^2) of the Southern Cold Water realm is defined as global marine wilderness, compared to <0.3% (13,263 km^2) of the Temperate Northern Atlantic (Table 1). This difference is due to significant fishing and shipping activity occurring in the waters around northern Asia, Europe, and North America [17]. Global marine wilderness extent also varies across ecosystem types and is generally much higher offshore than in coastal regions (Figure 2). All coastal ecosystems (except for naturally extensive soft-bottom areas), have <100,000 km^2 of wilderness remaining (Figure 2). In contrast, almost 40 million km^2 (12%) of deep benthic soft-bottom habitat is classified as wilderness, and all offshore ecosystems (except seamounts and the hard bottom coastal shelf) have retained >200,000 km^2 of wilderness (Figure 2).

An analysis of the most comprehensive (~23,000 species) and high-resolution data on the global distribution of marine biodiversity [19] shows that the geographic ranges of 93% (n = 21,322) of all marine species overlap with marine wilderness areas (Table S2). These overlaps are higher for species with large home ranges, such as marine mammals (8.4% average overlap), and lower for groups with more coastal distributions, such as reptiles (2.6% average overlap; Table S2). Marine wilderness overlaps with areas of high species richness, range rarity, and proportional range rarity (STAR Methods; Figures S3 and S4), as well as with previously identified hotspots of both functional diversity, such as the Gulf of Carpentaria in Australia [20], and of species endemism, such as the Desventuradas islands West of Chile [6]. On average, global wilderness areas have 31% higher species richness, 40% higher range rarity, and 24% higher proportional range rarity than non-wilderness areas, though this varies substantially across marine ecoregions (Table S3). For example, wilderness areas in the Solomon Sea have more than three times higher range rarity values than non-wilderness areas (Table S3). Conversely, in the Banda Sea, wilderness areas have approximately three times lower species richness than non-wilderness areas (Table S3).

Realm-Specific Wilderness

A primary objective of conservation is to achieve representative protection of biodiversity [21]. Oceanic realms and ecoregions are an increasingly important biogeographical classification for conservation planning and assessment [22] and are important surrogates for biological representativeness when assessing global marine protected area (MPA) coverage [23]. We therefore mapped realm-specific wilderness by identifying areas within each ocean realm [15] that have little impact (bottom 10%) from 15 anthropogenic stressors and also have very low (bottom 10%) cumulative human impact (STAR Methods; Table S1).

Realm-specific wilderness identifies the least impacted places within each ocean realm, meaning that the extent varies considerably, as it is dependent on the total level of human impact within realms. Consistent with global marine wilderness, most realm-specific wilderness is found in the high seas (66%; Figure 3). There is much more global wilderness than realm-specific wilderness overall (Table 1), and the location of wilderness areas differs substantially (Figures 1 and 3). In highly impacted realms (e.g., Temperate Northern Atlantic), the extent of realm-specific wilderness is four times that of global wilderness (Table 1).

Table 1. Global and Realm-Specific Wilderness Area and Protection across Ocean Realms

Ocean Realm (Area)	Global Marine Wilderness Area (Percentage of Realm)	Global Marine Wilderness Protection (Percentage of Realm's Wilderness)	Realm-Specific Wilderness Area (Percentage of Realm)	Realm-Specific Wilderness Protection (Percentage of Realm's Wilderness Area)
Arctic (8,740,149)	4,024,686 (46.0)	282,050 (7)	868,845 (9.9)	63,406 (7.3)
Atlantic Warm Water (69,141,433)	843,548 (1.2)	0 (0)	4,331,890 (6.3)	1,293 (0)
Central Indo-Pacific (6,787,301)	334,825 (4.9)	58,938 (17.6)	396,728 (5.8)	65,212 (16.4)
Eastern Indo-Pacific (173,647)	10,187 (5.9)	1,183 (11.6)	9,446 (5.4)	777 (8.2)
Indo-Pacific Warm Water (194,431,741)	15,739,747 (8.1)	708,293 (4.5)	16,711,560 (8.6)	729,597 (4.4)
Northern Cold Water (23,320,478)	6,037,333 (25.9)	44,343 (0.7)	2,377,516 (10.2)	1,373 (0.1)
Southern Cold Water (94,049,192)	2,5308,475 (26.9)	1,465,581 (5.8)	9,275,414 (9.9)	544,014 (5.9)
Southern Ocean (2,697,385)	2,386,053 (88.5)	83,091 (3.5)	1,551,322 (57.5)	2,187 (0.1)
Temperate Australasia (1,178,349)	33,417 (2.8)	2,310 (6.9)	43,228 (3.7)	4,861 (11.2)
Temperate Northern Atlantic (4,790,838)	13,263 (0.3)	255 (1.9)	55,012 (1.1)	7,116 (12.9)
Temperate Northern Pacific (3,477,947)	26,176 (0.8)	3,022 (11.5)	58,992 (1.7)	7,511 (12.7)
Temperate South America (1,958,501)	62,272 (3.2)	4,341 (7)	81,557 (4.2)	6,147 (7.5)
Temperate Southern Africa (326,680)	557 (0.2)	547 (98.2)	1,744 (0.5)	793 (45.5)
Tropical Atlantic (2,502,305)	62,932 (2.5)	6,575 (10.4)	90,105 (3.6)	14,578 (16.2)
Tropical Eastern Pacific (293,975)	4,146 (1.4)	472 (11.4)	10,438 (3.6)	1,239 (11.9)
Western Indo-Pacific (2,578,128)	88,248 (3.4)	14,086 (16)	118,313 (4.6)	17,359 (14.7)
Total (416,448,049)	54,975,865 (13.2)	2,675,087 (4.9)	35,982,110 (8.6)	1,467,463 (4.1)

Area is shown in square kilometers.

Conversely, areas of low human impact (e.g., the Arctic) have far less realm-specific wilderness than global wilderness (Table 1). Given the widespread nature of human impacts in some ocean realms [17], realm-specific wilderness can occur in places with significant human activity, such as the Gulf of Mexico and the Persian Gulf. Although these sites are under considerable human influence, they still represent some of the least impacted places within each ocean realm and are therefore important to protect.

Wilderness Protection

We found that only 4.9% of global marine wilderness (2.67 million km^2) is inside MPAs (Table 1), despite 6.97% of total ocean area being under protection. This protection occurs almost exclusively within national waters, with 12% (2.65 million km^2) of global wilderness within EEZs protected, but only 0.06% (0.02 million km^2) of wilderness in high seas protected. Global wilderness protection is high in some populated regions, with 98% protected in Temperate Southern Africa and 17% protected in the Central Indo-Pacific (Table 1). However, these areas also have very little total wilderness left (<5%; Table 1), suggesting that MPAs play a crucial role in preserving the small amount remaining. Wilderness protection is much lower in remote areas, such as the Southern Ocean and Northern Cold Water realms, where few MPAs are designated (Table 1).

Considerably more global marine wilderness remains in offshore ecosystems (49.7 million km^2) than in coastal ecosystems (5.5 million km^2; Figure 2), but the proportion of protected wilderness is similar (4.4% and 4.8%, respectively). In coastal ecosystems, the vast majority of protected wilderness (93%) is in soft-bottom areas, rather than habitats such as rocky reefs or coral reefs that people depend on for food and income [24] (Figure 2; Table S4). However, despite having low wilderness extent and areal protection, these ecosystems have high proportional levels of protection, with 66% and 26% of rocky reef and coral reef wilderness being covered by MPAs, respectively (Table S4). A substantial amount of wilderness in these ecosystems is contained in large, remote MPAs, such as the British Indian Ocean Territory MPA [5]. Offshore ecosystems generally have more protected wilderness area than coastal ecosystems (Figure 2) but lower proportional wilderness protection (Table S4).

Realm-specific wilderness has much higher MPA coverage than global marine wilderness, with half of all realms having >50% wilderness protection (Table 1). This is most likely because, when compared to global marine wilderness, there is more realm-specific wilderness in coastal waters where most MPAs are designated [23]. However, some realms have very poor wilderness coverage, with the Southern Ocean, Northern Cold Water, and Atlantic Cold Water realms all having <0.1% of realm-specific wilderness protection (Table 1).

Implications for Global Conservation Policy

Human pressures across the ocean are increasing rapidly, and nowhere in the sea is entirely free of human impacts [2, 17]. We show that there is very little marine wilderness in coastal areas, with most remaining wilderness relegated to extreme latitudes or the high seas (Figure 1). Although there are vast differences in the amount of wilderness remaining across marine ecosystems, the level of wilderness protection is low in most ecosystems (Figure 2). International conservation policies should now recognize the values of wilderness and target conservation actions toward reducing threats in these areas to ensure their retention.

Marine wilderness loss may impact the ability of nations to achieve global conservation goals within key multilateral environmental agreements, such as the Convention on Biological

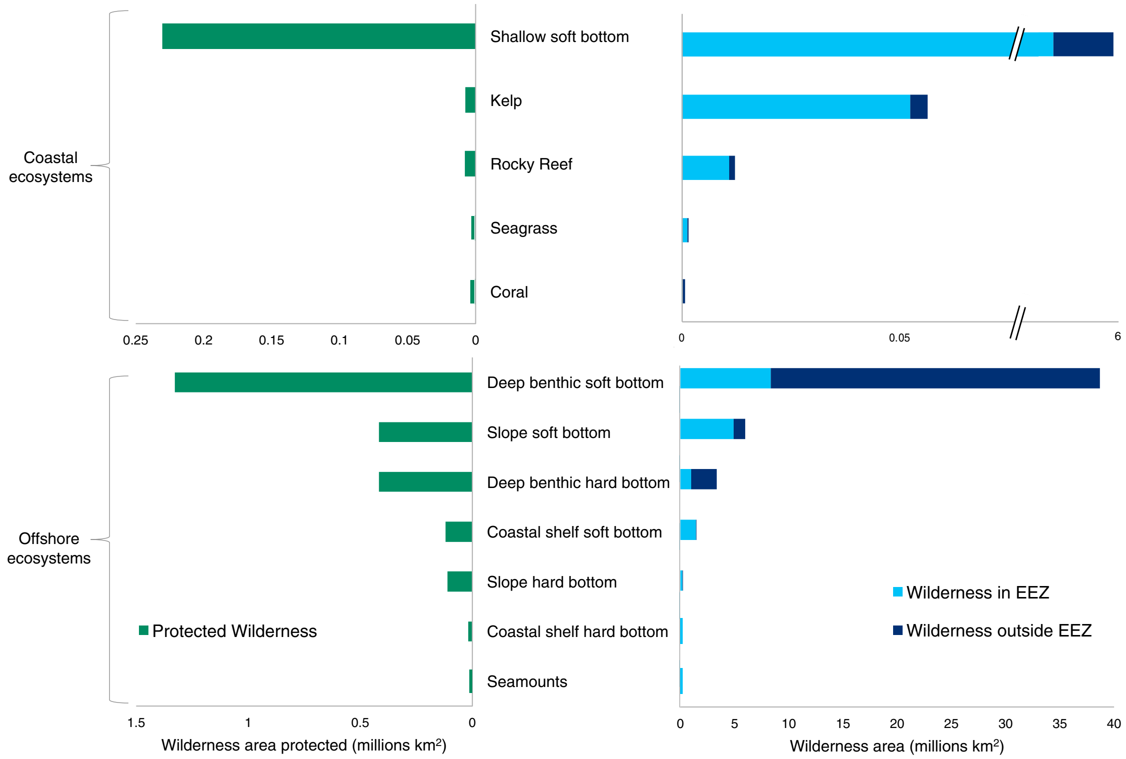

Figure 2. Global Marine Wilderness Extent and protection across Coastal and Offshore Ecosystems

Marine wilderness in exclusive economic zones (light blue), in areas outside national jurisdiction (dark blue), and marine protected areas (green). Top: coastal. Bottom: offshore. See also Table S4.

Diversity (CBD), which mandates inclusion of at least 10% of marine areas in effectively managed and ecologically representative MPAs by 2020 [21]. Achieving a truly representative MPA network will require the protection of global and realm-specific wilderness alongside imperiled biodiversity-rich areas, because wilderness areas support unique species compositions and higher biomass than populated areas [4, 5]. Wilderness areas can also exhibit extremely high endemism [6] and harbor functional traits rarely found in areas of higher impact [4]. Furthermore, although many marine wilderness areas are located in deep-water areas (Figure 1), recent research shows that these places are not as species impoverished as once thought, as they hold significant biodiversity [25] and maintain crucial ecosystem processes [26].

Marine wilderness areas may also be well placed to resist and recover from the impacts of climate change, though the evidence for this is mixed [12]. There are a number of studies showing that less degraded ecosystems can return more quickly to their original state after disturbances (including climate stressors) than more degraded ones [12, 13, 27]. Furthermore, there is also some evidence that local stressors can reduce ecosystem resilience to climate change, meaning that wilderness areas may have increased climate resilience [12, 13]. However, local stressors do not always affect susceptibility to climate change [12], and some areas of low anthropogenic activity are already severely impacted by climate change [27]. Nevertheless, conserving wilderness areas will provide numerous biodiversity benefits, including preserving unique species compositions and functional traits, and these areas may also be resilient to climate change.

Marine wilderness is often overlooked, both in global conservation policy and in national conservation strategies, because these areas are assumed to be free from threatening processes and therefore not a priority for conservation efforts [16]. Our results follow recent terrestrial analyses that debunk the myth that wilderness is not threatened [3], as we show only 13% of global marine wilderness remains. International policies are often blind to the benefits that flow from intact, functioning ecosystems, and there is no text within the CBD or the United Nations World Heritage Convention that recognizes the importance of retaining large intact landscapes or seascapes [3, 14]. Similarly, national-level conservation plans tend to focus on securing under-pressure habitats or endangered populations [28], rather than multi-faceted strategies that also focus on wilderness protection. Although conservation efforts in high-biodiversity, high-pressure regions (e.g., the Coral Triangle and Caribbean) are very important, they should be complemented by proactive action to prevent human pressures from eroding Earth's marine wilderness areas.

Future Conservation Actions

Multilateral environmental agreements should now recognize the importance of wilderness and the increasing threats it faces, both on land and in the ocean. Such recognition will help drive large-scale actions needed to secure wilderness into the future. These actions will vary across nations and regions, but they should focus on human activities that threaten wilderness. In the ocean, this includes preventing overfishing and destructive

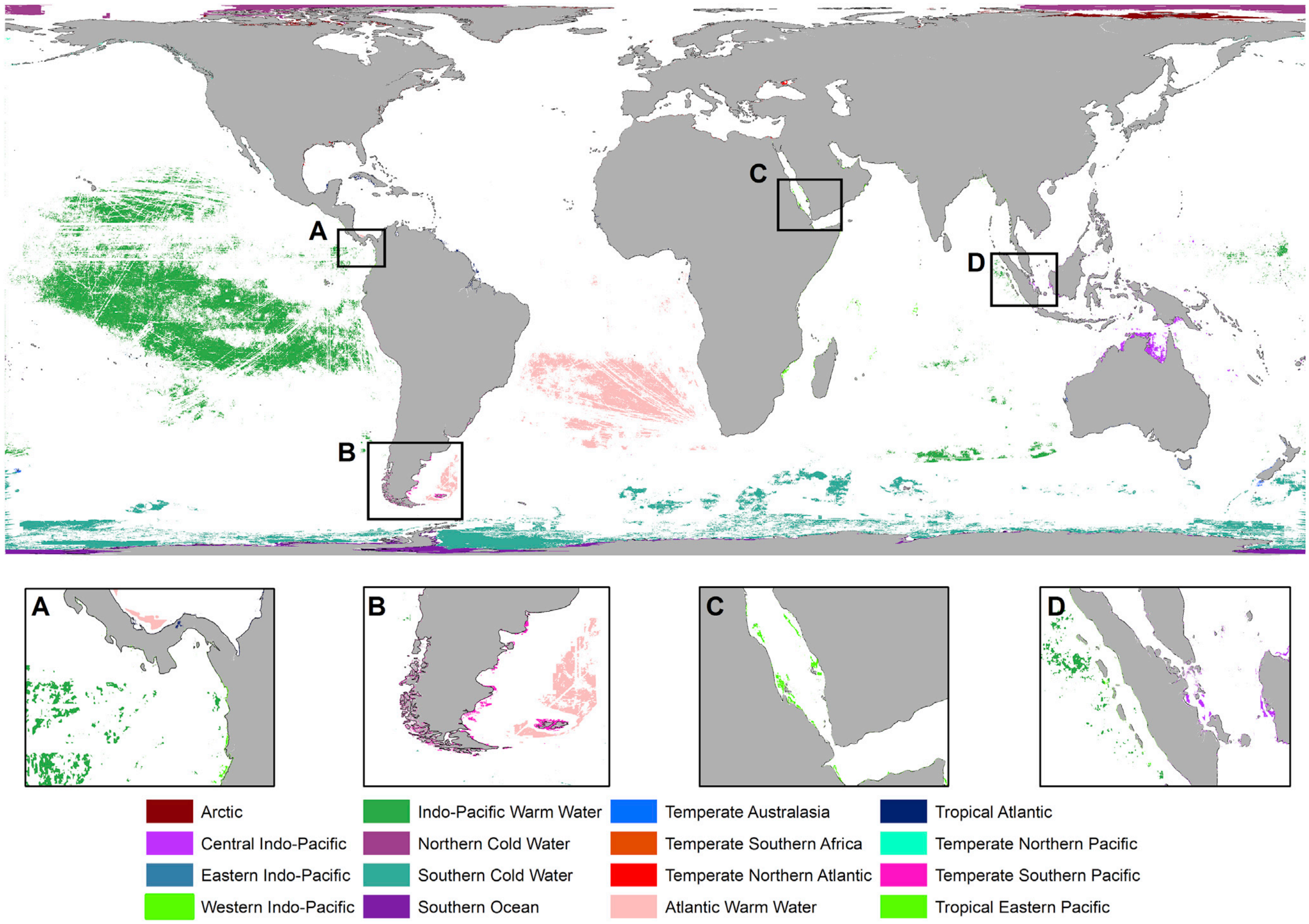

Figure 3. Realm-specific Wilderness Extent

Wilderness map showing the least impacted areas of each ocean realm.

fishing practices, minimizing ocean-based mining that extensively alters habitats, and limiting runoff from land-based activities. Better enforcement of existing laws is also needed to prevent illegal, unreported, and unregulated fishing, which makes up 10%–30% of global catch [29].

Along with ocean-based threats that erode wilderness, it is crucial to consider the impacts of climate change, which are already affecting marine biodiversity [27, 30]. Although we include climate change in our secondary cumulative impact classification, inclusion of climate variables in our individual stressor analysis resulted in almost zero marine wilderness remaining (Figure S1; STAR Methods). Our results must therefore be interpreted with the caveat that marine wilderness is already, and will continue to be, impacted by climate change. Although considering the direct impacts of climate change (e.g., temperature increases) is crucial, it is also important to predict and counter threatening human responses to climate change, such as shifting fishing grounds [31] or the opening of previously ice covered areas for shipping and fishing [18]. Given the devastating recent impacts of climate change on particular marine ecosystems (e.g., coral reefs [27]), we believe that priorities for wilderness protection could be informed by research assessing where such areas have been, or are likely to be, significantly impacted by climate change and where they can act as climate refugia.

Due to large-scale erosion of marine wilderness, those remaining areas are, almost by definition, irreplaceable—representing some of the last marine areas affected by no, or very low, human pressure. Protecting wilderness areas will help preserve large, biologically connected ecosystems [8, 9, 32]; species with large home ranges (e.g., tuna [33]); and hotspots of functional traits and endemic species [4–7]. It will also directly benefit humanity by preserving the carbon mitigation and adaptation values of intact marine ecosystems [34]. However, it is crucial to prioritize wilderness conservation to those areas most at risk of being lost and to not repeat past mistakes by designating MPAs to minimize conflict with other activities (e.g., fishing and mining [35]). In highly impacted regions and coastal ecosystems, retaining intact ecosystems will most likely require supplementing MPAs with other interventions to prevent impacts, such as land-based regulations to minimize sediment runoff [36]. Given that such little global marine wilderness remains in coastal areas, our realm-specific wilderness map (Figure 3) is useful to help direct such actions. It is also important to recognize that as with all global analyses, our wilderness maps rely on imperfect data, and we anticipate that refinements will occur as new data become available (e.g., Global Fishing Watch [37]), ensuring that wilderness is mapped with increasing precision.

As technological advances drive human impacts farther from land and deeper into the sea, it is also essential to consider the three-dimensional nature of the ocean. For example, fishing gear improvements have increased the mean depth of industrial fishing by 350 m since 1950 [38], and there are now almost 2,000 oil and gas wells operating deeper than 400 m [39]. Targeting conservation actions toward specific threats at specific depths will provide better protection of biodiversity across the entire water column. Wilderness conservation will also require an increased focus on high seas management. Although it is legally challenging, prioritizing conservation actions in at-risk areas beyond national jurisdiction is crucial for dealing with expanding human threats [40]. There is growing momentum behind the designation of large oceanic MPAs (e.g., Big Ocean [32]), and there are now extensive data to facilitate defensible selection and design of these large pelagic MPAs to protect high-seas wilderness [40]. Current difficulties with ensuring enforcement and compliance in these remote areas are beginning to be overcome, with recent advances in satellite and remote vessel-monitoring technology, such as Global Fishing Watch [37]. The need for improved high-seas management is also now being recognized by the international community, with the UN currently negotiating the "Paris Agreement for the Ocean"—a legally binding high-seas conservation treaty to be established under the existing Law of the Sea Convention [41].

Wilderness loss is a globally significant problem with largely irreversible outcomes: once lost, the many environmental values of wilderness are very unlikely to be restored. We show that there is very little global marine wilderness remaining, highlighting the need for immediate action to protect what is left and to prevent an ocean-based recurrence of the catastrophic wilderness declines seen on land [3]. Proactively prioritizing and protecting the world's most at-risk marine wilderness areas, while also securing highly threatened species and ecosystems, is now essential for conserving biodiversity and ensuring that large-scale ecological and evolutionary processes continue.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- CONTACT FOR REAGENT AND RESOURCE SHARING
- METHOD DETAILS
  - Marine human impact data
  - Mapping global marine wilderness
  - Mapping realm specific wilderness
  - Wilderness coverage across ecosystems
  - Wilderness protection
  - Wilderness and biodiversity
- DATA AND SOFTWARE AVAILABILITY

SUPPLEMENTAL INFORMATION

Supplemental Information includes four figures and four tables and can be found with this article online at https://doi.org/10.1016/j.cub.2018.06.010.

A video abstract is available at https://doi.org/10.1016/j.cub.2018.06.010#mmc4.

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AUTHOR CONTRIBUTIONS

K.R.J., C.J.K., B.S.H., O.V., and J.E.M.W. designed the research. K.R.J. performed the analysis. All authors wrote the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited Data		
Global and realm-specific marine wilderness maps	This paper	https://doi.org/10.5063/F1RR1WFT
Software and Algorithms		
ArcGIS	ESRI	http://www.arcgis.com/
Other		
Marine human impact data	[17]	https://www.nature.com/articles/ncomms8615
Marine Ecoregions and Pelagic Provinces of the World	UNEP-WCMC	http://data.unep-wcmc.org/datasets/38
Aquamaps marine species distribution data	Aquamaps	https://www.aquamaps.org/
Marine protected area location data	WDPA	https://www.protectedplanet.net/
Marine area polygon	National Geospatial-Intelligence Agency	https://doi.org/10.5061/dryad.6gb90.2

CONTACT FOR REAGENT AND RESOURCE SHARING

Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, Kendall R. Jones (krjones@wcs.org).

METHOD DETAILS

All spatial data described below were processed using ESRI ArcGIS v10 in Behrmann equal-area projection.

Marine human impact data

To map the global extent of marine wilderness we utilized data on the intensity and cumulative impact of 19 different anthropogenic stressors to marine environments globally in 2013 [17]. These data are the finest resolution marine cumulative threat maps available (1km^2 cells), as well as the most comprehensive, including data on land-based stressors (e.g., nutrient runoff), ocean-based stressors (e.g., fishing), and climate change. To create the map of cumulative impact on the ocean, data for each stressor is normalized (placed on a 0-1 scale), resampled to a 1km^2 resolution, transformed by vulnerability weights that are ecosystem-specific (see [17] for methods and vulnerability weights), and the values for all ecosystem-stressor combinations within each 1km^2 cell are averaged across cells to give a final cumulative impact value. We utilized both the individual stressor layers, and the cumulative impact map to identify marine wilderness.

We used the finest resolution human threat data available at a global scale, but there are some limitations which should be recognized. Given the lack of data available for the high-seas and polar regions, it is somewhat challenging to accurately determine whether low-threat regions are being identified due to a true absence of human impacts, or just an absence of data. However, it is clear that most of the human activities captured in our data occur primarily within EEZ's, because land-based impacts are concentrated in coastal waters, and most marine resources (and thus fishing catch) are located within shallower inshore areas rather than the high seas [42]. Furthermore, the most recent research available shows that for some of the individual threats used in this analysis (such as commercial fishing), polar regions and the high seas have generally low levels of impact [43]. Sensitivity analyses of the cumulative impact data we used have also shown that the maps are most robust at high and low extremes (e.g., they are accurate for identifying high and low impact areas) but are less accurate at medium levels of human impact (see supplementary materials in [2]. Given that we focus only on low impact areas in this study, and use the best available data, we have produced the most accurate marine wilderness map currently possible.

Mapping global marine wilderness

Because even relatively low levels of human activities can significantly impact vulnerable aspects of marine biodiversity (e.g., mobile top predators [4]), identifying wilderness requires finding those areas that have little to no impact across all human activities. We therefore identified marine wilderness by conducting a primary classification of each individual normalized stressor layer using a 10% threshold, so that cells within the bottom 10% of values for each stressor were assigned a score of zero and all other cells were assigned a score of one. By summing the values across all stressors, we identified areas within the bottom 10% across all individual stressors. In some cases, areas with a moderate cumulative impact still remained (e.g., when the impact value for multiple stressors was just below the 10% threshold). Therefore, we applied a secondary classification to identify our final map of marine wilderness, to only include areas within the bottom 10% of cumulative impact globally [17]. We conducted this analysis for 2 scenarios, one that included all 19 stressor layers in the primary stressor reclassification, and one that excluded climate change based stressors, leaving 15 stressor layers (see Table S1 for individual stressor layers). Both scenarios use the same layer (that includes climate change variables) for the secondary cumulative impact classification.

Mapping realm specific wilderness

We also created maps of realm specific wilderness for 2013, based loosely on the methodology used in the terrestrial realm [44]. We first followed the primary classification used to map marine wilderness, using a 10% threshold to classify each individual stressor so that cells within the bottom 10% of values for each stressor were assigned a score of zero and all other cells were assigned a score of one. By summing the values across all stressors, we identified areas within the bottom 10% for all individual stressors. We then used 2013 cumulative marine impact data [17] to identify the 10% least impacted areas of each ocean realm (using the Marine Ecoregions and Pelagic Provinces of the world dataset [15]). Finally, to identify realm specific wilderness, we identified all areas within the lowest 10% for all individual stressor layers, and within the 10% least impacted areas of each realm according to cumulative impact data. This created a different map to the global marine wilderness map because we identified the least impacted places within each marine realm, which highlights areas with higher impacts compared to when using a global threshold (as in the global marine wilderness map).

Wilderness coverage across ecosystems

To assess the distribution of marine wilderness across ecosystem types, we used the ecosystem maps developed by [2]. Because global maps for most marine ecosystems are largely non-existent, these data uses available distribution maps for several ecosystems, and models the distribution of many other ecosystems. We excluded all intertidal ecosystems from our analysis, along with suspension feeding reefs (mussel beds), as these ecosystem models are identical, such that all intertidal ecosystems (e.g., rocky intertidal, mudflats) occur in every cell within 1km from the shoreline. Thus, when calculating wilderness extent and protection, all intertidal ecosystems would have identical results. Excluding intertidal ecosystem data left 12 ecosystems – 5 coastal ecosystems (e.g., seagrass, coral reefs), and 7 deep-water ecosystems (e.g., soft bottom shelf, seamounts). Using our global maps of marine wilderness (not the realm-specific wilderness maps), we quantified the area of each ecosystem that overlapped with marine wilderness areas.

Wilderness protection

To assess protection of marine wilderness within MPAs we extracted data on MPA location, boundary, and year of inscription from the 2017 World Database on Protected Areas (WDPA) [45]. Following similar global PA studies [46], we extracted MPAs from the WDPA database by selecting those areas that had a status of "designated," "inscribed," or "established," and were not designated as UNESCO Man and Biosphere Reserves. We included only MPAs with detailed geographic information in the database, excluding those represented as a point only. We then used a layer of terrestrial country boundaries to clip MPA polygons to only include protected areas which have some overlap with marine area (https://doi.org/10.5061/dryad.6gb90.2). The resulting MPA data was overlaid with the global and realm specific marine wilderness maps to quantify the current level of global and realm specific wilderness protection, both across the globe and across the realms and ecosystem types used in the above analysis.

Wilderness and biodiversity

To assess overlap between marine wilderness areas and biodiversity, we first conducted an analysis using data on marine biodiversity from Aquamaps, a species distribution modeling tool that produces standardized global range maps for 22,885 aquatic species [19]. This is the most comprehensive and highest resolution data available on the distribution of marine biodiversity globally, and includes Animalia (fishes, marine mammals, and invertebrates), Plantae (fleshy algae, seagrass), Chromista (calcifying algae) and Protozoa. The species distribution maps predict relative probabilities of species occurrence (ranging from 0.00–1.00) at a resolution of 0.5-degree cells. It is assumed that the preferred range is where probability is 1, outside the range limits is where probability is 0, and between these two thresholds the relative environmental suitability decreases linearly. As there is no recommended threshold to use, we follow previous studies and use a probability threshold of 0.5 or greater [47]. We did not repeat our analysis using different thresholds, as previous studies have shown this makes very little difference to global scale analyses [47, 48].

To assess coverage of marine species distributions in wilderness areas, we determined the proportion of wilderness in each 0.5-degree cell. As we do not know the exact distribution of species within each cell, we assumed that the area of a species' range contained in wilderness was equal to the area of wilderness in each cell that species was present in. Using the same species distribution data, we also calculated species richness, species range rarity, and proportional species range rarity. Species richness was calculated as the number of species within each 0.5-degree cell. Species range rarity was calculated as:

$$R = \sum_{i=1}^{N} \frac{1}{A_i} \times w$$

where for each species *i* of *N* species per 0.5 degree cell, *Ai* is the total range area for that species *i* including all areas inside and outside of the cell and *w* is the proportion of the cell which is ocean (i.e., *w = 1* if the entire cell is ocean, or *w = 0.5* if half the cell is terrestrial). Species range rarity reflects both the number of species and the size of their ranges, which is a common way to delineate priorities based on endemism as it quantifies the number of relatively range-restricted species within a cell [48]. To calculate proportional species range rarity, we used the same formulation as species range rarity, but divided the value for each cell by the number of species found in that cell, to remove the confounding effect of species richness. We then calculated average species richness, range rarity and proportional range rarity for wilderness and non-wilderness areas across the marine ecoregions of the world [15].

DATA AND SOFTWARE AVAILABILITY

The global and realm-specific marine wilderness maps reported in this paper are available at https://doi.org/10.5063/F1RR1WFT.