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Global marine protected areas to prevent extinctions

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One goal of global marine protected areas (MPAs) is to ensure they represent a breadth of taxonomic biodiversity. Ensuring representation of species in MPAs, however, would require protecting vast areas of the global oceans and does not explicitly prioritize species of conservation concern. When threatened species are considered, a recent study found that only a small fraction of their geographic ranges are within the global MPA network. Which global marine areas, and what conservation actions beyond MPAs could be prioritized to prevent marine extinctions (Convention on Biological Diversity Aichi Target 12), remains unknown. Here, we use systematic conservation planning approaches to prioritize conservation actions for sharks, rays and chimaeras (class Chondrichthyes). We use chondrichthyans as they have the highest proportion of threatened species of any marine class. We find that expanding the MPA network by 3% in 70 nations would cover half of the geographic range of 99 imperilled endemic chondrichthyans. Our hotspot analysis reveals that just 12 nations harbour more than half (53) of the imperilled endemics. Four of these hotspot nations are within the top ten chondrichthyan fishing nations in the world, but are yet to implement basic chondrichthyan fisheries management. Given their geopolitical realities, conservation action for some countries will require relief and reorganization to enable sustainable fisheries and species protection.

A common assessment of global marine protected area (MPA) progress is the amount of area protected[1,2], or the degree to which the MPA network represents a broad taxonomic swath of biodiversity (gap analysis)[3,4] (that is, the Convention of Biological Diversity (CBD) Aichi Target 11). A recent gap analysis found that most (97.4% of 17,348) marine species have less than 10% of their geographic range inside MPAs[4]. To address this shortfall, MPAs would need to be expanded in almost every coastal country's waters as well as the open oceans[4]. This expansion of MPAs would stretch limited funds and capacity for conservation action. Furthermore, while representation is an important goal, it prioritizes species irrespective of conservation need and does not help countries strategically locate MPAs that would focus on their commitment to prevent extinctions as per the interdependent yet often overlooked CBD Aichi Target 12: "By 2020 the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained"[5–7].

An approach that narrows the focus and scale of conservation and protects those species at greatest risk of extinction is the classic hotspot analysis[8–11]. Hotspots are those global areas with the greatest numbers of threatened and endemic species. In the terrestrial realm, this focus on threatened endemics narrowed the spatial scale of action to 1.4% of the land that, if protected, would represent more than half of the threatened endemic plants and 35% of threatened vertebrate species[8]. Until now, it has not been possible to undertake a similar global marine hotspot analysis due to a lack of comprehensive International Union for the Conservation of Nature (IUCN) Red List assessments[12]. Furthermore, MPAs are not the only tool to protect species—fisheries and conservation management outside of MPAs can also protect biodiversity[13,14].

Here, we ask four questions: (1) by how much do we need to expand the current MPA network to avert the extinction of imperilled endemic chondrichthyans; (2) what are the priority hotspot countries harbouring the greatest number of imperilled endemic species; (3) how can we improve activities related to fisheries and conservation management in these hotspot countries; and (4) what is the likelihood of conservation in each of the countries? We focus on 1,007 marine sharks, rays and chimaeras (class Chondrichthyes) for six reasons: (1) their threat status was comprehensively assessed by the IUCN[12]; (2) they have the greatest percentage of threatened species in a taxonomic class of marine organisms[15] and at least 28 populations are locally or regionally extinct[12]; (3) they are found in every ocean basin and across broad latitudes; (4) they are threatened by targeted and indirect overfishing, which is the leading threatening pressure in the ocean; (5) they have expert-generated, peer-reviewed extent of occurrence (EOO) maps, which are more suitable for conservation planning as they are not biased towards survey effort and are less likely to produce results with omission errors[16]; and (6) as of 2015, 29% of total ocean area protected was designated exclusively for shark conservation (Fig. 1a)[17].

Results

We first asked how well does the global MPA network protect the most imperilled and irreplaceable chondrichthyan species? Here, we defined imperilled as those chondrichthyan species categorized by the IUCN Red List as Critically Endangered, Endangered, Vulnerable, or Data Deficient but predicted to be threatened[12]. We defined irreplaceable species[18] as those species with limited spatial conservation options (endemics with EOO < median; Fig. 1b). We found that only 12 of the 99 imperilled endemics have at least 10% of their range within a no-take MPA (IUCN category 1a–VI or not reported) but only one species—the imperilled Kermadec spiny dogfish (*Squalus raoulensis*)—is entirely within a no-take and strictly protected MPA (IUCN protected area category 1a; Fig. 1c, Supplementary Tables 1 and 2).

We identified the locations that, if protected, would provide protection for the 99 imperilled endemic chondrichthyans. We used Marxan[19] software to identify planning units that meet conservation targets for each species while minimizing cost (area) and expanding from the current no-take MPA network (of any IUCN protected area category)[17]. The exact amount of EOO that should be covered for long-term persistence requires a consideration of life cycle. Conservatively, we chose to protect 100% of the EOO of each of the 99 species and found that this conservation target could be achieved by protecting 13% of the world's ice-free exclusive economic zone

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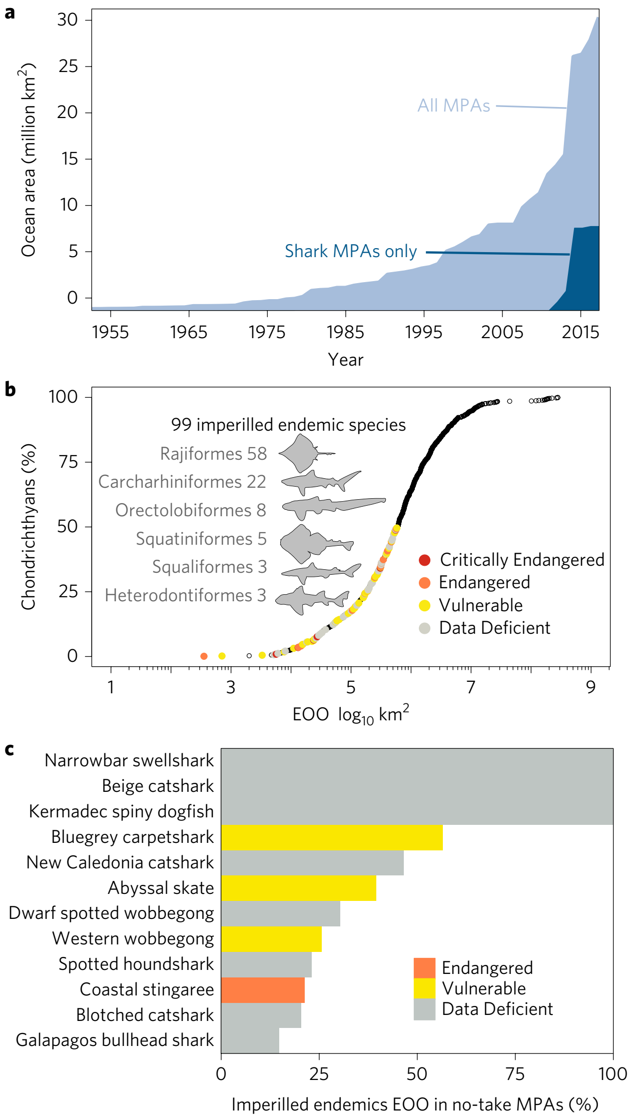

Figure 1 | Representation of the most imperilled and endemic chondrichthyans in the world's MPAs. a, Stacked plot of total ocean area designated with any spatial protection, excluding those exclusively for sharks (all MPAs, light blue) and those exclusively for sharks (shark MPAs only, dark blue). **b**, Cumulative percentage gain in species' geographic range size measured as EOO $\log_{10}$ km^2 of 1,007 marine chondrichthyans, the endemic cut-off (median EOO), the IUCN Red List categories for endemic species and the taxonomic composition of the 99 imperilled endemics. **c**, The 12 imperilled endemic species with >10% of their EOO within a no-take MPA of any IUCN protected area category (1a–VI or not reported). The bar colour represents the IUCN extinction risk category, grey bars represent Data Deficient species that are predicted to be threatened based on body size and ecological traits. Only the Kermadec spiny dogfish is found within a no-take, strictly protected MPA (IUCN protected area category 1a). Silhouettes were created by Christopher G. Mull from images by Nick G. Botner (Rajiformes, Carcharhiniformes) and R. Aidan Martin (Orectolobiformes, Squatiniformes, Squaliformes, Heterodontiformes), and reproduced with permission.

(EEZ) areas. These areas harbour not only imperilled endemic chondrichthyans, but also contain portions of the EOO of 78% ($n=114$) of the world's imperilled, non-endemic chondrichthyans. Alternatively, we found that protecting half of the EOO for each of the 99 species would only require expanding the MPA network to 3% of the global ice-free EEZ areas—well within the 2020 10% CBD target (Fig. 2a).

However, covering half of the EOO of the 99 chondrichthyan species would require MPA expansion in 70 nations. Therefore, we ask: what narrower suite of countries could protect the greatest number of imperilled endemics? We found that focusing on hotspots of imperilled endemics (4–14 species per cell) narrowed the scope of conservation action to just 12 countries in four locations (Figs 2b and 3a): (1) eastern and northern South America (Colombia, Brazil, Uruguay, Argentina); (2) western Indian Ocean (South Africa, Mozambique); (3) western Pacific (Taiwan Province of China, Japan, China and the Senkaku Island conflict zone between Taiwan Province of China, Japan and China); and (4) the Indo-Pacific (Australia, Indonesia, Philippines). These 12 countries harbour over half of the imperilled endemics ($n=53$) and cover only 1.25% of global EEZ waters. Hotspot locations were robust to different definitions of endemism (Supplementary Figs 1 and 2).

MPAs alone are probably not enough to secure the conservation of imperilled chondrichthyans, not least because the median size of global MPAs is 3.3 km^2 (ref. [20]) and the size of their average geographic range is more than 0.5 million km^2 (Fig. 1b). Assuming MPAs alone are insufficient, how can we improve activities related to fisheries and conservation management in hotspot countries? We found that the implementation and strength of fisheries management is highly variable in these countries and reveal some simple steps that would support chondrichthyan conservation (Fig. 3b, Supplementary Table 3). Of the 12 hotspot countries we identified as priorities, half have regulations to ban finning (cutting the fins off a shark and dumping the body overboard), but only four countries have the more enforceable fins-attached regulation (shark brought back to port with fins naturally attached). Just over half (58%) of these hotspot countries have finalized a 'shark-plan' (a non-binding plan to sustainably manage chondrichthyan fisheries), and three have a shark-plan that meets greater than 50% of the objectives of sustainable fishing. Four countries are signatory to the Convention on Migratory Species Memorandum of Understanding for sharks (CMS MoU sharks—a non-binding agreement to develop a conservation plan for listed species); five countries have taken meaningful steps towards curbing illegal, unreported and unregulated fishing by becoming parties to the Port State Measures Agreement (PSMA), but only three ratified this critical agreement (Fig. 3b). Finally, hotspot countries Brazil, Indonesia, Taiwan and Argentina are among the top ten chondrichthyan fishing[21] countries in the world (Fig. 3c).

What is the likelihood of conservation in each of the priority nations? We assessed the geopolitical realities that could influence conservation success in these 70 nations and distinguish four broad classes of intervention[22,23]. We created a composite conservation likelihood score from ten national measures including governance, economics and welfare, fishing, and human pressure (Fig. 4, Supplementary Table 4). We found Australia, South Africa and the USA have relatively higher conservation likelihood scores and management, but also a high percentage of planning units selected for MPA creation. In these countries, conservation and management action may be more successful (Fig. 4 (1)). Despite having relatively high conservation likelihood scores, Panama and Japan have relatively low chondrichthyan fisheries and conservation management (Fig. 4 (2)). Argentina and Brazil have high conservation value (high numbers of imperilled endemics and planning units selected for MPA expansion) but low conservation likelihood scores, and hence conservation actions could be enabled with further capacity building (Fig. 4 (3)). Malaysia, Papua New Guinea, Mozambique and Indonesia have opportunity for expanding conservation action (fisheries and conservation management, as well as MPA expansion) but require considerable relief and reorganization to enable this transition (Fig. 4 (4)). Meanwhile, China presents a unique challenge, with nine imperilled endemics and little evidence of chondrichthyan fisheries and conservation management (Fig. 4 (4)).

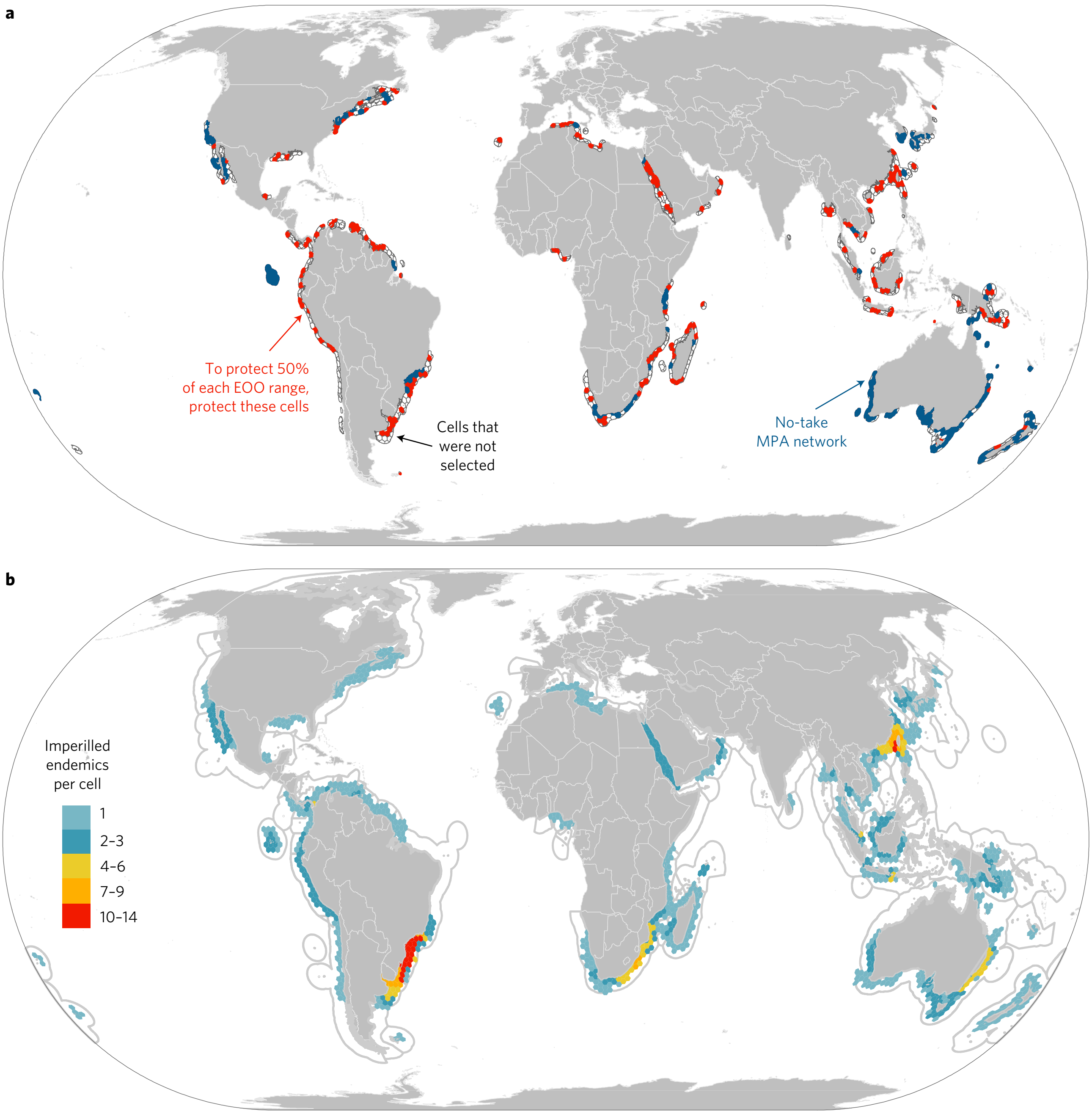

Figure 2 | Spatial conservation options for two systematic conservation planning approaches. a, Species conservation targets; locations for MPA creation or expansion to protect 50% of the geographic range of all 99 imperilled endemic chondrichthyans (using Marxan): planning units selected (red); planning units not selected (white); and planning units currently designated as a no-take MPA (blue). **b**, Hotspots; global locations of the highest numbers of imperilled endemic chondrichthyans within a country's national waters (EEZ). Warm colours represent areas with high numbers of overlapping imperilled and endemic chondrichthyans, cool colours show where there are fewer numbers of species per cell. Hottest hotspot countries are those with 4–14 imperilled endemics per grid cell. Maps were created in Arc GIS version 10.3.

Discussion

Area-focused protection goals have galvanized rapid gains in MPAs over the past decade[1,2,20,24,25]. Yet, we find that this approach has failed to protect those imperilled endemic chondrichthyan species in need of conservation action. We find that a reconfiguration could ensure that future MPAs contribute to preventing extinctions—similar to the approach taken by the Alliance for Zero Extinction for terrestrial and reef-building coral species[5,26]. Furthermore, only a small fraction (0.9%) of the global MPA network is fit for the purpose of preventing extinctions; therefore, new MPA designations could include a higher fraction of strictly enforced no-take areas[27–30]. This could be complemented by widespread improvements in fisheries management, to minimize the mortality of threatened species and ensure the sustainability of others[31].

The greatest challenge is to secure fisheries and conservation improvements in counties with lower conservation likelihood and hence adaptive capacity[32]. Climate change has led to a massive engagement of aid and development organizations to enable coastal adaptation. Following this template, there is a clear need to make fisheries management and marine conservation mainstream within development aid, poverty alleviation and adaptation activities[23,32,33].

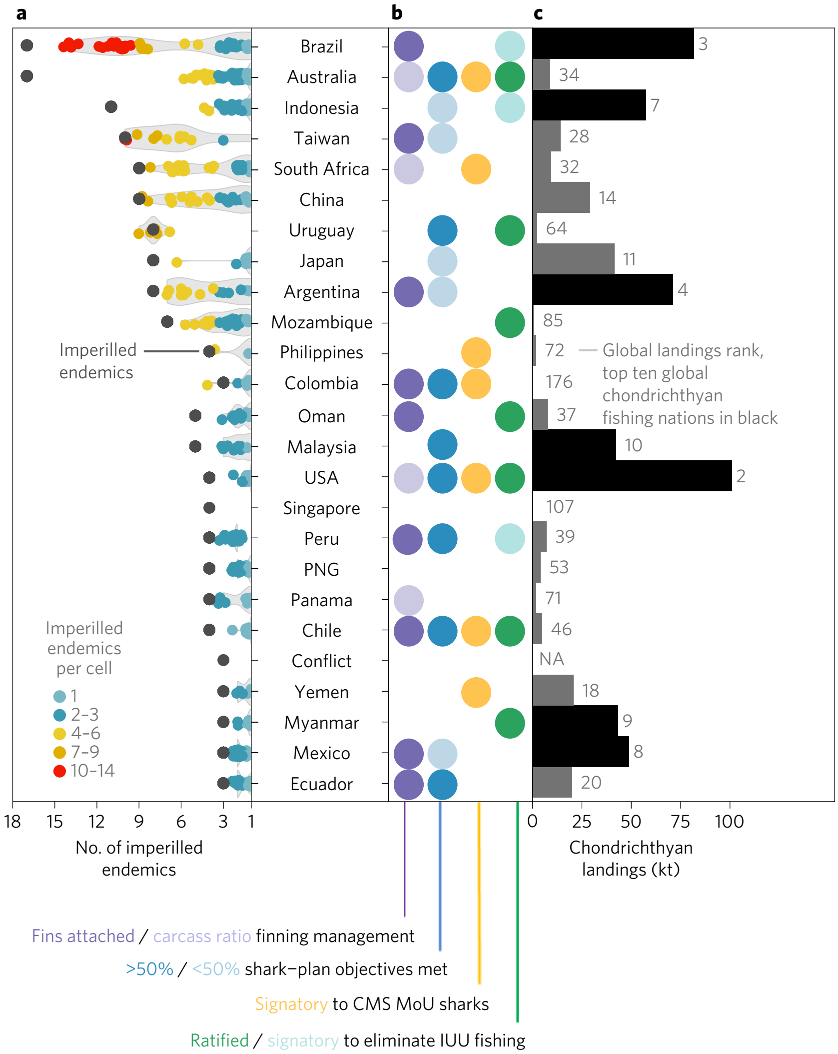

Figure 3 | Fisheries management and conservation needs beyond MPAs. **a**, Number of imperilled endemics in each country per cell (coloured points) and within the entire EEZ (black). **b**, Presence and strength of each of the fisheries management and conservation measures. Saturated colours across the four management measures represent a country (1) with the more enforceable fins-attached regulation; (2) with an adequate shark-plan; (3) that is a signatory to CMS MoU sharks; and (4) has ratified the legally binding PSMA to deter illegal, unregulated and unreported (IUU) fishing. **c**, Reported chondrichthyan landings (kilotonnes) from the Sea Around Us project catch reconstructions and the countries within the top ten chondrichthyan fishing nations in the world (black bars). PNG, Papua New Guinea.

Methods

We used expert-generated, peer-reviewed EOO geographic range maps for 1,007 marine chondrichthyan species that were taxonomically valid up to August 2011[12]. These maps are convex polygons around known locations, hence, we caution that our results are likely to contain commission rather than omission errors; that is, a species is shown to be present in an area when in fact it is not[34]. Notwithstanding the likelihood of commission errors, the use of these distribution maps for this type of analysis falls into the manual of best practices for IUCN maps, and priority countries should become the focus of local scaled planning[35]. All distribution maps were created through expert opinion from the IUCN shark specialist group (SSG). For this analysis, the pita skate (*Okamejei pita*) was not included due to its taxonomic uncertainty.

We used the IUCN Red List categories as a measure of extinction risk[36]. This index considers all threats, such as fishing pressure, coastal development, or pollution[37]; however, future smaller-scale studies will be needed to identify the mechanism of the species endangerment and to tailor conservation action. Here, we focussed on fishing pressure, as this is the predominant threat to chondrichthyan species[12].

To determine which species are imperilled and endemic, we used three definitions of marine endemism commonly used in the literature: those species within the (1) 25th percentile (183,616 km^2); (2) less than 500,000 km^2 (refs [12,38]); and (3) 50th percentile (595,749 km^2) of EOO geographic range sizes[39,40], resulting in 252, 468 and 504 species, respectively. We defined imperilled species as those categorized by the IUCN as Vulnerable, Endangered, or Critically Endangered, plus those Data Deficient species predicted to be threatened. Almost half (46.8%) of chondrichthyans are categorized as Data Deficient[12], meaning not enough information was available to assign them to a IUCN Red List category, but these Data Deficient species may be threatened. Indeed, based on body size and ecological characteristics, 68 out of the 487 data deficient species are predicted to be threatened with extinction[12]. Therefore, we include the distribution of predicted threatened Data Deficient species that meet our endemism criteria ($n=35$). The final number of imperilled endemic chondrichthyan species for each definition is 57, 92 and 99, respectively. We used the median (Supplementary Fig. 1a) definition of endemicity for the remaining analyses, and the hotspot locations revealed were robust to the definition of endemism (Supplementary Fig. 2a–c).

A total of 99 chondrichthyans are both endemic and imperilled (Fig. 1b). More than half ($n=58$) of these 99 are batoids (skates, stingrays, guitarfishes, wedgefishes and rays; order Rajiformes). The remaining imperilled endemics include 22 ground sharks (order Carcharhiniformes), three dogfish (order Squaliformes), eight carpet sharks (order Orectolobiformes), three horn sharks (order Heterodontiformes) and five angel sharks (order Squatiniformes). Eighty percent ($n=79$) of the imperilled endemics are coastal and continental species, and the remainder ($n=20$) are deepwater.

We used the MPAtlas[17] to determine how much of the world's MPAs are designated for, sharks, rays, or chimaeras. To determine ocean area protected, we excluded proposed parks and those without in the year the park was created.

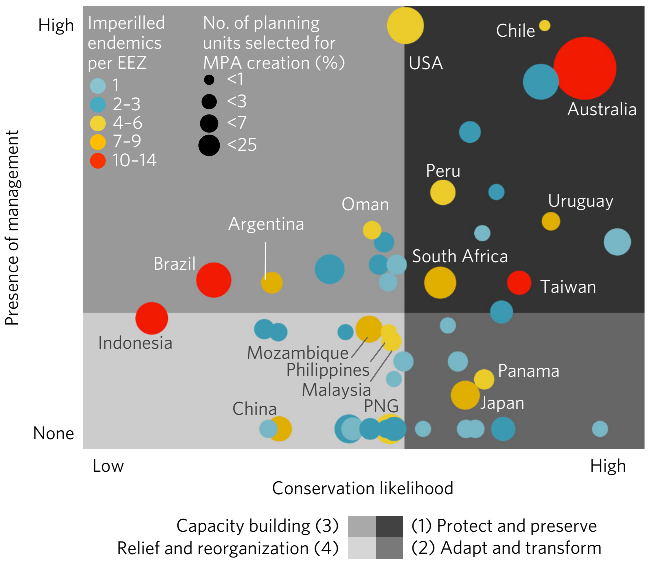

Figure 4 | Priority countries, conservation likelihood, and the presence and strength of the chondrichthyan management. Quadrants are delimited by the median index scores. Conservation and management action is more feasible in countries with relatively higher conservation likelihood scores (quadrant (1)). Conservation value is represented by the combination of the percentage of Marxan planning units identified for MPA expansion (radius of each point, from Fig. 2a) and the number of imperilled endemics (point colour, from Fig. 2b) within that country's national waters. PNG, Papua New Guinea.

Any marine designation was included as an MPA, such as whale sanctuaries, sites of community importance and shellfish management areas, to give a total of 12,157 MPA sites. Fifteen sites were designated as 'shark sanctuaries' and were used to calculate the percentage of total area designated exclusively for sharks (Fig. 1a). In the main text we excluded the Southern Ocean Marine Sanctuary (designated in 1994) from the area calculations, as it covers the marine portion of Antarctica and is an unusually large sanctuary at about 65 million km^2. Had we included this large ocean area, the amount of MPAs designated exclusively for sharks in 2015 would be 9.3%.

To determine the number of imperilled endemic species with at least 10% of their EOO within a MPA, we subset the MPAtlas to include (1) any park that was designated ($n=12{,}582$); (2) any park designated as no-take (all or part, IUCN category 1a–VI or not reported) and designated exclusively for sharks ($n=988$); and (3) those areas designated as no-take (all or part, IUCN category 1a–VI or not reported, $n=973$). Despite the differences in the number of parks and ocean area, we found little difference in the number of imperilled endemics protected: 24, 12 and 12, respectively (Supplementary Table 2). To calculate the area coverage from any MPA, we eliminated erroneous percentages that would arise from overlapping spatial protections (such as overlapping areas for trap/pot closures and national heritage sites in the eastern USA) by dissolving the boundaries of MPAs in ArcGIS version 10.3. We note that coastal[41], deepwater[42], or time–area closures for nursery populations of highly mobile sharks and rays[31,43] are shown to provide favourable conservation outcomes.

Almost 10% (7.7%, $n=973$ of 12,582) of global MPAs entirely restrict fishing (no-take, part or all) but have varying enforcement and restrictions (IUCN protected area categories 1a–VI and those for which status is 'not reported')[2,20]. A much smaller subset, only 0.9% ($n=110$ of 12,582) of global MPAs entirely restrict fishing (no-take) and are strictly enforced (IUCN protected area category 1a). These marine reserves have the attributes shown to increase biomass and hence contribute to preventing extinctions[30,44]. We found that only the Kermadec spiny dogfish (*S. raoulensis*) is entirely within the recently designated, strictly protected marine reserve (IUCN protected area classification 1a): Kermadec Islands in New Zealand. A portion of the EOO (16%) for narrowbar swellshark (*Cephaloscyllium zebrum*) is found within the Coral Sea marine reserve in Australia.

We used Marxan[19] to determine which global areas could be prioritized for protected area expansion if we were to extend coverage to 25, 50 and 75% of the range of all 99 imperilled endemics. We integrated area as cost[45] and a cell was considered protected ($n=206$ out of 1,132 cells) if at least half of the cell overlapped with a no-take MPA. Marxan is iterative and therefore we used the best scenario to determine which cells had the highest frequency of selection.

We chose a boundary length modifier of one, as we are interested in expanding from the current no-take MPA network rather than creating disconnected new ones. We ran 100 iterations for each scenario. We found that 2.2, 3.3 and 4.5% of the world's ice-free EEZs would need to be the focus of MPA expansion or creation to cover 25, 50 and 75% of each of the 99 imperilled endemic chondrichthyan EOOs, respectively (see Fig. 2a for cells selected to protect 50% of EOOs). Some countries, particularly small ones such as Egypt, Uruguay and Brunei, would have to protect large proportions of their EEZs.

We defined hotspots[8] as areas with the number of imperilled endemic chondrichthyan species on two spatial scales: (1) per hexagonal grid cell (23,322 km^2); and (2) per EEZ, (200 nautical miles from the coast, Fig. 3a). We assigned cells to an EEZ based on the location of the centre of the cell. We calculated the percentage area of hotspot using ocean area from the National Oceanic and Atmospheric Administration[46]. We also calculated how many non-endemic, imperilled species have parts of their range that overlap within hotspots. All spatial overlay analyses were completed in ArcGIS version 10.3. Hexagons sometimes extended beyond the boundaries of some EEZs (for example, Uruguay); therefore, on occasion some hexagons have a higher number of species than is found within the country's EEZ.

Most hotspots are found in national coastal waters. Only five hotspot cells are oceanic; three are adjacent to Western Australia's southwest tip near Geographe Bay, while two are outside Brazil's EEZ near the mouth of the Amazon River. Three cells fall within the Senkaku/Diayudao/Diaoyutai Islands, which is a disputed territory between Taiwan, China and Japan. Another two cells are in a disputed marine area between Chile and Peru.

The most important hotspot countries (hereafter 'hottest hotspots') are those with counts of 4–14 imperilled endemic species per cell (Figs 2b and 3a). These areas cover less than 1% (0.56%) of the global ice-free ocean surface or 1.25% of global EEZ waters and contain 54% ($n=53$) of the EOO of the imperilled endemic species.

We ranked countries according to the total number of imperilled endemics within their national waters (EEZ) as this is generally the scale of fisheries management. We also retained the number of species per cell to highlight the countries with high numbers of overlapping imperilled endemic species. Countries such as Uruguay have many imperilled endemics homogeneously distributed throughout a small EEZ (Fig. 3a). But most other priority countries, as typified by Australia, have many non-overlapping imperilled endemics throughout their EEZ (Fig. 3a). Hence, it is unlikely that any one national MPA will serve to protect all the imperilled endemics for which a nation is responsible.

To evaluate the sustainability and conservation initiatives in hotspot countries we compiled country-level chondrichthyan fisheries management measures that are global and comparable[47] (Fig. 3b, Supplementary Table 3). While these are not ultimate measures of fisheries management, the challenge is to find consistent measures that indicate or approximate good local management. We used four measures: (1) strength of finning management regulation; (2) strength of shark-plan (national plans of action for sharks); (3) whether a country is a signatory to the CMS MoU sharks; and (4) whether a country is signatory to, or has ratified the PSMA. These indirect and direct measures are intended to give a broad analysis of the state of chondrichthyans fisheries and may or may not be relevant to imperilled endemic species. For example, Rajiformes are not included in the finning policy of any country (rays and skates could be 'winged' at sea).

We used a modified conservation likelihood framework to determine, broadly, the types of intervention needed for the different hotspot countries. First, we determined the likelihood that conservation actions would be successful in a country following the methods outlined in ref. [22]. Governance included political stability, government effectiveness, control of corruption and regulatory quality; economics and welfare included gross domestic product, purchasing power parity and human development index; human pressure included annual human population growth, human population 100 km from the coast and Sea Around Us reconstructed chondrichthyan landings (see Supplementary Table 4 for references). We used 2014 measurements unless none were available, in which case we used the most recent year (no later than 2011). Taiwan does not have an entry in this database; however, the Taiwan government calculated their human development index to be 0.882. We summed the standardized score for each of the broad category classes and took the mean. The following overseas territories were excluded from the analysis due to lack of data: Bassas da India, Bonaire, Curacao, Ile Europa, Juan de Nova Island, Falkland Islands and New Caledonia (these areas each have only one imperilled endemic in their waters). Also, Somalia had no information on governance and economics, and was excluded from the analysis. Second, we summed a standardized score of the presence and strength of the management and conservation measures that we considered. Our presence of management axis is our derivative of the 'environmental susceptibility' axis found in the original framework in ref. [23], where a higher score for management presence and strength represents a lower environmental susceptibility.

Data availability. The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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Author contributions

L.N.K.D. and N.K.D. conceived the project, designed the study, analysed the data and wrote the paper.

Additional information

Supplementary information is available for this paper.

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Competing interests

The authors declare no competing financial interests.