

Supplementary Information

Half a century of rising extinction risk of coral reef sharks and rays

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Supplementary Notes

National Traits Predict Threat Level

Most of the national variation in extinction risk of coral reef sharks and rays is explained by abiotic factors related to population size, fishing pressure, and management capacity indices. The drivers of risk differed slightly between sharks and rays. The national extinction risk of sharks was more determined by the abiotic factors related to population size of sea surface temperature (19.8% [19.4–20.1%]), primary production (15.3% [14.9–15.6%]), and shelf area (15.2% [14.8–15.6%]); followed by fishing pressure indexed by coastal population (12.3% [12.0–12.6%]), marine protein consumption (9.1% [8.8–9.4%]), catch (3.6% [3.4–3.8%]), catch-per-unit-effort (CPUE) (0.9% [0.8–1.1%]), sightings-per-unit-effort (SPUE) (0.8% [0.7–0.9%]), and fishing effort (0.4% [0.3–0.5%]); and finally, management capacity indices of Gross Domestic Product (GDP) (11.3% [11.0–11.6%]), World Governance Index (WGI) (7.8% [7.5–8.1%]), and Human Development Index (HDI) (3.5% [3.3–3.7%]; Fig. 3). National extinction risk of rays was also determined by variable groupings in the same order of importance; however, management capacity indices were less than half the importance to rays as they were for sharks. Additionally, national extinction risk for rays was almost equally determined by ecological factors that affect carrying capacity and fishing pressure. The most important group of variables for rays were abiotic factors related to population size including sea surface temperature (32.4% [31.8–32.9%]), shelf area (10.1% [9.8–10.5%]), and primary production (4.1% [3.8–4.4%]); followed closely by fishing pressure indexed by CPUE (19.2% [18.7–19.6%]), catch (6.4% [6.1–6.8%]), marine protein consumption (5.6% [5.3–5.9%]), fishing effort (5.2% [4.9–5.6%]), SPUE (4.3% [4.1–4.6%]), and coastal population (2.8% [2.6–3.0%]). Finally, management capacity indices of HDI (4.4% [4.1–4.6%]), WGI (3.4% [3.1–3.6%]), and GDP (2.1% [1.9–2.4%]), were of little importance to rays (Fig. 3).

Where Are Reef Species Threatened?

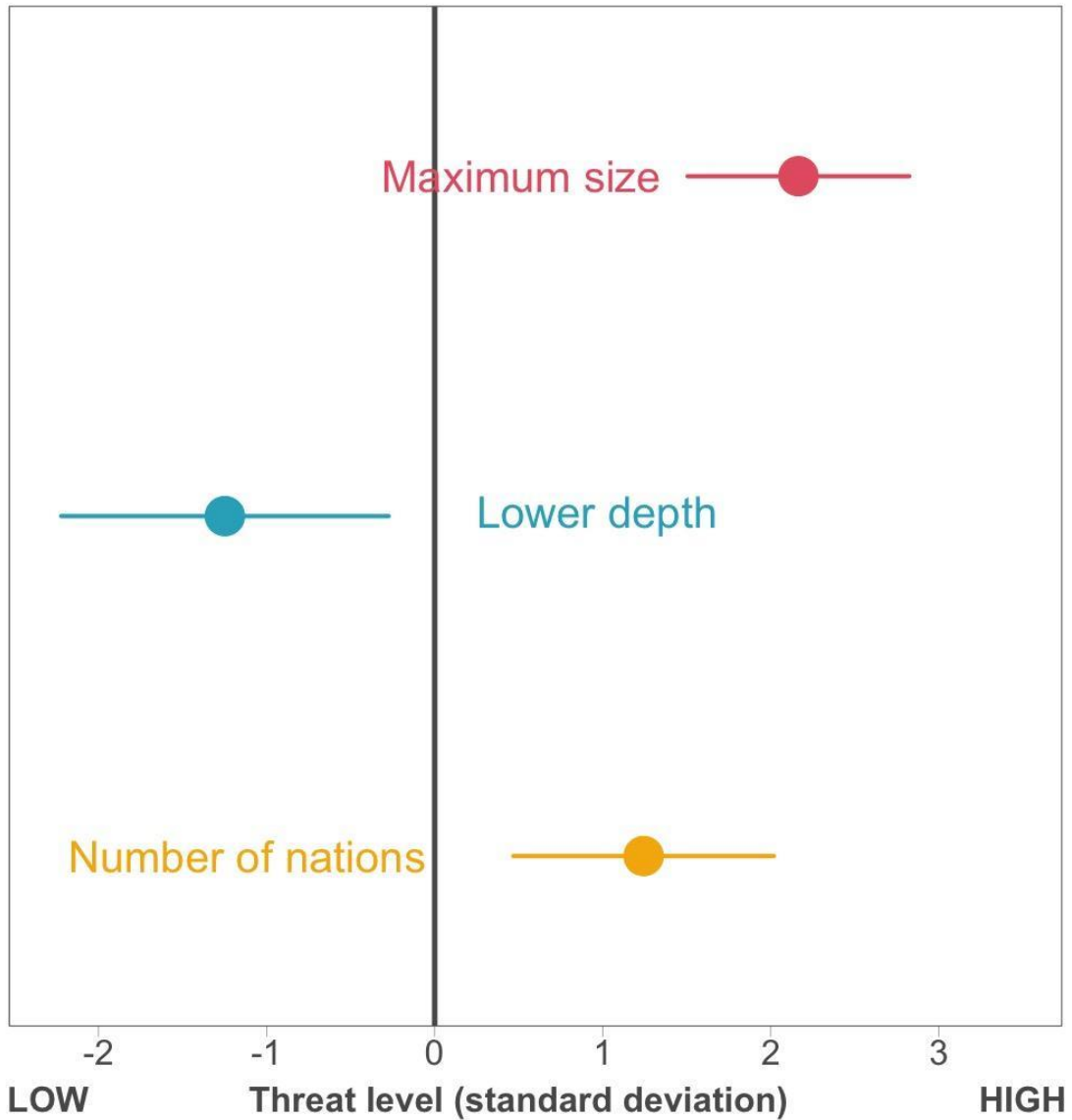
The highest richness of coral reef sharks and rays combined occurs in the Indo-Pacific Coral Triangle with up to 52 species per 23,322 km² hexagonal grid cell (39% of all species; Supplementary Fig. 4a). This region is already well known for having the highest diversity of reef-building corals and coral reef teleosts^{1,2}. The highest number of threatened species occurs in southern and southeast Asia with up to 42 species threatened per grid cell, reflecting the high levels of regional fisheries catch, effort, coastal population densities, and marine protein consumption (Supplementary Fig. 4b). However, the highest proportion of threatened reef sharks and rays occurs off the northeast coast of South America, the Andaman and Nicobar Islands, northeastern Taiwan, and western Africa (this area has few coral reefs but many transient, large-bodied, apex predator species that occur on coral reefs in other regions) (Supplementary Fig. 4c).

Similarly, the highest number of threatened species occurs in southern and Southeast Asia with up to 16 shark species and 26 ray species threatened within a single grid cell (Figs 4c,g). However, the region with the highest proportion of threatened sharks is the western Atlantic (Fig. 4c), possibly due to the comparatively low level of endemism and diversity in the region. For rays, the proportion threatened is greatest throughout Asia and in southeast Africa with over 75% of species threatened in these areas (Fig. 4g). Reef rays have a higher proportion of their distribution where >90% of species within the map grid cell are threatened than sharks, suggesting rays have less spatial refuge from threats in reefs than sharks do (Figs 4d,h).

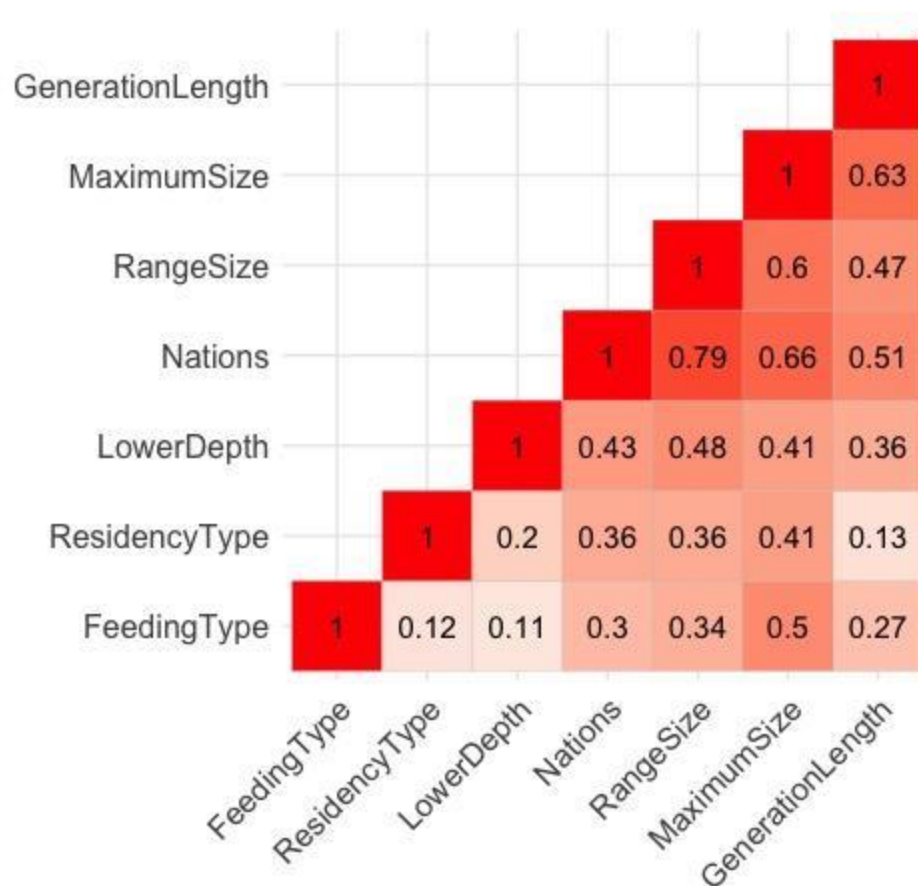
Supplementary Information References

- 1 Veron, J. E. N. *et al.* Delineating the Coral Triangle. *Galaxea, Journal of Coral Reef Studies* **11**, 91-100 (2009). <https://doi.org:10.3755/galaxea.11.91>
- 2 Asaad, I., Lundquist, C. J., Erdmann, M. V. & Costello, M. J. An interactive atlas for marine biodiversity conservation in the Coral Triangle. *Earth System Science Data* **11**, 163-174 (2019). <https://doi.org:10.5194/essd-11-163-2019>
- 3 MacNeil, M. A. *et al.* Global status and conservation potential of reef sharks. *Nature* **583**, 801-806 (2020). <https://doi.org:10.1038/s41586-020-2519-y>

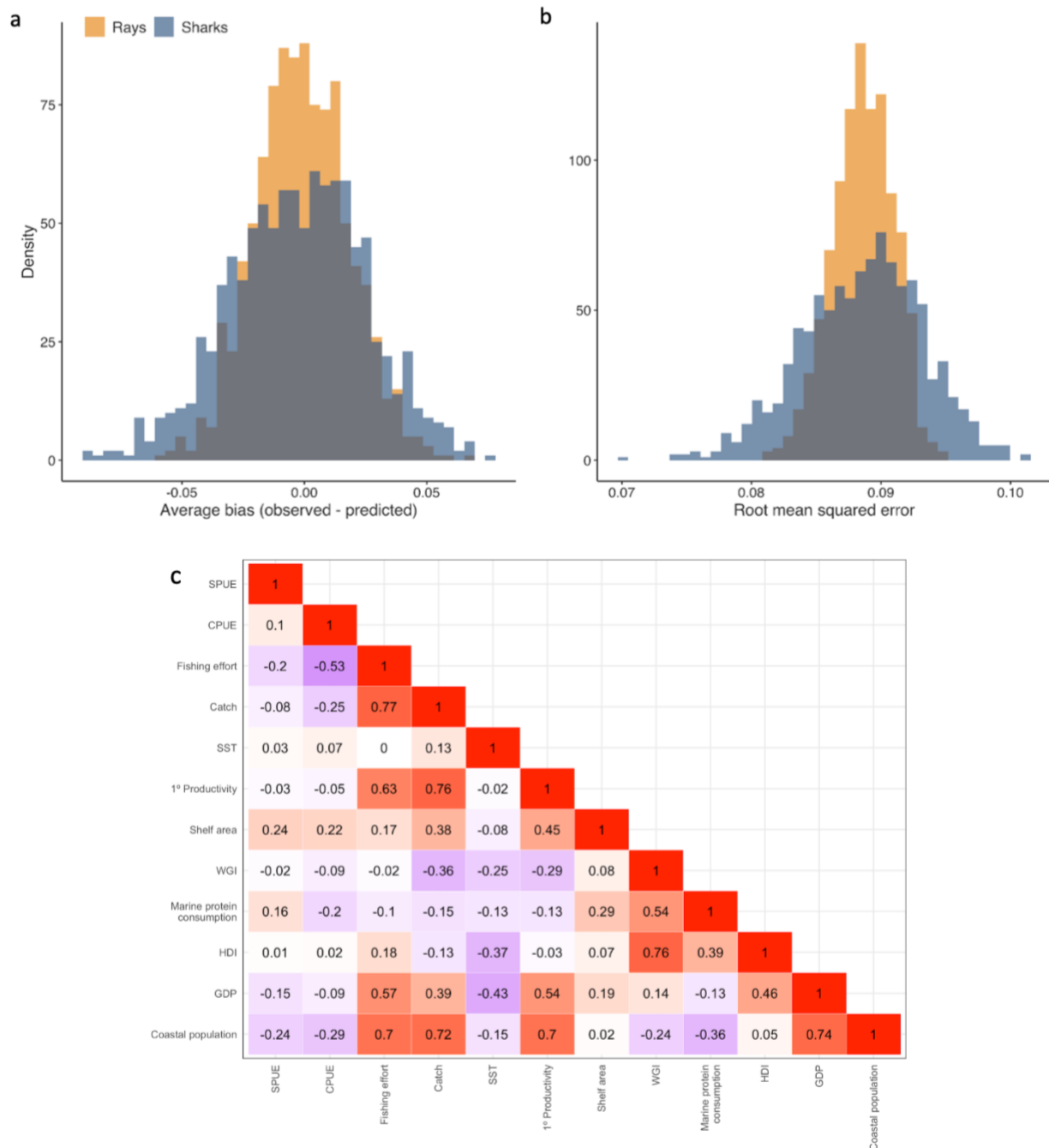
Supplementary Figures



Supplementary Figure 1. Effects of body size, lower depth, and the number of nations a species occurs in, on the IUCN Red List status of sharks and rays. Circles represent the mean standardised effect sizes with bars representing 95% confidence intervals, $n = 134$ species.



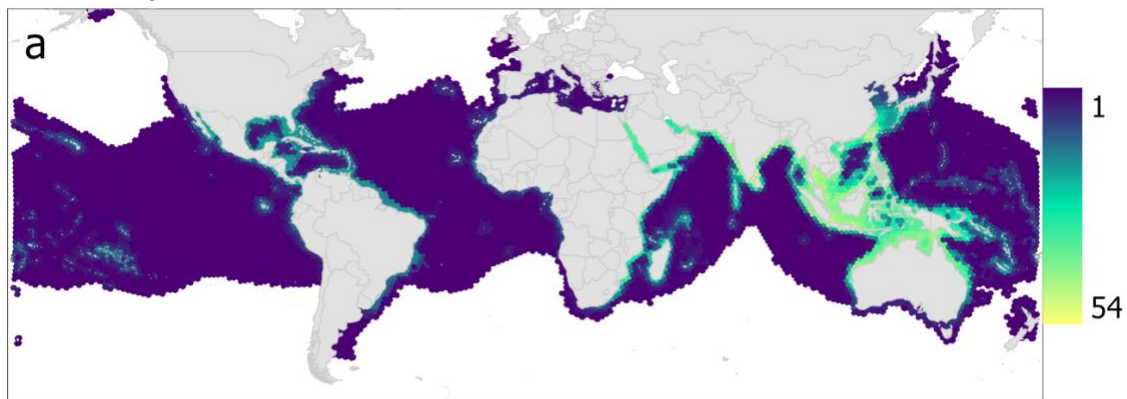
Supplementary Figure 2. Correlation matrix of all variables considered in the ordinal logistic regression models. While there is positive pairwise correlation between most pairs, those variables with correlation greater than 0.7 were not included in the same models. Empty boxes indicate pairwise relationships with negligible correlation. Other variables, though correlated, were included in additive models and tested for overall collinearity using variance inflation factors (VIF) <2.



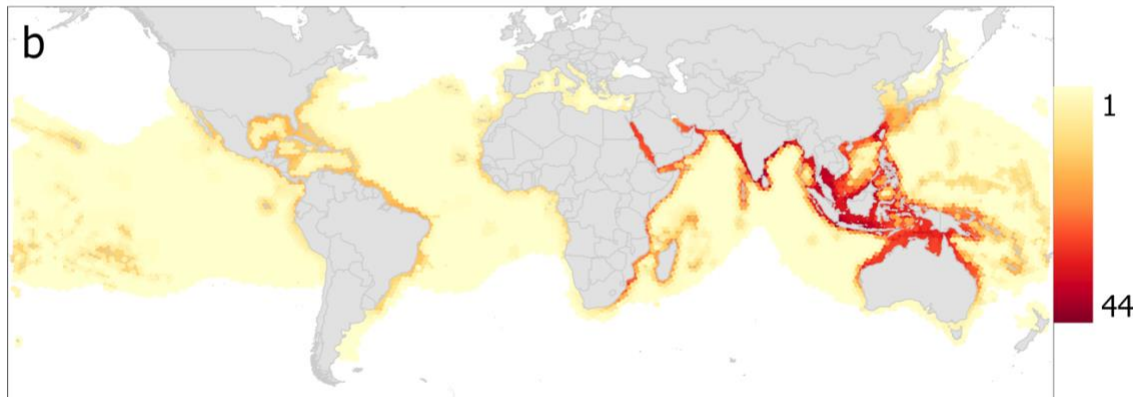
Supplementary Figure 3. Variation between each bootstrapped boosted regression tree iteration in the (a) average bias (calculated as the observed – predicted value from the test set) and (b) the root mean square error loss function for sharks and rays. (c) Correlations between national attributes.

Sharks and rays

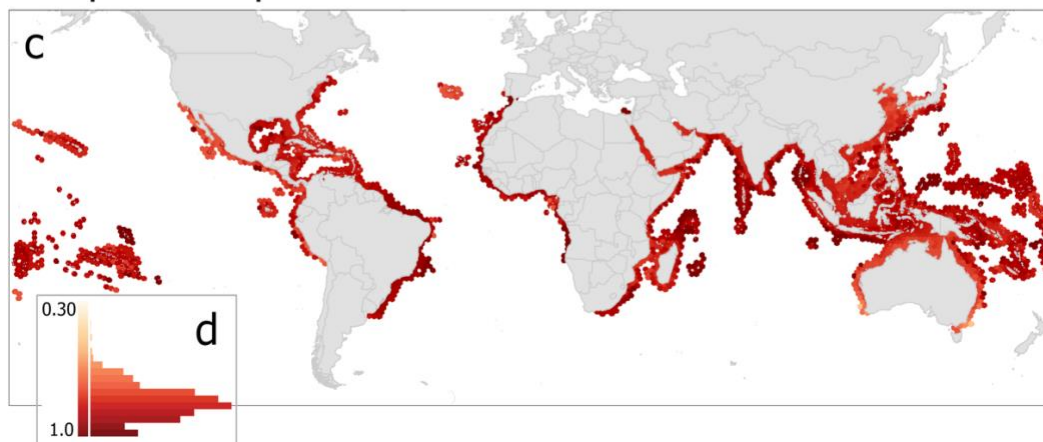
Total species richness



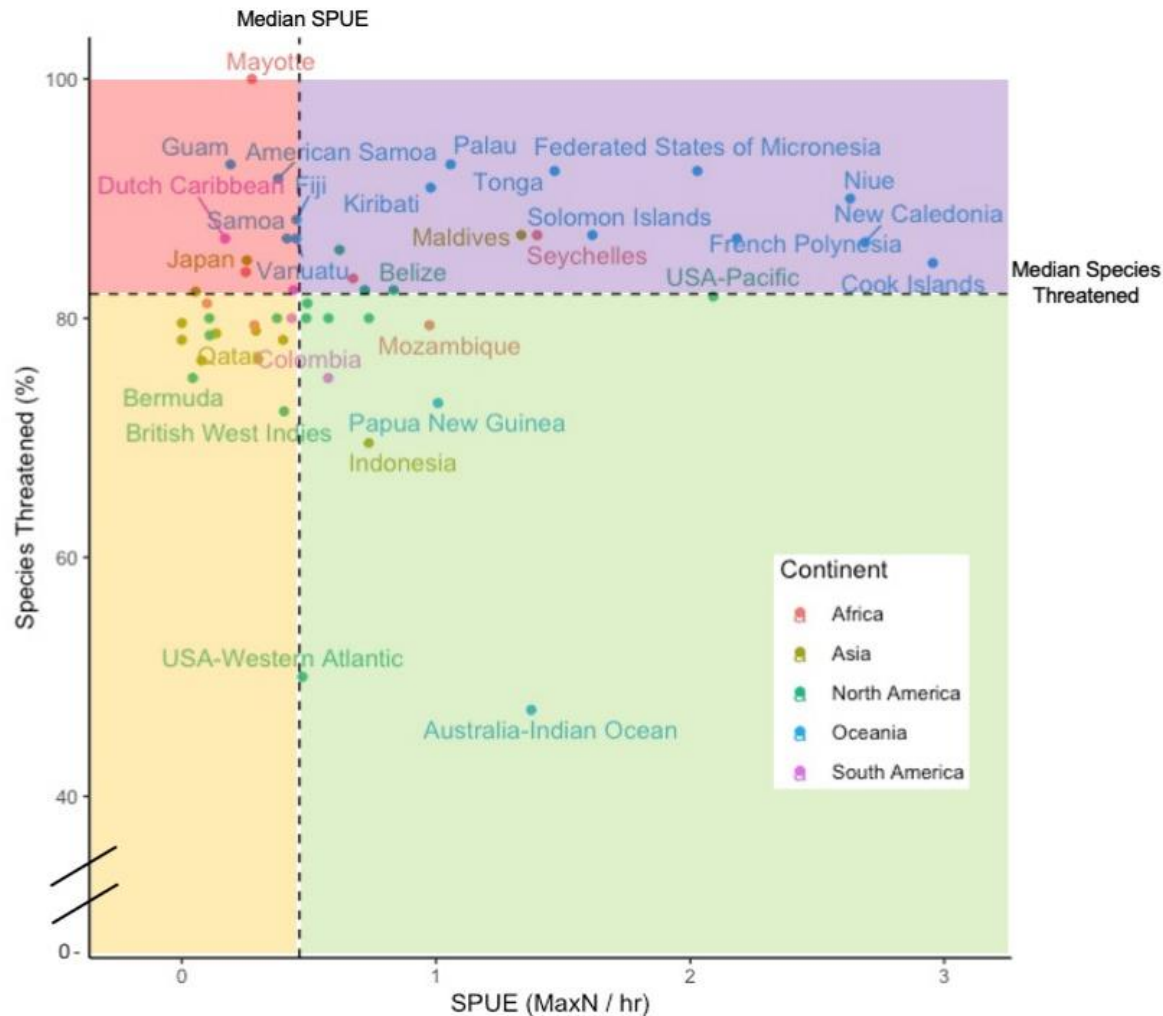
Threatened species richness



Proportion species threatened



Supplementary Figure 4. Global combined shark and ray species richness, threat, and proportion threatened. (a) species richness, (b) number of threatened species, (c) threatened species as a proportion of total richness (for cells with >5 species), and (d) histograms represent the number of grid cells containing different percentages of threatened species.



Supplementary Figure 5. Percent of coral reef sharks and rays threatened per nation compared to local abundance of sharks and rays over 371 coral reefs in 52 nations³. No significant relationship was found. Dotted lines indicate the median values of Sightings Per Unit Effort (SPUE) and Threat Percentage. SPUE was calculated by summing the total MaxN per nation and dividing this by the total hours of footage analysed. The proportion of species threatened was calculated by dividing the total number of Critically Endangered, Endangered, and Vulnerable species in a nation over the total number of coral reef sharks and rays in the nation. The purple quadrant represents nations with higher abundances of threatened species, acting as a refuge for these species. The red and yellow quadrants represent nations with low abundances of sharks and rays, and a high proportion of species threatened, and should be the focus of conservation capacity building. The green quadrant represents nations with fewer threatened species and higher abundances of sharks and rays.

Supplementary Tables

Supplementary Table 1. Percent of all 132 species threatened by Biological Resource Use (i.e., fishing) classified by intentionality (intentional vs. unintentional) and scale of the fishery (subsistence/small-scale vs. large-scale) separated by unique and pairwise, and combined threats. For unique threats, species are scored only when coded for the unique threat, or the column, or row pairwise combination. For the combined threats, species can be coded for up to all four combinations.

Unique threat	Intentional (target catch)	Unintentional catch	Both intentional and unintentional	Scale total
Subsistence/small scale	1.5% (2)	3.0% (4)	9.1% (12)	13.6% (18)
Large-scale	0.0% (0)	4.5% (6)	0.8% (1)	5.3% (7)
Both subsistence and large-scale	0.0% (0)	24.2% (32)		
Intentionality total	1.5% (2)	31.8% (42)		
Combined threats	Intentional (target catch)	Unintentional catch		Scale total
Subsistence/small scale	64.4% (85)	91.7% (121)		94.7% (125)
Large-scale	40.9% (54)	85.6% (113)		86.4% (114)
Intentionality total	68.2% (90)	98.5% (130)		

Supplementary Table 2. Observed number and percent of shark and ray species in IUCN Red List categories separated for lineages - rays (Subclass Batoidea), sharks (Subclass Selachimorpha), and combined, for residency type - transient, partial resident, resident, and for trophic level - apex predator, mesopredator, filter feeder, large invertivores, and small invertivores.

	Species Number (% of 134)	Number threatened (% of 79)	Number threatened (% of group)	CR (%)	EN (%)	VU (%)	NT (%)	LC (%)	DD (%)
Taxon									
Rays	70 (52.2)	45/79 (57.0)	45/70 (64.3)	9 (12.8)	14 (20.0)	22 (31.4)	6 (8.6)	13 (18.6)	6 (8.6)
Sharks	64 (47.8)	34/79 (43.0)	34/64 (53.1)	5 (7.8)	10 (15.6)	19 (29.7)	12 (18.8)	15 (23.4)	3 (4.7)
Total	134		79/134 (59.0)	14 (10.5)	24 (17.9)	41 (30.6)	18 (13.4)	28 (20.9)	9 (6.7)
Residency									
Transient	25 (18.7)	19/79 (24.1)	19/25 (76.0)	2 (8.0)	11 (44.0)	6 (24.0)	3 (12.0)	1 (4.0)	2 (8.0)
Partial Resident	54 (40.3)	36/79 (45.6)	36/54 (66.7)	11 (20.4)	6 (11.1)	19 (35.2)	6 (11.1)	10 (18.2)	2 (3.7)
Resident	55 (41.0)	24/79 (30.4)	24/55 (43.6)	1 (1.8)	7 (12.7)	16 (29.1)	9 (16.4)	17 (30.9)	5 (9.1)
Trophic Level									
Apex	6 (4.5)	5/79 (6.3)	5/6 (83.3)	2 (33.3)	1 (16.7)	2 (33.3)	1 (16.7)	0 (0.0)	0 (0.0)

Mesopredator	41 (30.6)	27/79 (34.2)	27/41 (65.9)	10 (24.4)	9 (22.0)	8 (19.5)	4 (9.8)	9 (22.0)	1 (2.4)
Filter Feeder	7 (5.2)	7/79 (8.9)	7/7 (100.0)	0 (0.0)	6 (85.7)	1 (14.3)	0 (0.0)	0 (0.0)	0 (0.0)
Large Invertivores	19 (14.2)	18/79 (22.8)	18/19 (94.7)	0 (0.0)	5 (26.3)	13 (68.4)	1 (5.3)	0 (0.0)	0 (0.0)
Small Invertivores	61 (45.5)	22/79 (27.8)	22/61 (36.1)	2 (3.3)	3 (4.9)	17 (27.9)	12 (19.7)	19 (31.1)	8 (13.1)

Supplementary Table 3. All models trialled in order of weighting, including their difference in AIC from the top model (ΔAIC), AIC weight, and the largest variance inflation factor (VIF) value. Only models with VIF values <2 were considered, models not considered are in grey.

Model	ΔAIC	Weight	VIF
Maximum Linear Dimension + Lower Depth + Nations	0	0.78	1.86
Maximum Linear Dimension + Lower Depth	4.42	0.09	1.20
Maximum Linear Dimension + Lower Depth + Residency	4.98	0.06	1.40
Maximum Linear Dimension + Ordinal Residency	8.08	0.01	1.21
Maximum Linear Dimension + Nations	8.43	0.01	1.76
Maximum Linear Dimension + Generation Length + Nations	9.40	0.01	2.22
Maximum Linear Dimension + Residency + Range	9.46	0.01	1.30
Maximum Linear Dimension + Range	9.56	0.01	1.57
Maximum Linear Dimension + Residency	9.74	0.01	1.10
Maximum Linear Dimension + Nations + Ordinal Residency + Ordinal Trophic Group	10.25	0	2.32
Maximum Linear Dimension + Generation Length	10.32	0	1.65
Maximum Linear Dimension	10.54	0	-
Maximum Linear Dimension + Ordinal Trophic Group	10.94	0	1.34
Maximum Linear Dimension + Generation Length + Range	11.08	0	2.06
Maximum Linear Dimension + Generation Length + Residency	11.24	0	1.44
Maximum Linear Dimension + Trophic Group	16.53	0	1.67
Maximum Linear Dimension + Trophic Group + Generation Length	17.71	0	1.84
Nations	21.36	0	-

Nations + Ordinal Trophic Group	21.73	0	1.10
Generation Length + Nations	22.71	0	1.34
Trophic Group + Nations	23.25	0	1.32
Trophic Group	27.79	0	-
Residency + Trophic Group	28.86	0	1.13
Nations + Ordinal Residency	29.07	0	1.15
Trophic Group + Range	29.21	0	1.31
Residency + Generation Length	30.81	0	1.04
Residency	36.98	0	-
Generation Length + Range	38.69	0	1.28
Residency + Lower Depth	38.98	0	1.03
Generation Length	39.41	0	-
Generation Length + Lower Depth	41.16	0	1.15
Ocean Basin	43.50	0	-
Shark or Ray	46.93	0	-
Null	47.54	0	-
Threat of Climate Change	47.64	0	-
Lower Depth	49.04	0	-

Supplementary Table 4. Species with ‘coral reef’ habitat listed in their IUCN Red List assessment but omitted from this analysis and the reason for their exclusion.

Species	Reason Not To Include
<i>Aulohalaelurus labiosus</i>	Occurs on temperate rocky reefs, distribution does not include coral reefs
<i>Carcharhinus hemiodon</i>	Occurs in estuaries and soft bottom coastal habitats
<i>Carcharhinus longimanus</i>	Occurs in open ocean pelagic habitats
<i>Fontitrygon margaritella</i>	Range is in western Africa, where there are almost no coral reefs
<i>Galeus mincaronei</i>	Occurs only on deep reefs >130 m
<i>Orectolobus floridus</i>	Occurs on temperate rocky reefs, distribution does not include coral reefs
<i>Rhynchobatus luebberti</i>	Range is in western Africa, where there are almost no coral reefs
<i>Schroederichthys saurisqualus</i>	Occurs on deep-water reefs off the coast of Brazil
<i>Scyliorhinus haeckelii</i>	Occurs on deep-water reefs
<i>Scyliorhinus stellaris</i>	Range is in Europe and western Africa, where there are almost no coral reefs
<i>Sutorectus tentaculatus</i>	Occurs on temperate rocky reefs, distribution does not include coral reefs
<i>Triakis maculata</i>	Occurs on temperate rocky reefs, distribution does not include coral reefs

Supplementary Table 5. Species included as ‘coral reef species’ despite their IUCN Red List assessments not including this in their list of habitats.

Scientific Name	Common Name
<i>Aetobatus laticeps</i>	pacific eagle ray
<i>Chiloscyllium caeruleopunctatum</i>	bluespotted bambooshark
<i>Heterodontus japonicus</i>	Japanese bullhead shark
<i>Hypanus longus</i>	longtail stingray
<i>Maculabatis ambigua</i>	Baraka’s whipray
<i>Narcine entemedor</i>	Cortez numbfish
<i>Neotrygon annotata</i>	plain maskray
<i>Neotrygon kuhlii</i>	Kuhl’s maskray
<i>Neotrygon picta</i>	speckled maskray
<i>Pristis pectinata</i>	smalltooth sawfish
<i>Rhincodon typus</i>	whale shark
<i>Rhynchobatus laevis</i>	smoothnose wedgefish
<i>Sphyrna lewini</i>	scalloped hammerhead
<i>Sphyrna mokarran</i>	great hammerhead
<i>Styracura pacifica</i>	Pacific chupare
<i>Triakis scyllium</i>	banded houndshark
<i>Urobatis halleri</i>	round stingray
<i>Urogymnus granulatus</i>	mangrove whipray
<i>Urotrygon chilensis</i>	Chilean round ray
<i>Zapteryx xyster</i>	southern banded guitarfish

Supplementary Table 6. Species that do not have previous assessments online due to revised taxonomic concept since their first assessment, but that we have not classified as previously Not Evaluated.

Species	Previous Taxonomic Concept	Revised Taxonomic Concept
<i>Aetobatus narinari</i>	NT (2006)	EN (2020)
<i>Aetomylaeus nichofii</i>	VU (2003)	VU (2016)
<i>Bathytoshia lata</i>	LC (2007)	VU (2021)
<i>Chiloscyllium plagiosum</i>	NT (2006)	NT (2020)
<i>Ginglymostoma cirratum</i>	DD (2006)	VU (2019)
<i>Himantura uarnak</i>	VU (2015)	EN (2021)
<i>Hypanus americanus</i>	DD (2006)	NT (2019)
<i>Neotrygon kuhlii</i>	DD (2015)	DD (2018)
<i>Taeniura lymma</i>	NT (2005)	LC (2020)