

Supplementary Materials for

Functional diversity of marine megafauna in the Anthropocene

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Supplementary Text

Definition of marine megafauna.

We define marine megafauna following Estes et al. (1), which considers marine animals ≥ 45 kg kg maximum reported mass. This definition is, to our knowledge, the most recent and the list of species comes from a comprehensive review (1). Although it is based on an arbitrary body size cut-off, the strength of this definition lies in that it can be applied to all species in the oceans, regardless of their taxonomic identity. Further, it is inspired by body size patterns during the Pleistocene extinction in terrestrial mammals, hence allowing to draw parallels between the extinctions in the marine and terrestrial realms. This definition excludes colonial organisms such as corals or sponges.

Definition of the Anthropocene.

The formal definition of the start of the Anthropocene is still being debated, with the most likely date between 1610 and 1964 (61). Here, we use it to refer to the current geological epoch we are living in, which has been deeply affected by human activities.

Dataset.

From the 338 species originally included in (1), we removed those already extinct: *Monachus tropicalis*, *Zalophus japonicus* and *Hydrodamalis gigas*. We also corrected synonyms as follows: *Pristis perotteti* and *Pristis microdon* as *Pristis pristis*, and *Mesoplodon bahamondi* as *Mesoplodon traversii* for a total of 334 species.

Trait assignments.

We used the following main references from the literature to assign traits to the marine megafaunal species: mammals (44, 62); sharks (63-65); sea turtles (42). Below we describe the assignment of the different traits.

Maximum body mass: Maximum weight (kg) for each species was gathered from (1).

Thermoregulation: The trait of “endothermy” was assigned to all mammals and birds (28). “Mesothermy” (or regional endothermy) was assigned to: all lamnid sharks (family Lamnidae), two species of thresher shark (*Alopias superciliosus* and *A. vulpinus*) (66-72), tunas (*Thunnus* spp.) (73), billfishes (families Xiphiidae and Istiophoridae [*Istiophorus* spp., *Makaira* spp. and *Tetrapturus* spp.]) (74), *Gasterochisma melampus* (75), *Lampris guttatus* (76) and *Dermochelys coriacea* (77). “Ectothermy” was assigned to all remaining sea turtles (42), fish (73), sharks and rays (78, 79), including *Mobula tarapacana* and *Manta birostris* (78). The last two species possess an anatomical characteristic (i.e., *retia mirabilia*) that indicates the presence of a heat-exchange system (80, 81) and the first species is known to have the ability to dive into waters of $< 4^{\circ}\text{C}$ (82). These characteristics have suggested the possibility of a mesothermic capability for these two species of rays. However, we have considered them to be ectothermic because: 1) it has been established that there is no reliable temperature measures to confirm that the *retia* in

these species actually maintains a higher internal temperature relative to the sea temperature (78); 2) more extreme dives (hence, tolerance to colder waters) have been reported in ectothermic sharks such as the whale shark (82) and have been explained by behavioral thermoregulation (83) and their large body size (84) rather than by regional endothermy; and 3) it has been empirically demonstrated that the ecological benefit of mesothermy in fishes, an energetically demanding feature, is enhanced predation (via elevated cruising speeds) (85), which contrasts with the filter feeding *M. tarapacana* and *M. birostris* (both tropical species).

Terrestriality: A “land” trait designation was assigned to all species that interact with continental land masses, such as sea turtles (42), sea birds (86), pinnipeds, sea otters and the polar bear (44). A “freshwater” trait designation was assigned to all animals that enter rivers or estuaries, such as the Irrawaddy dolphin, West Indian and African manatees (*Trichechus manatus* and *T. senegalensis*) (62), and all fish known to migrate between freshwater and the sea [*Carcharhinus leucas*, *Negaprion brevirostris*, *Himantura polylepis*, *H. uarnak*, *Aetobatus narinari*, *Dasyatis thetidis*, *Pristis pectinata*, *P. pristis*, and 40 species of bony fishes (87)]. It is worth noting that some of the bony fishes catalogued as “freshwater” live mainly in rivers and estuaries and use the marine environment marginally (i.e., use brackish waters). These include: Jullien's golden carp (*Probarbus jullieni*), Siberian Sturgeon (*Acipenser baerii*) Siberian Taimen (*Hucho taimen*), Alligator gar (*Atractosteus spatula*), Wallago (*Wallago attu*), Broadhead Catfish (*Clarias macrocephalus*), Giant sea catfish (*Arius gigas*), Kumakuma (*Brachyplatystoma filamentosum*), Rita (*Rita rita*), *Hemibagrus microphthalmus*, Lake sturgeon (*Acipenser fulvescens*), Blue catfish (*Ictalurus furcatus*), Pangas catfish (*Pangasius pangasius*), and Roho labeo (*Labeo rohita*).

Habitat zone and vertical position: We categorized the habitat where organisms occur based on the zone where they occur as adults (i.e., trait designations: continental shelf, slope, offshore, some of these, or all). Vertical position was assigned based on the most frequent part of water column where they feed (i.e., trait designations: benthic [or demersal], pelagic or both). These data were gathered from the primary literature and databases (see main text).

Migration: We assigned a “marine” trait designation to all organisms that are known to migrate within the marine environment (as is the case of some cetaceans, pinnipeds, sharks, bony fishes [including tunas], cephalopods, and all sea turtles), a “freshwater” trait designation to those migrating within freshwaters (as is the case of anadromous, amphidromous, catadromous and potamodromous fishes), and a “land” designation to those migrating between aquatic and terrestrial environments (e.g., the polar bear and Emperor penguin). This information was gathered from the primary literature and databases (see main text).

Feeding mechanism: We assigned a “predatory” feeding mechanism to all organisms that are known to actively hunt or catch prey, such as the majority of sharks, pinnipeds, cetaceans, and sea turtles, the coelacanth (*Latimeria chalumnae*), the Emperor penguin (*A. forsteri*) and a number of bony fishes. This trait designation includes bottom and suction feeders that prey upon invertebrates and/or fish. Such information was gathered from the primary literature and databases (see main text). A “browsing” feeding mechanism was assigned to all grazing organisms that feed on plants, such as the green sea turtle (*Chelonia mydas*) (42), the dugong (*Dugong dugon*) and the West Indian and African manatees (*T. manatus* and *T. senegalensis*) (44), as well as three species of bony fishes (*P. jullieni*, *Labeo rohita* and *Bolbometopon*

muricatum) (87). A “filter-feeding” mechanism was assigned to all species that consume plankton or krill via suspension feeding, bulk, or selective filter-feeding, which included three species of sharks (*Cetorhinus maximus*, *Megachasma pelagios* and *Rhincodon typus*), two species of rays (*M. tarapacana* and *M. birostris*) (88), 12 species of cetaceans (*Balaenoptera musculus*, *B. mysticetus*, *B. acutorostrata*, *B. physalus*, *B. borealis*, *B. bonaerensis*, *B. edeni*, *Eubalaena japonica*, *E. glacialis*, *E. australis*, *Megaptera novaeangliae*, *Caperea marginata*) and two species of pinnipeds—the Antarctic fur seal (*Arctocephalus gazella*) and the Crabeater seal (*Lobodon carcinophaga*) (44). It is worth noting that although the Leopard seal (*Hydrurga leptonyx*) is also known to be a filter feeder, we assigned a “predatory” trait designation to this species given that its main feeding strategy is that of actively hunting higher-order vertebrates, including other seals and penguins (44).

Diet: We classified the diet of each species based on the principal type of food it consumes as an adult. Diets were expressed as broad categories, including: fish; high vertebrates; invertebrates; plankton; plants. This information was gathered from the primary literature and databases (see main text).

Breeding site: A “coastal” trait designation was assigned to animals that breed near or at the continental shelf, or within the neritic zone (i.e., above 200 meters depth). An “estuarine or riverine” designation was assigned to organisms that breed in fresh- or brackish-waters (e.g., the bull shark *Carcharhinus leucas*). An “ice or land” designation was assigned to all animals that breed in the terrestrial realm (e.g., the Emperor penguin, the polar bear, all pinnipeds and sea turtles). Finally, an “oceanic” designation was assigned to animals that breed offshore. This information was gathered from the primary literature and databases (see main text).

Group size or sociality: A “schooling or aggregating” trait designation was assigned to all animals that are commonly found in groups of individuals of the same species. A “social” trait designation was assigned to animals known to display social interactions with individuals of the same species (e.g., some cetaceans, pinnipeds, the Emperor penguin, the coelacanth, and a few species of sharks and fish). Finally, a “solitary” trait designation was assigned to species that are mostly found alone, which includes most sharks, some fish, all invertebrates within the marine megafauna and some marine mammals (44). This information was gathered from the primary literature and databases (see main text).

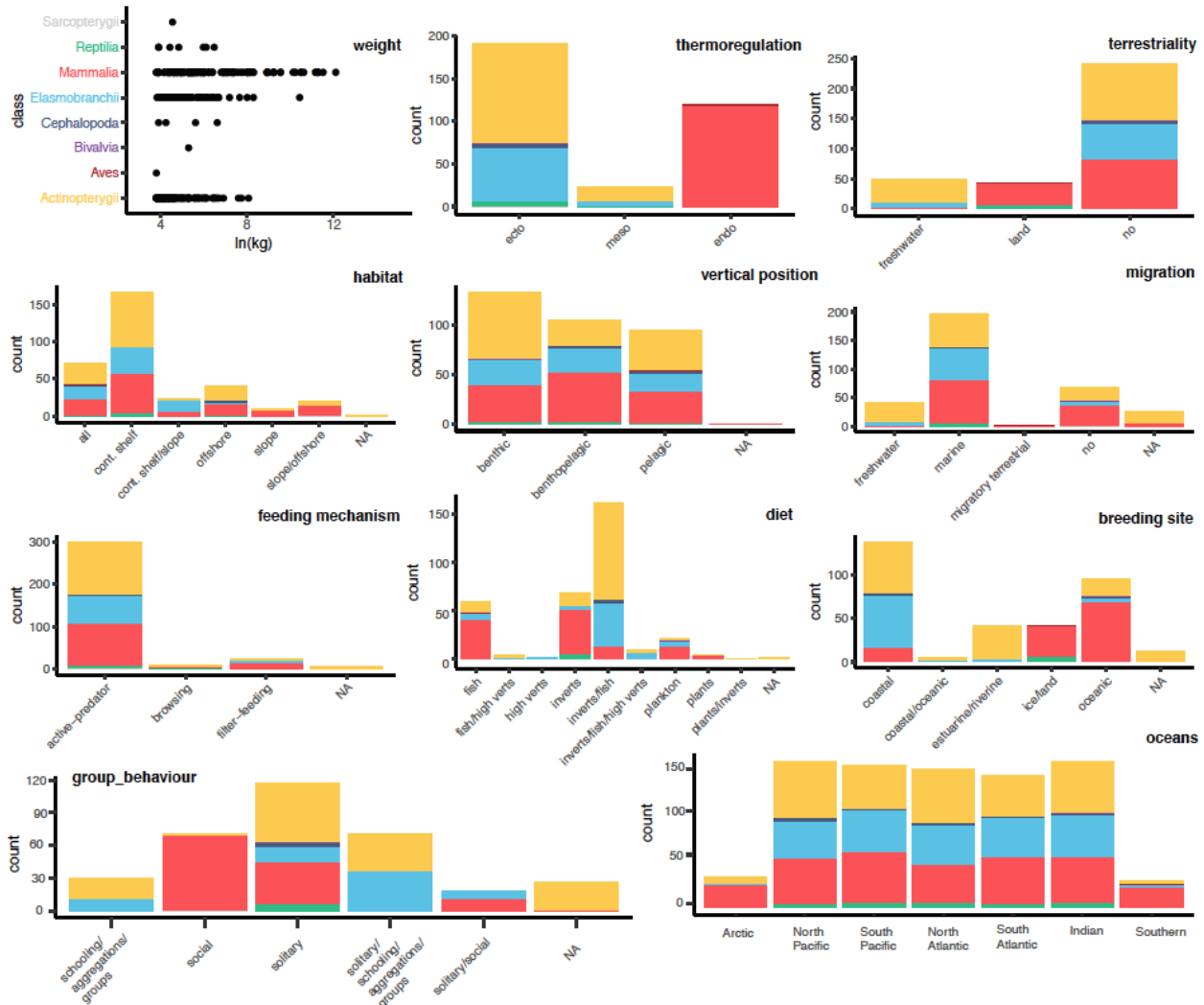


Figure S1. Distribution of trait modalities among marine megafauna and across oceans.

NAs represent missing values (which were imputed in all analyses, see main text). See Table S1 for details on trait categories. The most distinctive modalities are: thermoregulation = mesothermic; terrestriality = freshwater and land; habitat = continental shelf/slope, offshore, slope, slope/offshore; migration = freshwater and terrestrial; feeding mechanism = browsing and filter-feeding; diet = all non-piscivorous; and a breeding site = coastal and oceanic waters (see Table S1 for more details). The North Pacific and Indian Oceans include the largest representation of taxonomic classes.

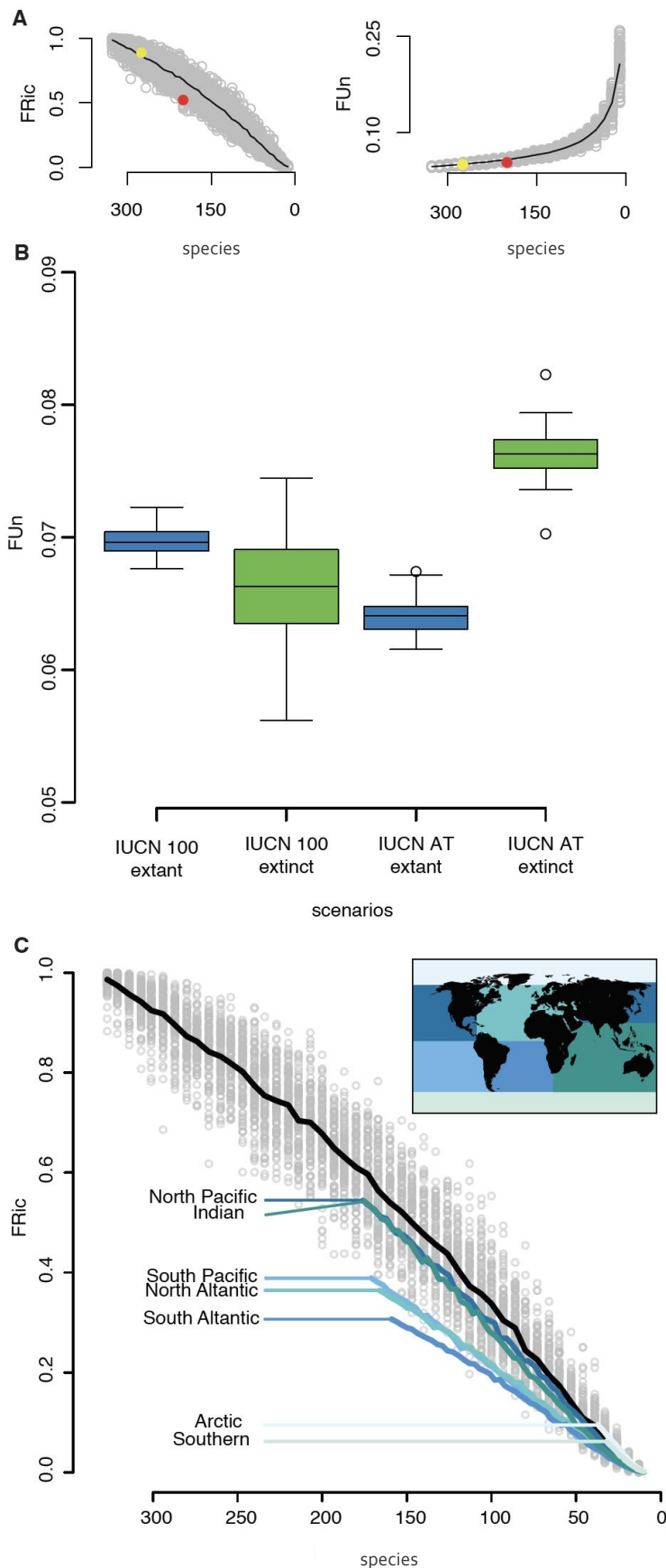


Figure S2. Changes in functional diversity in the face of species loss across oceans and extinction scenarios.

(A) Changes in functional richness (FRic) and functional uniqueness (FUn) in response to randomizing a sequence of species loss, from 10 to the total number of species, 100 times each. Color dots represent the values from empirical data across extinction scenarios: IUCN 100 (yellow), IUCN AT (red). (B) Functional uniqueness (FUn) of extant (blue) vs. extinct (green) species across extinction scenarios. Analyses based on 1,000 imputations. The frequencies of $FUn(\text{extant}) > FUn(\text{extinct})$ were 0.767, and 0 for the IUCN 100 and IUCN AT scenarios, respectively. (C) Simulated changes in functional richness (FRic) under random species loss. Comparison of global (grey dots = 100 randomizations, black line = mean value from 100 randomizations) and regional scales (coloured lines = mean values from 100 randomizations).

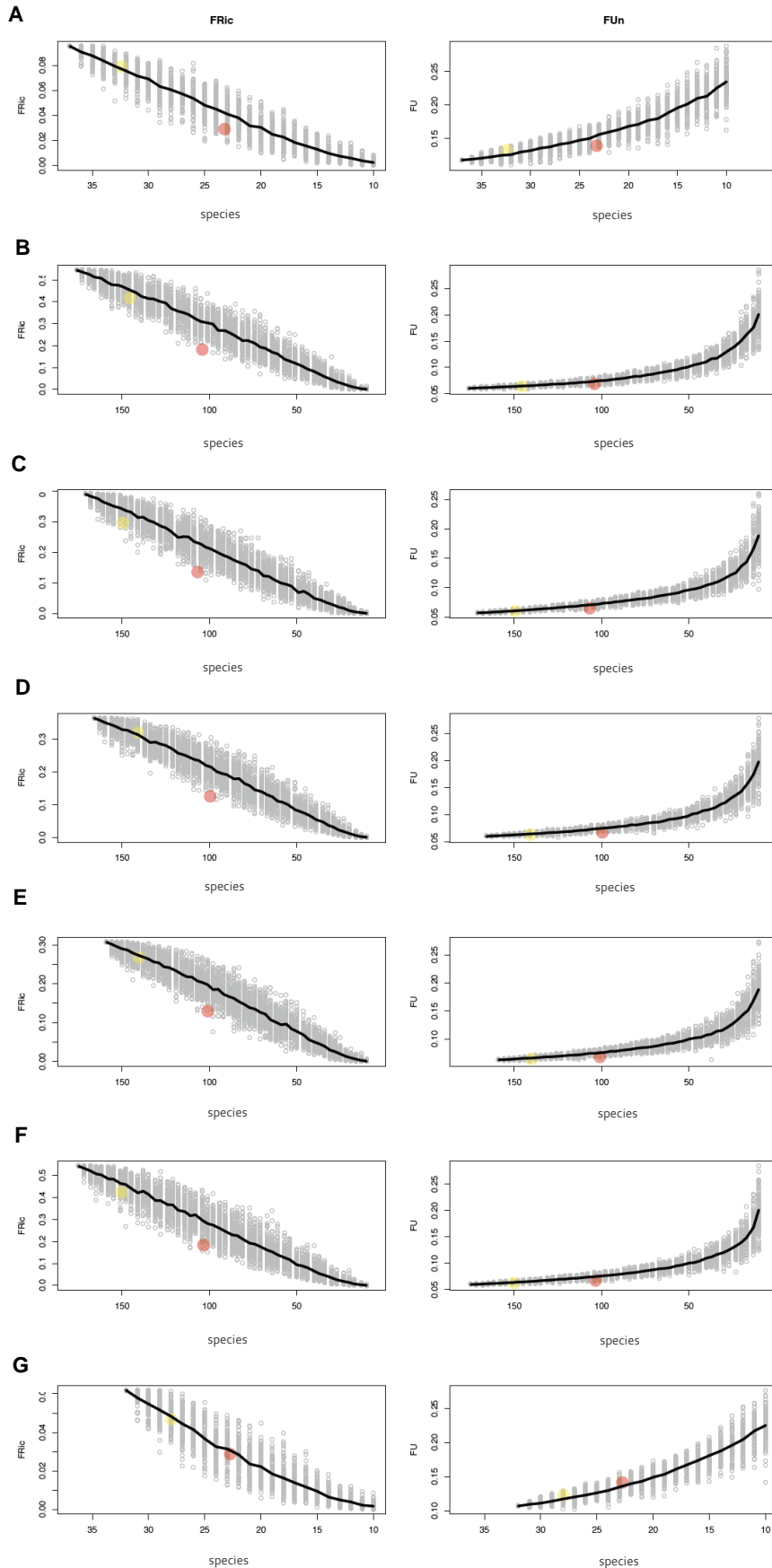
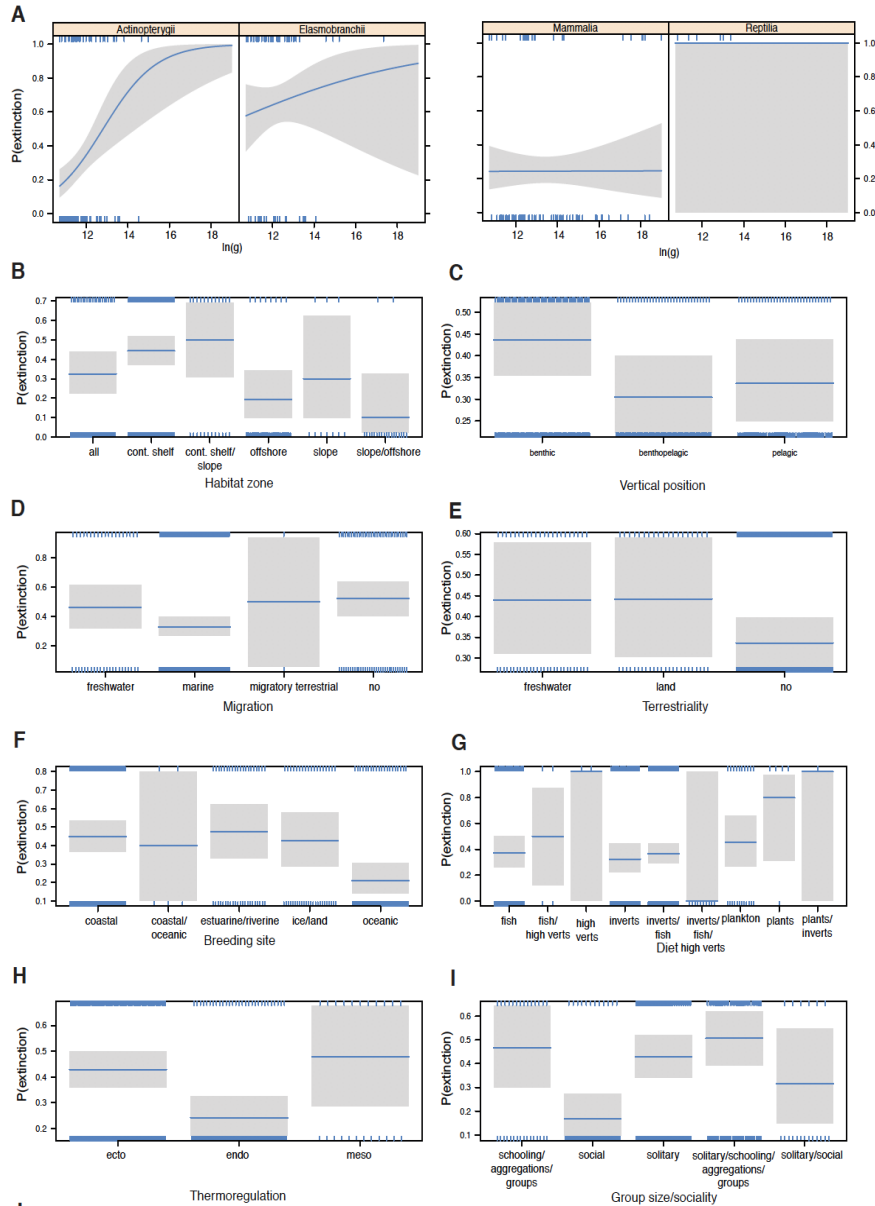


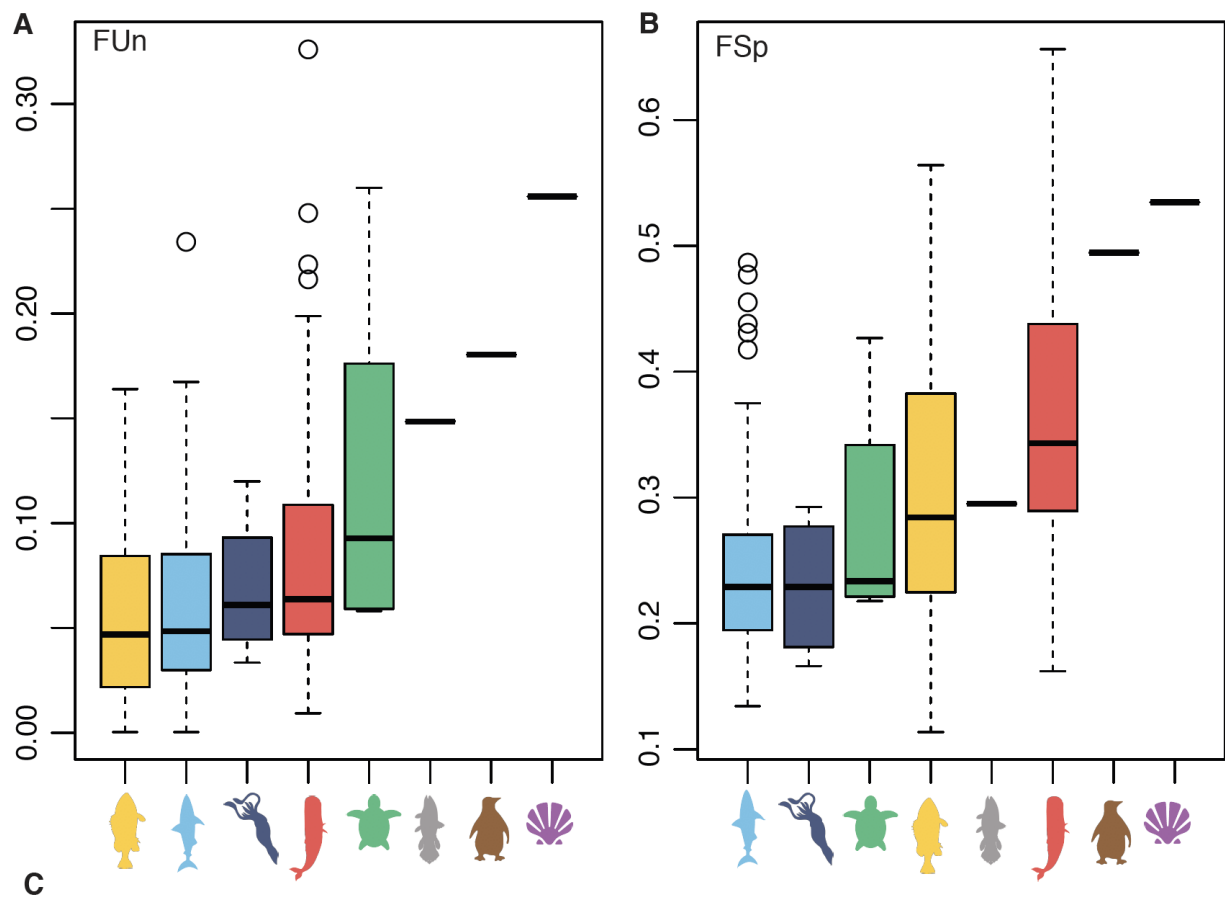
Figure S3. Simulated changes in functional richness (FRic) and uniqueness (Fun) per ocean under species loss. (A) Arctic, (B) North Pacific, (C) South Pacific, (D) North Atlantic, (E) South Atlantic, (F) Indian and (G) Southern oceans. Grey dots = 100 randomizations, black line = mean value from 100 randomizations). Coloured dots show empirical values from extinction scenarios: IUCN 100 = yellow; and IUCN AT = red.



Scenario	AIC (full)	AIC (drop1)	LRT	P
IUCN 100	293.17	296.4	9.2329	0.02635
IUCN AT	367.22	378.05	10.832	0.01267

	IUCN 100		IUCN AT	
	LRT	P	LRT	P
log(mass)	0.8327	0.3615	0.5196	0.471
Thermoregulation	3.6155	0.164	12.9561	0.0015
Terrestriality	15.2821	0.0005	3.1318	0.2089
Habitat zone	23.7731	0.0002	19.8163	0.0014
Vertical	8.2047	0.0165	4.8473	0.0886
Migration	22.4298	0.0001	8.8614	0.0312
Feeding	1.1598	0.5599	8.1847	0.0167
Diet	14.025	0.0811	20.6616	0.0081
Breeding site	20.738	0.0004	17.4096	0.0016
Group size/sociality	10.344	0.035	22.1927	0.0002

Figure S4. Trait modalities affected by extinction (as provided by Binomial Generalized Linear Models). (A) Interactions between body size and taxonomic Class on extinction probabilities, based on a binomial GLM. Plot shows results for the IUCN AT scenario in which all threatened species go extinct. IUCN 100 displays the same pattern: Large fishes (Actinopterygii) have higher probabilities of going extinct. (B-F) Other traits under the IUCN 100 and (G-I) IUCN AT extinction scenarios. Vertical lines denote the individual species going extinct (top) and not going extinct (bottom). Y-axis represents the probability of extinction, as provided by IUCN status (mean values across 1,000 imputations). (J) Binomial GLM output for the effect of body size on extinction probabilities. Inference is drawn by dropping the interaction term ('drop1') from the full model. (K) Binomial GLM output for the effect of traits on extinction probabilities. LRT denotes likelihood ratio test and DF degrees of freedom. Bold values denote statistical significance.



	fish vs. mammal	fish vs. shark	fish vs. turtle	mammal vs. shark	mammal vs. turtle	shark vs. turtle
uniqueness	<0.01	0.86	0.01	<0.01	0.11	0.01
specialization	<0.01	<0.05	0.75	<0.05	0.04	0.20

Figure S5. Functional uniqueness and specialization per taxonomic group across 1,000 imputations. Yellow = Actinopterygii; brown = Aves; purple = Bivalvia; dark blue = Cephalopoda; light blue = Elasmobranchii; red = Mammalia; green = Reptilia; gray = Sarcopterygii. (A). Mean uniqueness; (B). Mean specialization. (C) P-values of Mann -Whitney- Wilcox Test comparisons. Bold value denote significance.

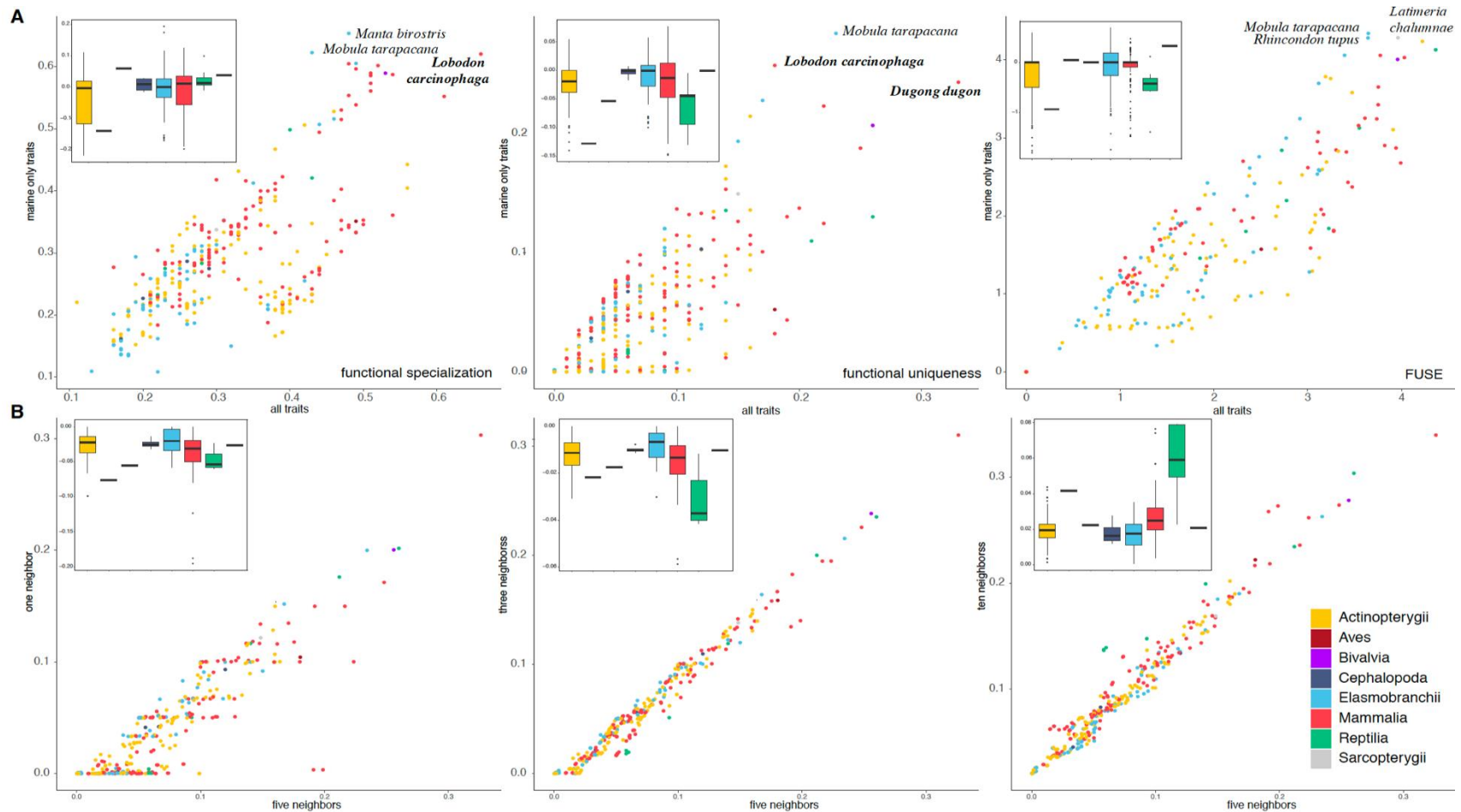


Figure S6. Complementary and sensitivity analyses. (A) Relationship between functional specialization ($\rho = 0.62$), uniqueness ($\rho = 0.67$) and FUSE scores ($\rho = 0.92$) using marine traits only vs. all traits. Species names show top 3 species using marine-only traits (bold denote those also found as top using all traits). (B) Relationship between functional uniqueness calculated based on one ($\rho = 0.84$); three ($\rho = 0.98$) and ten neighbors ($\rho = 0.97$). Top 3 species are always: *Dugong dugong*, *Chelonia mydas* and *Tridacna gigas*. Inserted boxplots show deviation (y-axes) between values obtained in the empirical analyses (shown in main text) vs. obtained in sensitivity analyses, across taxonomic Class (see bottom right guide).

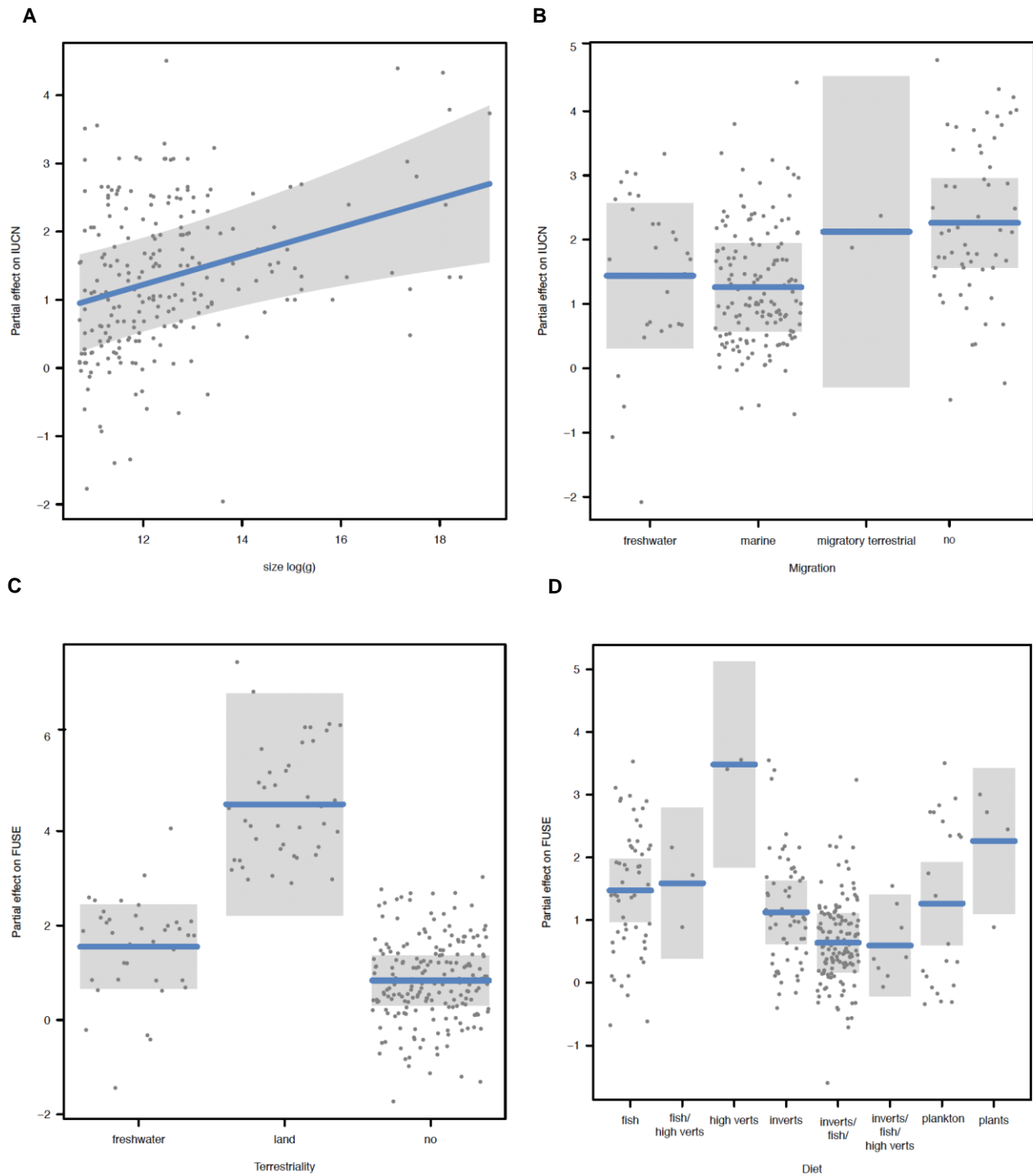


Figure S7. Partial effect of traits on IUCN status and FUSE scores. (A-B) High IUCN status are associated with large body size and no migration. (C) High FUSE scores are associated with the ability to use inland systems. (D) High FUSE (calculated using marine-only traits) scores are also associated to specialized diet (high vertebrates, piscivorous or herbivorous).

Table S1. Traits assigned to marine megafauna and their relations to individual- and ecosystem- level functions.

Trait	Function	Nature	Modality/Unit
Max body mass	Metabolic demand (89, 90); Capacity to vector energy and nutrients among habitats; Capacity to connect disparate ecosystems; Capacity to physically alter habitat (1, 91, 92)	Cont.	ln(g)
Thermoregulation	Metabolic demand; Mobility and foraging under a wide range of thermal conditions (93)	Ordinal	Endo > Meso > Ectothermic
Terrestriality	Habitat use (44); Cross-system energy and nutrient transfer (2, 94); Productivity and biodiversity enhancement (95, 96)	Nominal	Freshwater; Land; No
Habitat zone	Habitat use; Location of ecosystem contributions	Binary	Shelf; Offshore; Slope
Vertical position	Habitat use; Location of ecosystem contributions, including feeding (97-99); Potential to physically alter benthic habitat (100, 101)	Binary	Benthic; Pelagic
Migration	Reproduction; Spatial breadth of ecological impacts (102, 103); Potential for food web stabilization (104); Large-scale nutrient and energy transfer	Nominal	Freshwater; Marine; Land; No
Feeding mechanism	Trophic impact, including capacity to exert cascading effects within food web; Capacity to consume plants vs. animals; Capacity to directly or indirectly alter physical habitat via feeding (1, 105)	Nominal	Predator; Browser; Filter feeder
Diet	Potential impacts on prey and competitors, including the capacity to alter ecosystem structure (98, 106); Capacity to partition the trophic niche; Capacity to provide trophic functional redundancy within the ecosystem (107-110)	Binary	Fish; Higher vertebrates; Invertebrates; Plankton; Plants
Breeding site	Location of reproduction (111); Location of nutrient and energy deposition	Binary	Coastal; Estuarine or riverine; Ice or land; Oceanic
Group size/sociality	Capacity for coordinated group foraging (112); Potential for aggregations to concentrate nutrients and modify physical habitat (89)	Binary	Schooling or aggregations; Social; Solitary

Table S2. Axes and dimensions of the marine megafauna functional space. Top: A1-A6 are the PCoA coordinates of the reduced six-dimensional trait space. Values under PcoA axes are the correlation (r-squared) between traits and coordinates of the trait space. Bold values indicate the trait explaining the highest variance in each axis. Bottom: Weight (as provided by the mean squared deviation given by quality_space function (56), using all permutations) and total inertia represented in all possible 6 dimensions. Bold denotes the number of dimensions used in the analyses.

	A1	A2	A3	A4	A5	A6
Body mass	0.07	0	0.18	0.03	0	0.05
Thermoregulation	0.27	0.33	0	0.04	0	0
Terrestriality	0.53	0.03	0	0.07	0.13	0
Habitat zone	0.06	0.02	0.03	0.04	0.01	0.06
Vertical position	0.35	0.01	0.01	0.37	0.05	0.02
Migration	0.01	0.18	0.03	0.02	0.31	0.08
Feeding mechanism	0.06	0	0.53	0.06	0	0.13
Diet	0.01	0.21	0.08	0.01	0.01	0.03
Breeding site	0.05	0.49	0.04	0.06	0.25	0.04
Group size/sociality	0.02	0.07	0.04	0.02	0	0.02
<hr/>						
Dimensions	2D					
Weight	0.0181					
Sum inertia (%)	41.5					
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Dimensions	3D					
Weight	0.0094					
Sum inertia (%)	50.24					
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Dimensions	4D					
Weight	0.0049					
Sum inertia (%)	57.87					
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Dimensions	5D					
Weight	0.0031					
Sum inertia (%)	65.14					
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Dimensions	6D					
Weight	0.0024					
Sum inertia (%)	71.3					

Table S3. ANOVA output of Linear Mixed Effects Model testing how IUCN status and FUSE score (estimated using all and marine-only traits) related to species' traits. The models include traits as fixed effects and Order as a random effect: lmer(IUCN ~ trait1 + trait 2... (1 | Order)). Bold values denote statistical significance.

	IUCN						FUSE score (all traits)						FUSE score (marine only)					
	Sum Sq	Mean Sq	DF	Den DF	F value	Pr(>F)	Sum Sq	Mean Sq	DF	Den DF	F value	Pr(>F)	Sum Sq	Mean Sq	DF	Den DF	F value	Pr(>F)
log(mass)	13.47	13.5	1	196.53	9.98	0.002	18.5	18.5	1	247.28	18	3E-05	15.6	15.56	1	243.75	19.5	2E-05
Thermo-regulation	6.98	3.49	2	21.59	2.58	0.099	5.58	2.79	2	21.59	2.72	0.0883	2.73	1.37	2	18.6	1.71	0.2082
Terres-triality	6.06	3.03	2	166.7	2.25	0.109	14	7	2	201.85	6.83	0.0014	4.79	2.4	2	169.74	3	0.0525
Habitat zone	7.83	1.57	5	195.73	1.16	0.33	5.7	1.14	5	245.99	1.11	0.3543	10.4	2.08	5	241.68	2.61	0.0256
Vertical position	0.47	0.23	2	196.66	0.17	0.84	2.41	1.21	2	244.91	1.18	0.3099	1.02	0.51	2	243.04	0.64	0.5283
Migration	24.71	8.24	3	166.2	6.1	6E-04	39.6	13.2	3	191.1	12.9	1E-05	15.1	5.05	3	178.17	6.31	0.0004
Feeding mechanism	0.34	0.34	1	186.01	0.25	0.616	2.81	2.81	1	232.42	2.74	0.0992	4.67	4.67	1	222.95	5.84	0.0164
Diet	13.32	1.9	7	190.25	1.41	0.203	19.4	2.77	7	239.93	2.7	0.0103	25.8	3.68	7	237.22	4.6	0.0001
Breeding site	6.34	1.58	4	187.39	1.17	0.324	12	3	4	226.68	2.92	0.022	6.31	1.58	4	223.86	1.97	0.0994
Group size/ sociality	6.19	1.55	4	195.96	1.15	0.336	9.3	2.32	4	245.71	2.27	0.0626	12.8	3.2	4	246.41	4.01	0.0036

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