Supplementary information

Identifying climate refugia through analysis of functional diversity

Elena Gissi[1,2,3], Jamie M. McDevitt-Irwin[2,4], Kristin Kaschner[5], Kathleen Kesner-Reyes[6], Elliott L. Hazen[7,2,8], Rosalia Santoleri[1], Fiorenza Micheli[2,9]

[1] National Research Council, Institute of Marine Sciences, Venice, Italy, E-mail: elena.gissi@cnr.it
[2] Oceans Department, Hopkins Marine Station, Stanford University, Pacific Grove, CA, USA,
[3] National Biodiversity Future Center, Palermo, 90133, Italy
[4] Marine Science Institute, University of California Santa Barbara, Santa Barbara, CA, USA
[5] Department of Biometry and Environmental Systems Analysis, Albert-Ludwigs-University of Freiburg, Freiburg, Germany.
[6] Quantitative Aquatics, Los Baños, Philippines.
[7] NOAA Southwest Fisheries Science Center, Environmental Research Division, Monterey, CA, USA.
[8] University of California - Santa Cruz, Department of Ecology and Evolutionary Biology, Santa Cruz, CA, USA.
[9] Stanford Center for Ocean Solutions, Pacific Grove, CA, USA

Supplementary Methods

Table S1: Species included in the analysis. NE = not evaluated

No.	Class	Order	Family	Species – scientific name	Common name	IUCN status
1	Actinopterygii	Acipenseriformes	Acipenseridae	*Acipenser medirostris*	Green sturgeon	NT
2	Actinopterygii	Acipenseriformes	Acipenseridae	*Acipenser transmontanus*	White sturgeon	LC
3	Actinopterygii	Gadiformes	Macrouridae	*Albatrossia pectoralis*	Giant grenadier	NE
4	Actinopterygii	Lampriformes	Lampridae	*Lampris guttatus*	Opah	LC
5	Actinopterygii	Lampriformes	Regalecidae	*Regalecus glesne*	King of herrings	LC
6	Actinopterygii	Perciformes	Carangidae	*Elagatis bipinnulata*	Rainbow runner	LC
7	Actinopterygii	Perciformes	Carangidae	*Seriola dumerili*	Greater amberjack	LC
8	Actinopterygii	Perciformes	Carangidae	*Seriola lalandi*	Yellowtail amberjack	LC
9	Actinopterygii	Perciformes	Carangidae	*Seriola rivoliana*	Longfin yellowtail	LC
10	Actinopterygii	Perciformes	Gempylidae	*Lepidocybium flavobrunneum*	Escolar	LC
11	Actinopterygii	Perciformes	Gempylidae	*Ruvettus pretiosus*	Oilfish	LC
12	Actinopterygii	Perciformes	Icosteidae	*Icosteus aenigmaticus*	Ragfish	NE
13	Actinopterygii	Perciformes	Istiophoridae	*Istiompax indica*	Black marlin	DD
14	Actinopterygii	Perciformes	Istiophoridae	*Istiophorus platypterus*	Indo-Pacific sailfish	LC
15	Actinopterygii	Perciformes	Istiophoridae	*Kajikia audax*	Striped marlin	NT
16	Actinopterygii	Perciformes	Istiophoridae	*Makaira nigricans*	Blue marlin	VU
17	Actinopterygii	Perciformes	Istiophoridae	*Tetrapturus angustirostris*	Shortbill spearfish	DD
18	Actinopterygii	Perciformes	Luvaridae	*Luvarus imperialis*	Luvar	LC
19	Actinopterygii	Perciformes	Nematistiidae	*Nematistius pectoralis*	Roosterfish	NE
20	Actinopterygii	Perciformes	Polyprionidae	*Stereolepis gigas*	Giant seabass	CR
21	Actinopterygii	Perciformes	Scombridae	*Acanthocybium solandri*	Wahoo	LC
22	Actinopterygii	Perciformes	Scombridae	*Thunnus alalunga*	Albacore	NT
23	Actinopterygii	Perciformes	Scombridae	*Thunnus albacares*	Yellowfin tuna	NT
24	Actinopterygii	Perciformes	Scombridae	*Thunnus obesus*	Bigeye tuna	VU
25	Actinopterygii	Perciformes	Scombridae	*Thunnus orientalis*	Pacific bluefin tuna	VU
26	Actinopterygii	Perciformes	Serranidae	*Mycteroperca jordani*	Gulf grouper	EN
27	Actinopterygii	Perciformes	Serranidae	*Mycteroperca xenarcha*	Broomtail grouper	LC
28	Actinopterygii	Perciformes	Sphyraenidae	*Sphyraena barracuda*	Great barracuda	LC
29	Actinopterygii	Perciformes	Xiphiidae	*Xiphias gladius*	Swordfish	LC
30	Actinopterygii	Pleuronectiformes	Pleuronectidae	*Hippoglossus stenolepis*	Pacific halibut	NE
31	Actinopterygii	Salmoniformes	Salmonidae	*Oncorhynchus tshawytscha*	Chinook salmon	NE
32	Actinopterygii	Scorpaeniformes	Anoplopomatidae	*Erilepis zonifer*	Skilfish	NE
33	Actinopterygii	Scorpaeniformes	Hexagrammidae	*Ophiodon elongatus*	Lingcod	NE
34	Actinopterygii	Tetraodontiformes	Molidae	*Masturus lanceolatus*	Sharptail mola	LC
35	Actinopterygii	Tetraodontiformes	Molidae	*Mola mola*	Ocean sunfish	VU
36	Cephalopoda	Octopoda	Octopodidae	*Enteroctopus dofleini*	North Pacific giant octopus	NE
37	Cephalopoda	Teuthida	Ommastrephidae	*Dosidicus gigas*	jumbo flying squid	DD
38	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Carcharhinus albimarginatus*	Silvertip shark	NT
39	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Carcharhinus altimus*	Bignose shark	DD
40	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Carcharhinus brachyurus*	Copper shark	NT
41	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Carcharhinus falciformis*	Silky shark	NT
42	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Carcharhinus galapagensis*	Galapagos shark	NT
43	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Carcharhinus leucas*	Bull shark	NT
44	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Carcharhinus limbatus*	Blacktip shark	NT
45	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Carcharhinus longimanus*	Oceanic whitetip shark	VU
46	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Carcharhinus obscurus*	Dusky shark	VU
47	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Carcharhinus plumbeus*	Sandbar shark	VU

48	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Galeocerdo cuvier*	Tiger shark	NT
49	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Negaprion brevirostris*	Lemon shark	NT
50	Elasmobranchii	Carcharhiniformes	Carcharhinidae	*Prionace glauca*	Blue shark	NT
51	Elasmobranchii	Carcharhiniformes	Sphyrnidae	*Sphyrna lewini*	Scalloped hammerhead	EN
52	Elasmobranchii	Carcharhiniformes	Sphyrnidae	*Sphyrna mokarran*	Great hammerhead	EN
53	Elasmobranchii	Carcharhiniformes	Sphyrnidae	*Sphyrna zygaena*	Smooth hammerhead	VU
54	Elasmobranchii	Hexanchiformes	Hexanchidae	*Hexanchus griseus*	Bluntnose sixgill shark	NT
55	Elasmobranchii	Hexanchiformes	Hexanchidae	*Notorynchus cepedianus*	Broadnose sevengill shark	DD
56	Elasmobranchii	Lamniformes	Alopiidae	*Alopias pelagicus*	Pelagic thresher	VU
57	Elasmobranchii	Lamniformes	Alopiidae	*Alopias superciliosus*	Bigeye thresher	VU
58	Elasmobranchii	Lamniformes	Alopiidae	*Alopias vulpinus*	Thresher	VU
59	Elasmobranchii	Lamniformes	Cetorhinidae	*Cetorhinus maximus*	Basking shark	VU
60	Elasmobranchii	Lamniformes	Lamnidae	*Carcharodon carcharias*	Great white shark	VU
61	Elasmobranchii	Lamniformes	Lamnidae	*Isurus oxyrinchus*	Shortfin mako	VU
62	Elasmobranchii	Lamniformes	Lamnidae	*Lamna ditropis*	Salmon shark	LC
63	Elasmobranchii	Lamniformes	Megachasmidae	*Megachasma pelagios*	Megamouth shark	LC
64	Elasmobranchii	Lamniformes	Odontaspididae	*Odontaspis ferox*	Smalltooth sand tiger	VU
65	Elasmobranchii	Myliobatiformes	Aetobatidae	*Aetobatus narinari*	Spotted eagle ray	NT
66	Elasmobranchii	Myliobatiformes	Aetobatidae	*Aetobatus ocellatus*	Ocellated eagle ray	NE
67	Elasmobranchii	Myliobatiformes	Dasyatidae	*Dasyatis brevis*	Whiptail stingray	NE
68	Elasmobranchii	Myliobatiformes	Dasyatidae	*Pteroplatytrygon violacea*	Pelagic stingray	LC
69	Elasmobranchii	Myliobatiformes	Dasyatidae	*Taeniurops meyeni*	Round ribbontail ray	VU
70	Elasmobranchii	Myliobatiformes	Mobulidae	*Manta birostris*	Giant manta	VU
71	Elasmobranchii	Myliobatiformes	Myliobatidae	*Mobula tarapacana*	Chilean devil ray	DD
72	Elasmobranchii	Myliobatiformes	Myliobatidae	*Myliobatis californica*	Bat eagle ray	LC
73	Elasmobranchii	Orectolobiformes	Ginglymostomatidae	*Ginglymostoma cirratum*	Nurse shark	DD
74	Elasmobranchii	Orectolobiformes	Rhincodontidae	*Rhincodon typus*	Whale shark	VU
75	Elasmobranchii	Rajiformes	Rajidae	*Raja binoculata*	Big skate	NT
76	Elasmobranchii	Squaliformes	Somniosidae	*Somniosus pacificus*	Pacific sleeper shark	DD
77	Mammalia	Carnivora	Mustelidae	*Enhydra lutris*	sea otter	EN
78	Mammalia	Carnivora	Otariidae	*Arctocephalus townsendi*	Guadalupe fur seal	LC
79	Mammalia	Carnivora	Otariidae	*Callorhinus ursinus*	northern fur seal	VU
80	Mammalia	Carnivora	Otariidae	*Eumetopias jubatus*	Steller's sea lion	NT
81	Mammalia	Carnivora	Otariidae	*Zalophus californicus*	California sea lion	LC
82	Mammalia	Carnivora	Phocidae	*Histriophoca fasciata*	ribbon seal	DD
83	Mammalia	Carnivora	Phocidae	*Mirounga angustirostris*	northern elephant seal	LC
84	Mammalia	Carnivora	Phocidae	*Phoca vitulina*	Harbour seal	LC
85	Mammalia	Carnivora	Phocidae	*Pusa hispida*	ringed seal	LC
86	Mammalia	Cetacea	Balaenidae	*Eubalaena japonica*	North Pacific right whale	EN
87	Mammalia	Cetacea	Balaenopteridae	*Balaenoptera acutorostrata*	northern minke whale	LC
88	Mammalia	Cetacea	Balaenopteridae	*Balaenoptera borealis*	sei whale	EN
89	Mammalia	Cetacea	Balaenopteridae	*Balaenoptera edeni*	Eden's whale	DD
90	Mammalia	Cetacea	Balaenopteridae	*Balaenoptera musculus*	blue whale	EN
91	Mammalia	Cetacea	Balaenopteridae	*Balaenoptera physalus*	fin whale	EN
92	Mammalia	Cetacea	Balaenopteridae	*Megaptera novaeangliae*	humpback whale	LC
93	Mammalia	Cetacea	Delphinidae	*Delphinus capensis*	long-beaked common dolphin	DD
94	Mammalia	Cetacea	Delphinidae	*Delphinus delphis*	common dolphin	LC
95	Mammalia	Cetacea	Delphinidae	*Feresa attenuata*	pygmy killer whale	DD
96	Mammalia	Cetacea	Delphinidae	*Globicephala macrorhynchus*	short-finned pilot whale	DD
97	Mammalia	Cetacea	Delphinidae	*Grampus griseus*	Risso's dolphin	LC
98	Mammalia	Cetacea	Delphinidae	*Lagenodelphis hosei*	Fraser's dolphin	LC
99	Mammalia	Cetacea	Delphinidae	*Lagenorhynchus obliquidens*	Pacific white-sided dolphin	LC
100	Mammalia	Cetacea	Delphinidae	*Lissodelphis borealis*	Northern right whale dolphin	LC
101	Mammalia	Cetacea	Delphinidae	*Orcinus orca*	killer whale	DD
102	Mammalia	Cetacea	Delphinidae	*Peponocephala electra*	melon-headed whale	LC

103	Mammalia	Cetacea	Delphinidae	*Pseudorca crassidens*	false killer whale	DD
104	Mammalia	Cetacea	Delphinidae	*Stenella attenuata*	Pantropical spotted dolphin	LC
105	Mammalia	Cetacea	Delphinidae	*Stenella coeruleoalba*	striped dolphin	LC
106	Mammalia	Cetacea	Delphinidae	*Stenella longirostris*	spinner dolphin	DD
107	Mammalia	Cetacea	Delphinidae	*Steno bredanensis*	rough-toothed dolphin	LC
108	Mammalia	Cetacea	Delphinidae	*Tursiops truncatus*	bottlenose dolphin	LC
109	Mammalia	Cetacea	Eschrichtiidae	*Eschrichtius robustus*	gray whale	LC
110	Mammalia	Cetacea	Kogiidae	*Kogia breviceps*	pygmy sperm whale	DD
111	Mammalia	Cetacea	Kogiidae	*Kogia sima*	dwarf sperm whale	DD
112	Mammalia	Cetacea	Monodontidae	*Delphinapterus leucas*	beluga	NT
113	Mammalia	Cetacea	Phocoenidae	*Phocoena phocoena*	harbour porpoise	LC
114	Mammalia	Cetacea	Phocoenidae	*Phocoenoides dalli*	Dall's porpoise	LC
115	Mammalia	Cetacea	Physeteridae	*Physeter macrocephalus*	sperm whale	VU
116	Mammalia	Cetacea	Ziphiidae	*Berardius bairdii*	Baird's beaked whale	DD
117	Mammalia	Cetacea	Ziphiidae	*Indopacetus pacificus*	longman's beaked whale	DD
118	Mammalia	Cetacea	Ziphiidae	*Mesoplodon carlhubbsi*	Hubb's beaked whale	DD
119	Mammalia	Cetacea	Ziphiidae	*Mesoplodon densirostris*	Blainville's beaked whale	DD
120	Mammalia	Cetacea	Ziphiidae	*Mesoplodon perrini*	Perrin's beaked whale	DD
121	Mammalia	Cetacea	Ziphiidae	*Mesoplodon peruvianus*	pygmy beaked whale	DD
122	Mammalia	Cetacea	Ziphiidae	*Mesoplodon stejnegeri*	Stejneger's beaked whale	DD
123	Mammalia	Cetacea	Ziphiidae	*Ziphius cavirostris*	Cuvier's beaked whale	LC
124	Reptilia	Testudines	Cheloniidae	*Caretta caretta*	loggerhead turtle	VU
125	Reptilia	Testudines	Cheloniidae	*Eretmochelys imbricata*	hawksbill turtle	CR
126	Reptilia	Testudines	Cheloniidae	*Lepidochelys olivacea*	Olive ridley turtle	VU
127	Reptilia	Testudines	Dermochelyidae	*Dermochelys coriacea*	leatherback turtle	VU

Figure S1. Distribution of species by 0.5° grid cell size at the baseline and for scenarios at year 2050 and 2100 across Representative concentration pathways (RCP).

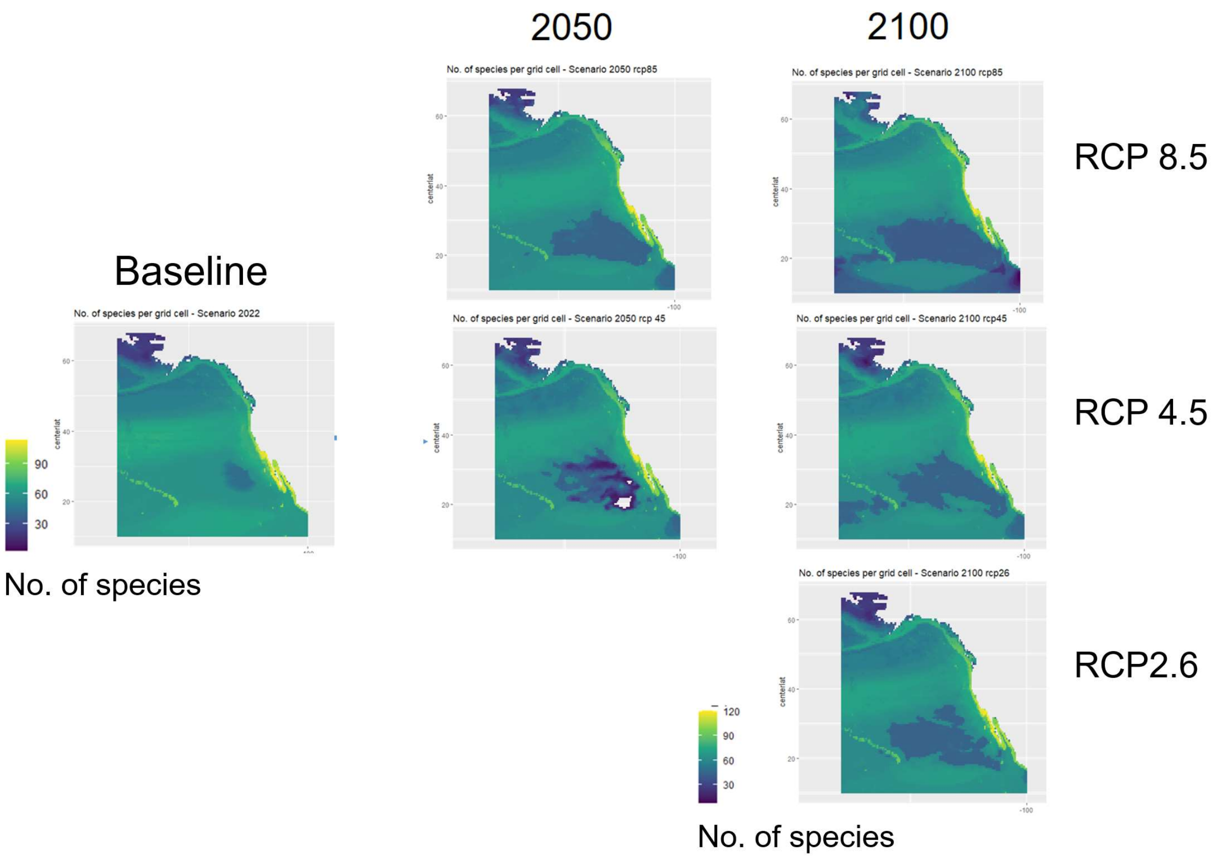


Figure S2. Species abundance by ecoregion at year 2100. North American Pacific Fjoirdland=N.A.P.F., Puget Trough Georgia Basin = P.T.G.B., Oregon Washington Vancouver Coast and Shelf = O.W.V.C.S., Southern California Bight = S.C:B., Magdalena Transition = M.T.

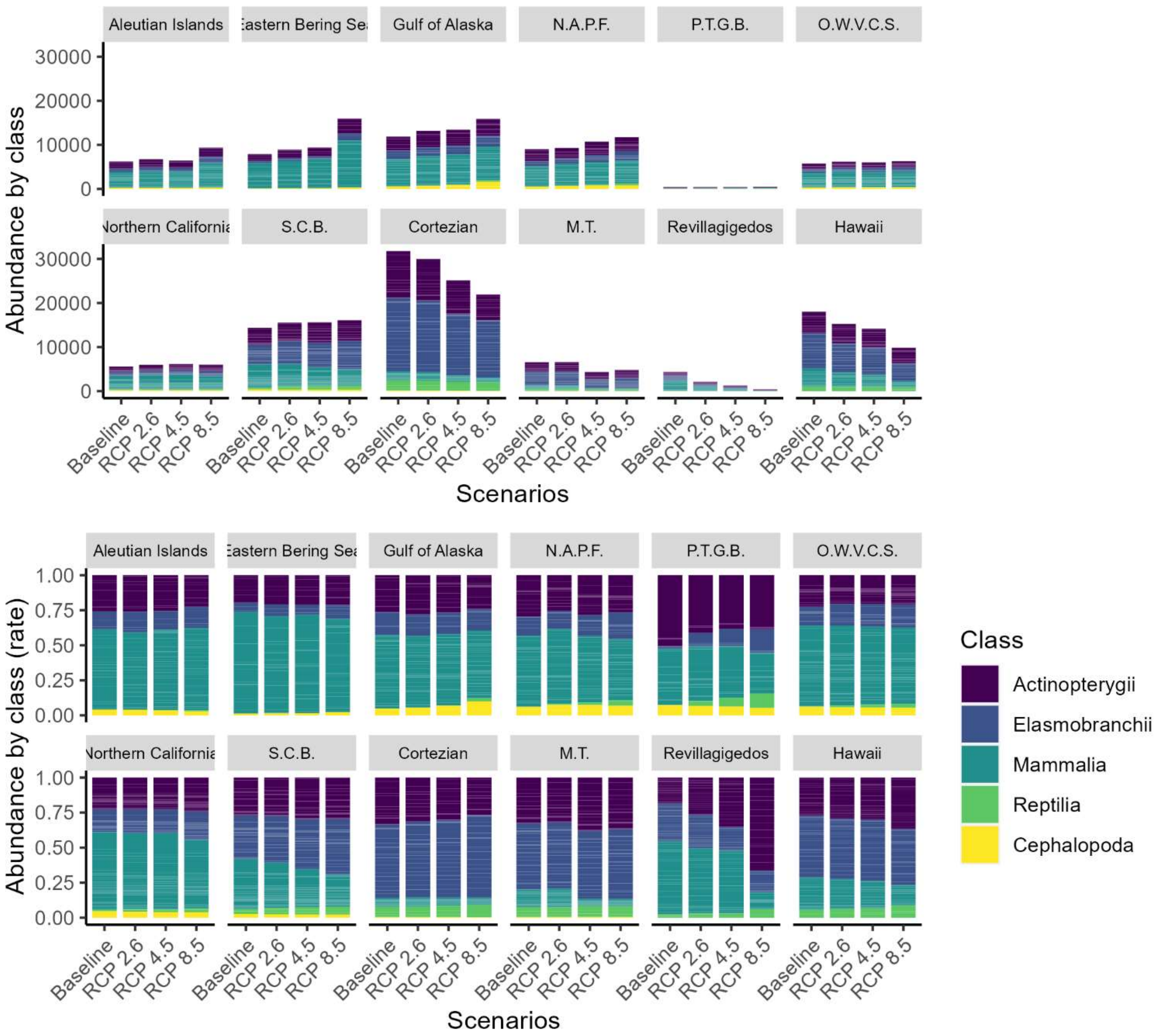


Figure S3. Species abundance by ecoregion at year 2050. North American Pacific Fjoirdland=N.A.P.F., Puget Trough Georgia Basin = P.T.G.B., Oregon Washington Vancouver Coast and Shelf = O.W.V.C.S., Southern California Bight = S.C:B., Magdalena Transition = M.T.

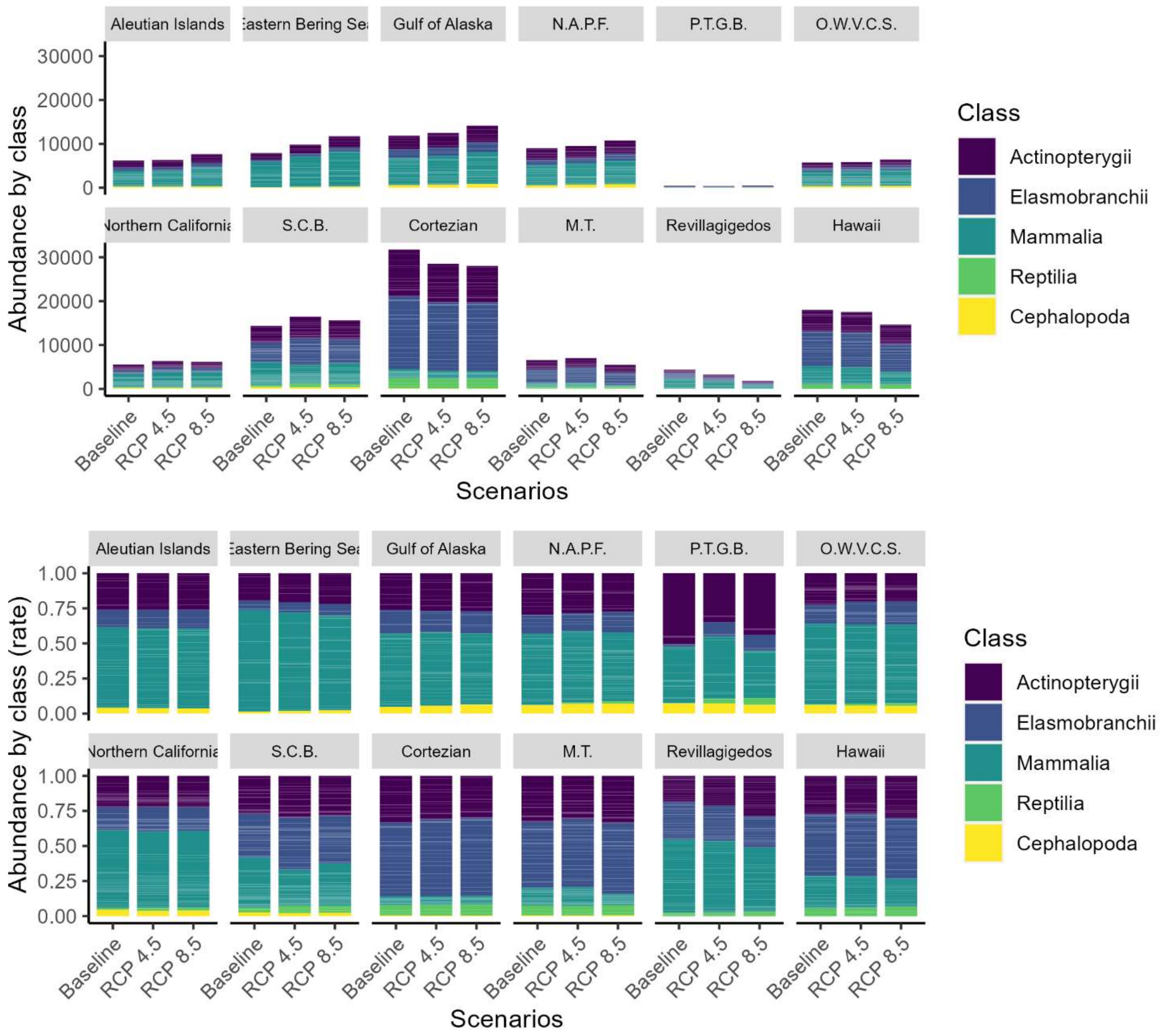


Table S2. Summary of the traits used for this study. The traits were selected after assessing the correlation among them. About types of traits, Co= continuous, Ca=categorical; Q = quantitative, N=nominal, NA=not applicable.

#	Trait measurement	Definition	Type	Classes	# of classes	Unit	trait_type	Relevant ecosystem functions	Reference
Morphology									
1	Length (length_max)	Total length in cm	Co	NA	NA	cm	Q	Nutrient storage and transport, food acquisition; capacity to connect disparate ecosystems	(Butt et al., 2022; García et al., 2007; McLean et al., 2021; Pimiento et al., 2020; Spitz et al., 2014; Tavares et al., 2019; Waechter et al., 2022)
2	Weight max	Total weight in gr	Co	NA	NA	gr	Q	Nutrient storage and transport; Metabolic demand; food acquisition; per capita excretion rates. capacity to vector energy and nutrients among habitats; capacity to connect disparate ecosystems; capacity to physically alter habitat.	(Albouy et al., 2017; Butt et al., 2022; Pimiento et al., 2020; Tavares et al., 2019; Waechter et al., 2022)
3	Body shape	Different body shapes based on lateral body shape/length/cross section of species, with categories reflecting the most striking feature	Ca	bag-shaped; cardiform or elliptical; eel-like; elongated; fusiform / normal; other; short and / or deep	7	NA	N	Mobility within/between habitat(s); social interactions. The body shape of a species relates to ecological behaviours, such as migration patterns.	(Pimiento et al., 2020; Trindade-Santos et al., 2022)
4	Sexual dimorphism	Dimorphism trait tells whether there are none or high differences in size or body mass between individuals of opposite sexes within the same species.	Ca	yes; no	2	NA	N	Natural and sexual selection favouring sex-based fitness leads to sexual dimorphism and differences in individual sex-based age and growth within or between populations	(Albouy et al., 2017)
Demography									
5	Sociality	Based on the number of individuals per group or flock, sociality represents, for instance, the harem size of Pinnipeds, size of the migration group of Mysticetes, and the smallest stable group size of	Ca	solitary; small groups; medium groups; large groups	4	NA	O	Nutrient storage, ecosystem engineering via bioturbation, soil fertilization via excretion and community shaping by altering primary productivity; capacity for coordinated group foraging, potential for aggregations to concentrate nutrients and modify physical habitat	(Albouy et al., 2017; Butt et al., 2022; McLean et al., 2021; Pimiento et al., 2020; Spitz et al., 2014; Tavares et al., 2019)

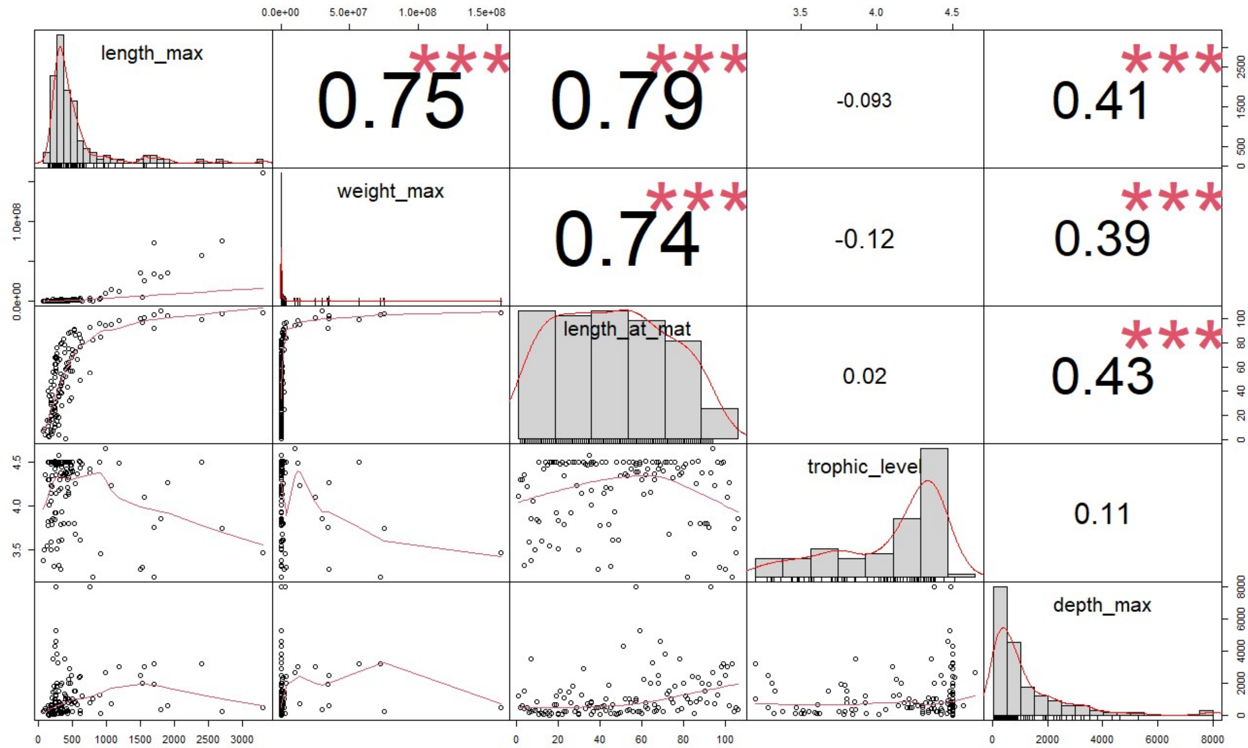
		Odontocetes(Albouy et al., 2017, 2020)							
6	Length at maturity (length_at_mat)	The size at which organisms reach sexual maturity and are able to reproduce	Co	NA	NA	cm	Q	Species with higher age at maturity are more vulnerable to climate change	(Butt et al., 2022; García et al., 2007; McLean et al., 2019; Trindade-Santos et al., 2022)
7	Fecundity	Number of eggs or neonates per reproductive season.	Ca	<1, 1, 1-2, 2-5, 5-10, 10-20, 20-50, 50-100, 100-1000, 1000-10000, >10000	11	NA	N	Nutrient storage. Low fecundity increases vulnerability to climate change	(Butt et al., 2022; McLean et al., 2019; Tavares et al., 2019)
Reproduction									
8	Reproductive strategy	A reproductive strategy is defined as the way in which a species allocates or budgets energy to produce viable offspring. Energy is diverted into actual offspring and into parental care.	Ca	dioecism; protogyny	2	NA	N	Reproductive traits have a direct influence on population dynamics and species resilience. Dioecious = high vulnerability; colonial = low vulnerability	(Trindade-Santos et al., 2022)
9	Reproductive mode	Type of reproduction, which may involve different mechanisms of fertilization and development	Ca	histotrophic viviparity; oophagic; oviparous; ovoviviparous; placental	5	NA	N	Reproductive traits have a direct influence on population dynamics and species resilience.	(García et al., 2007)
10	Parental investment (pre birth)	It describes the type of pre-birth parental care which involve different behaviors that increase the chances of offspring survival.	Ca	bearers_internal live bearers; guarders_NA; guarders_nesters; live birth/egg care; nonguarders_Brood hiders; nonguarders_Clutch tenders; nonguarders_NA; nonguarders_open water/substratum egg scatterers	8	NA	N	Lower vulnerability for species with low parental investment	(Butt et al., 2022)
11	Parental care (post birth)	Postbirth/hatching parental dependence	Ca	none; Week-month; Month-year; >year	4	NA	O	Parental care affects the feeding strategy of juveniles and influence trophic web. In two thirds of marine mammals, for instance, weaning - the mean duration of lactation - occurs early (in less than 20 months). The lower is the lactating length,	(Albouy et al., 2017; Butt et al., 2022; Spitz et al., 2014)

								the faster the pups need to develop proper diving capacities. In the end, lactating length affects the feeding strategies of juveniles (i.e. foraging layer).	
	Behaviour (foraging)								
12	Diet (main component)	Main diet component on the species based on the principal type of food it consumes as an adult. Diets were expressed as broad categories.	Ca	fish; invertebrates; invertebrates (squid excepted); high vertebrates; zooplankton; omnivorous; sponges; squid	8	NA	N	Nutrient storage and trophic-dynamic regulations of populations , potential impacts on prey and competitors, including the capacity to alter ecosystem structure; capacity to partition the trophic niche; capacity to provide trophic functional redundancy within the ecosystem; controlling food webs; nutrient transport and storage; capacity to partition the niche; capacity to provide trophic functional redundancy.	(Albouy et al., 2017; McLean et al., 2019, 2021; Pimiento et al., 2020; Tavares et al., 2019; Waechter et al., 2022)
13	Trophic level (food)	The position of a given species in the food chain is expressed as its trophic level.	Co	NA	NA	abs	Q	It can be assessed as the amount of "energy-transfer steps to that level". The trophic level also gives information on interactions between species, for example predator-prey and trophic cascades.	(Froese & Pauly, 2022; García et al., 2007; McLean et al., 2019; Trindade-Santos et al., 2022; Waechter et al., 2022)
14	Extreme diet specialization (ext_diet_spec)	Describe if species are generalists or specialists.	Ca	specialist; generalist	2	NA	N	Specialists are more vulnerable than generalist species	(Butt et al., 2022)
	Behaviour (movement)								
15	Adult mobility	Based on the zone where organisms occur or migrate as adults	Ca	amphidromous; anadromous; non-migratory; oceanodromous; oceano-estuarine	5	NA	N	Nutrient transport and community shaping through organism dispersal; reproduction, Spatial breadth of ecological impacts, potential for food web stabilization, large-scale nutrient and energy transfer.	(Butt et al., 2022; Tavares et al., 2019)
16	Depth max	The maximum diving depth in meters	Co	NA	NA	m	Q	Nutrient storage, nutrient storage and trophic-dynamic regulations of population, habitat use; location of ecosystem contributions; nutrient transport and storage; trophic–dynamic regulation. This trait reflects the environmental conditions that each species occur.	
17	Terrestriality	A "yes" was assigned to species that interact with continental land masses, such as sea turtles, pinnipeds, sea otters	Ca	yes; no	2	NA	N	Habitat use, Cross-system energy and nutrient transfer, Productivity and biodiversity enhancement , sensitivity: both = more vulnerable to multiple stressors	(Albouy et al., 2017; Butt et al., 2022; Pimiento et al., 2020)
18	Zones	Vertical position was assigned based on the most frequent part of water column where organisms feed.	Ca	bathydemersal, bathypelagic, benthic, benthopelagic,	8	NA	N	Nutrient storage, nutrient storage and trophic-dynamic regulations of populations. habitat use; location of ecosystem contributions, including feeding, potential to physically alter benthic	(Albouy et al., 2017; Butt et al., 2022; Spitz et al., 2014; Tavares et al., 2019; Trindade-Santos et al., 2022; Waechter et al., 2022)

	demersal, pelagic, pelagic_neritic, pelagic_oceanic, reefassociated	habitat. The vertical position of a species indicates its feeding habitat and its influence on the process of transferring nutrients through the water column.	(McLean et al., 2019, 2021; Pimiento et al., 2020; Trindade-Santos et al., 2022)

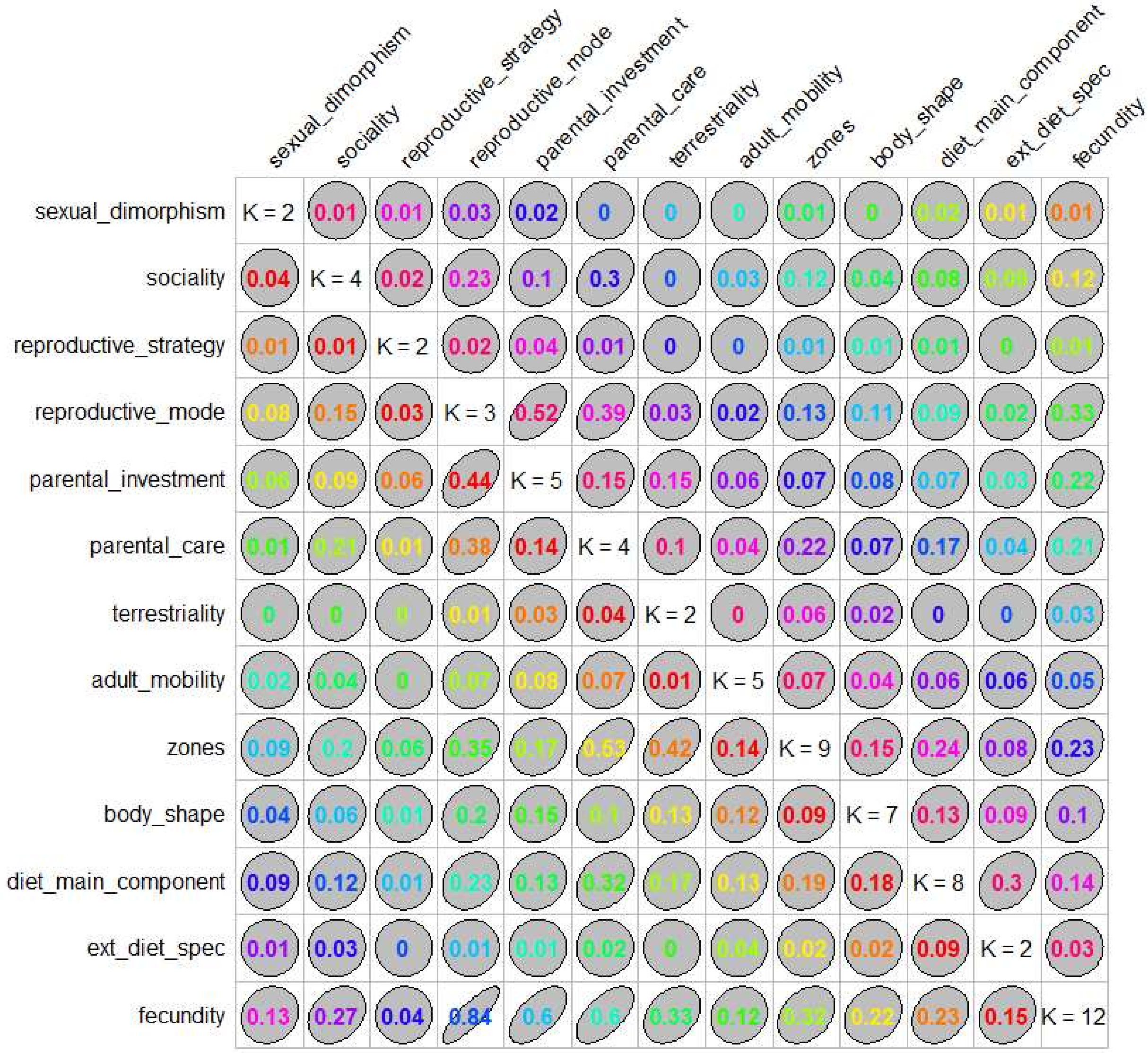
Correlation between traits

Figure S4: Pairwise correlation matrix of continuous traits using Spearman's correlation coefficient. We first analyzed the correlation between 5 continuous traits Plot and correlations calculated using the R package *PerformanceAnalytics* **(Peterson & Carl, 2020)**. The distribution of each variable is shown on the diagonal. On the bottom of the diagonal: the bivariate scatter plots with a fitted line are displayed. On the top of the diagonal : the value of the correlation plus the significance level as asterix. Text size indicates the strength of the correlation. Asterix indicate the significance of the correlation (* = p-value < 0.05, ** = p-value < 0.01, *** = p-value < 0.001).



Of the continuous traits we selected length (length_max), which is correlated with the discarded maximum body size and length at maturity; we also selected trophic level and dive depth (depth_max), which are not correlated with any other continuous variables.

Figure S5. Pairwise correlation test between categorical traits. We run the Goodman and Kruskal's tau test to explore the association between categorical variables using the GKtauDataframe function of the R package 'GoodmanKruskal' (Pearson, 2020). The resulting plot is in the form of a 12×12 array, with the variable names across the top and down the left side. The diagonal entries in this display give the numbers of unique levels for each variable, while the off-diagonal elements give both numeric and graphical representations of the Goodman-Kruskal τ values. Specifically, the numerical values appearing in each row represent the association measure τ(x,y) from the variable x indicated in the row name to the variable y indicated in the column name, to represent the asymmetry possible for the Goodman-Kruskal τ measure. This asymmetry arises because the tau measure is based on the fraction of variability in the categorical variable y that can be explained by the categorical variable x.



Considering the Goodman-Kruskal τ values, we synthesize the results as following:

- Reproductive mode is quite mild predictive of parental care (0.39) and parental investment (0.52);
- Parental investment is quite mild predictive of reproductive mode (0.44);
- Parental care is quite mild predictive of reproductive mode (0.38);
- Zones is quite mild predictive of reproductive mode (0.35), parental care (0.53) and terrestriality (0.42);
- Diet (main component) is quite mild predictive of parental care (0.32);

- Fecundity is highly predictive of reproductive mode (0.84) and parental care (0.6), and quite mild for terrestriality (0.33) and zones (0.32)
- The only traits with reciprocal mild predictive associations are parental care, parental investment, reproductive mode.
- All the other traits have a low predictive association, meaning that they are independent from each other.

We explored the contingency tables for the traits with reciprocal mild predictive associations mentioned above.

	Reproductive mode			
Fecundity	oviparous	ovoviviparous	placental	tot
<1			28	28
1			16	16
1-2		2	2	4
2-5		11	1	12
5-10		3	2	5
10-20		1	9	10
20-50		2	4	6
50-100		3		3
100-1000	5	1		6
1000-10000	1			1
>10000	36			36
tot	42	23	62	127

	Parental care				
reproductive_mode	none	week_month	month_year	more_t_year	tot
oviparous	42				42
ovoviviparous	23				23
placental	15	2	25	20	62
tot	80	2	25	20	127

	Parental care				
Parental investment	none	week_month	month_year	more_t_year	tot
bearers_internal_live_bearers	44	2	25	18	89
guarders	3			1	4
live_birth_egg_care				1	1
nonguarders_other	8				8
nonguarders_open water_substratum_egg_scatterers	25				25
tot	80	2	25	20	127

	Reproductive mode			
Parental investment	oviparous	ovoviviparous	placental	tot
bearers_internal_live_bearers	6	23	60	89
guarders	3		1	4
live_birth_egg_care			1	1
nonguarders_others	8			8

nonguarders_open water_substratum_egg_scatterers	25			25
tot	42	23	62	127

From the analysis of the contingency table, the traits are only minimally associated; for this reason, we decided to keep these three traits.

	Reproductive mode			
Fecundity	oviparous	ovoviviparous	placental	tot
<1			28	28
1			16	16
1-2		2	2	4
2-5		11	1	12
5-10		3	2	5
10-20		1	9	10
20-50		2	4	6
50-100		3		3
100-1000	5	1		6
1000-10000	1			1
>10000	36			36
tot	42	23	62	127

Fecundity and reproductive mode are strongly associated, with fecundity being highly predictive of reproductive mode. For this reason, we discarded reproductive mode and keep fecundity.

Table S3: Correlation test between continuous and categorical variables. We applied the non-parametric Kruskal-Wallis rank sum test using the R package rstatix, with p-values < 0.05 (significance level). For the traits for which p>0.05, we analyzed the eta-squared estimate calculated through the Kruskal-Wallis effect size test . The eta-squared estimate assumes values from 0 to 1 and multiplied by 100 indicates the percentage of variance in the dependent variable explained by the independent variable. The interpretation values commonly found in published literature are: < 0.06 (small effect), 0.06 - < 0.14 (moderate effect) and >= 0.14 (large effect).

	Numerical traits (Depentent var.)		
Categorical traits (independent var.)	depth_max	length_max	trophic_level
Kruskal-Wallis rank sum test			
adult_mobility	0.009337928*	0.11416501	0.068934
body_shape	0.364530036	0.00066714*	0.000102*
diet_main_component	0.000146676*	5.9353E-07*	5.8E-08*
ext_diet_spec	0.170943152	0.00834665*	0.030067*
fecundity	0.02779762*	3.0866e-05*	0.288998
parental_care	0.02438912*	0.02518453*	0.535472
parental_investment	0.074190913	0.00185493*	0.065161
reproductive_mode	0.125632744	9.737E-06*	0.069426
reproductive_strategy	0.025895102*	0.05640778	0.092876
sexual_dimorphism	0.644530298	0.38216009	0.41099
sociality	0.065271183	0.00137479*	0.128654
terrestriality	0.032383142	0.00049558*	0.904014
zones	2.37924E-06*	5.4911E-06*	0.093442*
Effect size test			
adult_mobility	-	0.028237	0.038559
body_shape	0.004579	-	0.181756
diet_main_component	-	-	-
ext_diet_spec	0.006997	-	-
fecundity	-	0.245816	-
parental_care	-	0.04325	-
parental_investment	0.049711	0.132681	-
reproductive_mode	0.026239	0.201068	-
reproductive_strategy	-	0.02112	0.01459
sexual_dimorphism	0.0063	0.00189	0.00259
sociality	0.034291	0.102372	-
terrestriality	0.028625	0.089058	0.00788
zones	-	-	-

Although the effect is considered as “large”, the association only explains the 18%, 20%, and 24% of variability respectively of trophic level based on body shape, and of length_max based on reproductive mode and fecundity. Therefore, we decided to keep all the numerical traits.

Table S4. Summary of the traits used for this study. The traits were selected after assessing the correlation among them.

	Trait type	Trait name	Selected
1	Morphological	length_max	yes
	Morphological	weight_max	**no**
2	Morphological	body_shape	yes
3	Morphological	sexual_dimorphism	yes
4	Demographic	sociality	yes
	Demographic	length_at_mat	**no**
5	Demographic	fecundity	yes
6	Reproduction	reproductive_strategy	yes
	Reproduction	reproductive_mode	**no**
7	Reproduction	parental_investment	yes
8	Reproduction	parental_care	yes
9	Behavioural (Foraging)	diet_main_component	yes
10	Behavioural (Foraging)	trophic_level_food	yes
11	Behavioural (Foraging)	ext_diet_spec	yes
12	Behavioural (Movement)	adult_mobility	yes
13	Behavioural (Movement)	depth_max	yes
14	Behavioural (Movement)	terrestriality	yes
15	Behavioural (Movement)	zones	yes

Multidimentional trait space

Figure S6. Gower dissimilarity matrix of the species by trait table. We computed Gower distances between species based on functional traits and report here the traits-based distances between all pairs of species.

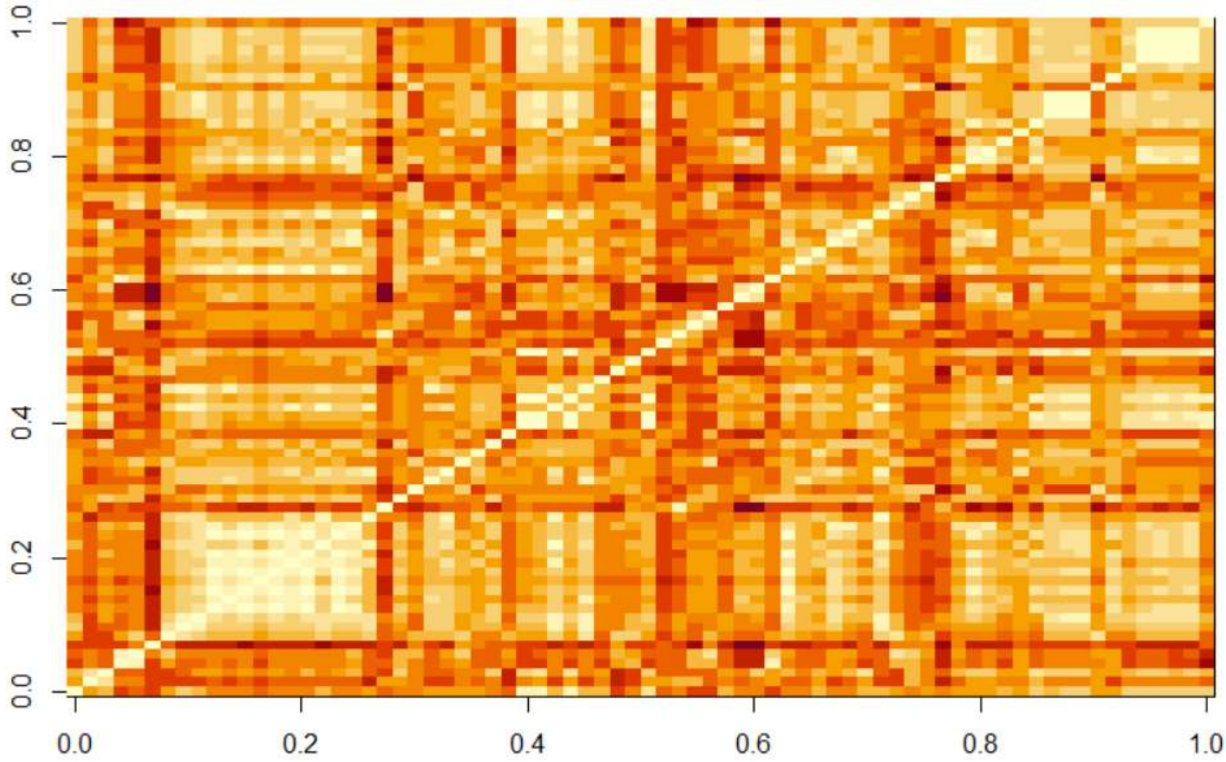


Figure S7. Minimal quality metric of the functional space. We calculated the minimal quality metric associated to each functional space and the percentage of total variance explained by the set of Principal Coordinates. PCoA at 5 dimensions explained the 75.2% of the total variance across all scenarios.

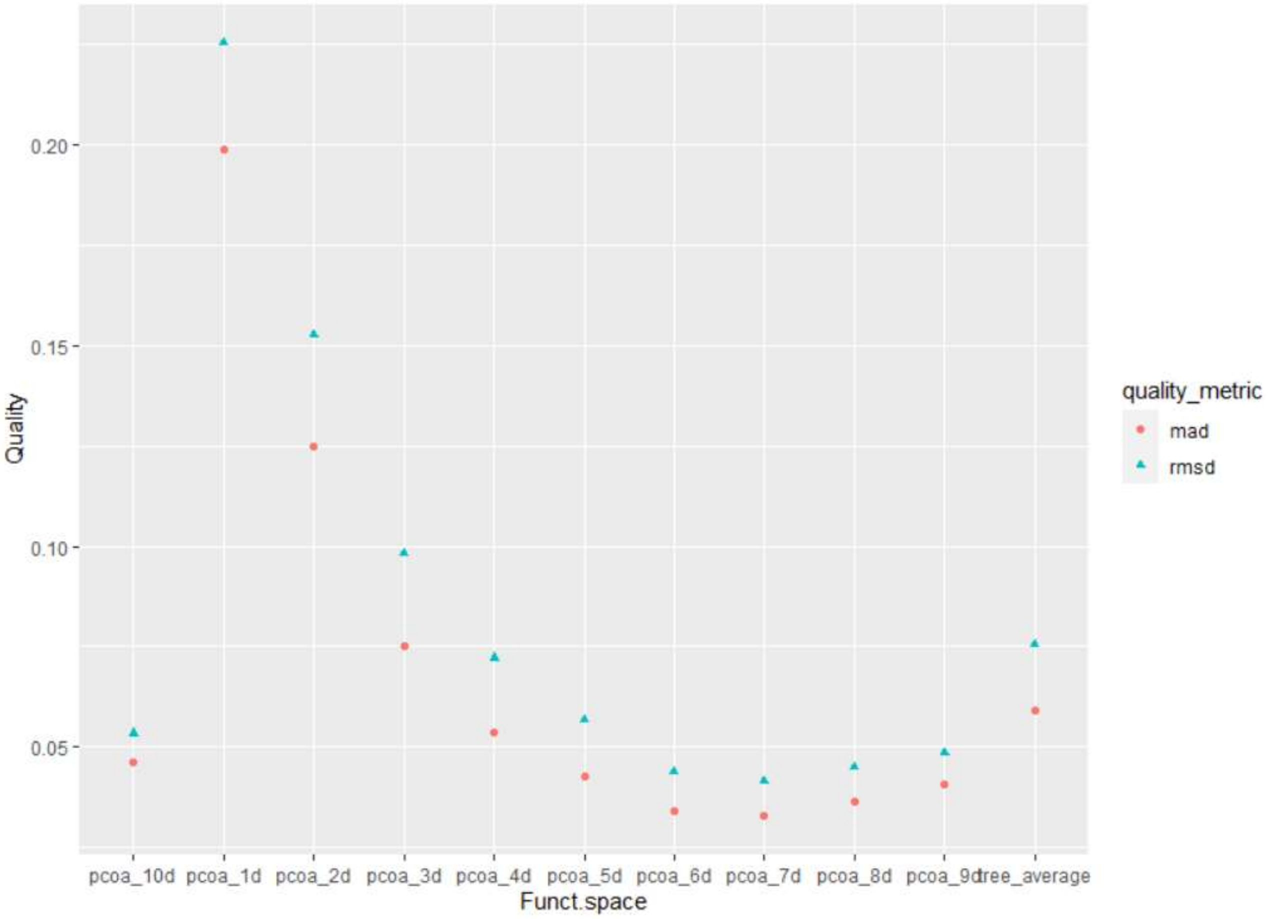


Figure S8. Quality metric of the functional space. We calculated For each functional space (PCoA 3d to PCoA 7d), the panels represent the correlation of the trait-based distance respectively with (a) the species functional distances in the multidimensional space, (b) the raw deviation of species distances in the functional space compared to trait-based distances, (c) the absolute or squared deviation of the distance in the functional space taken into account for computing the quality metric.

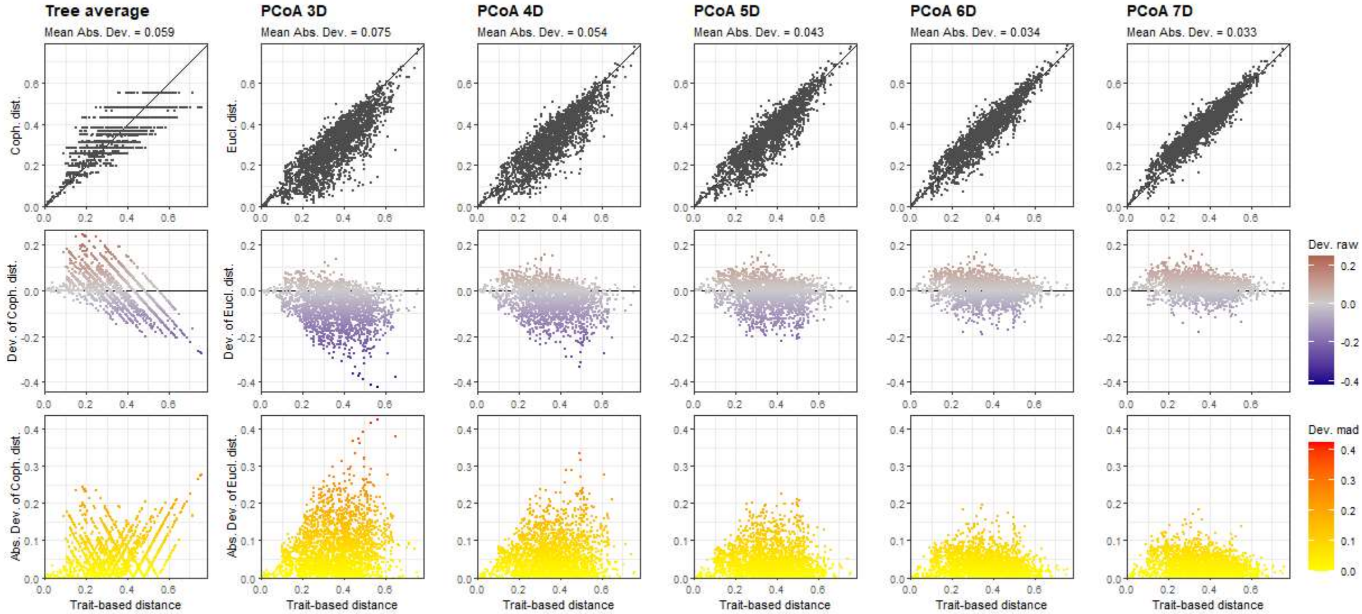
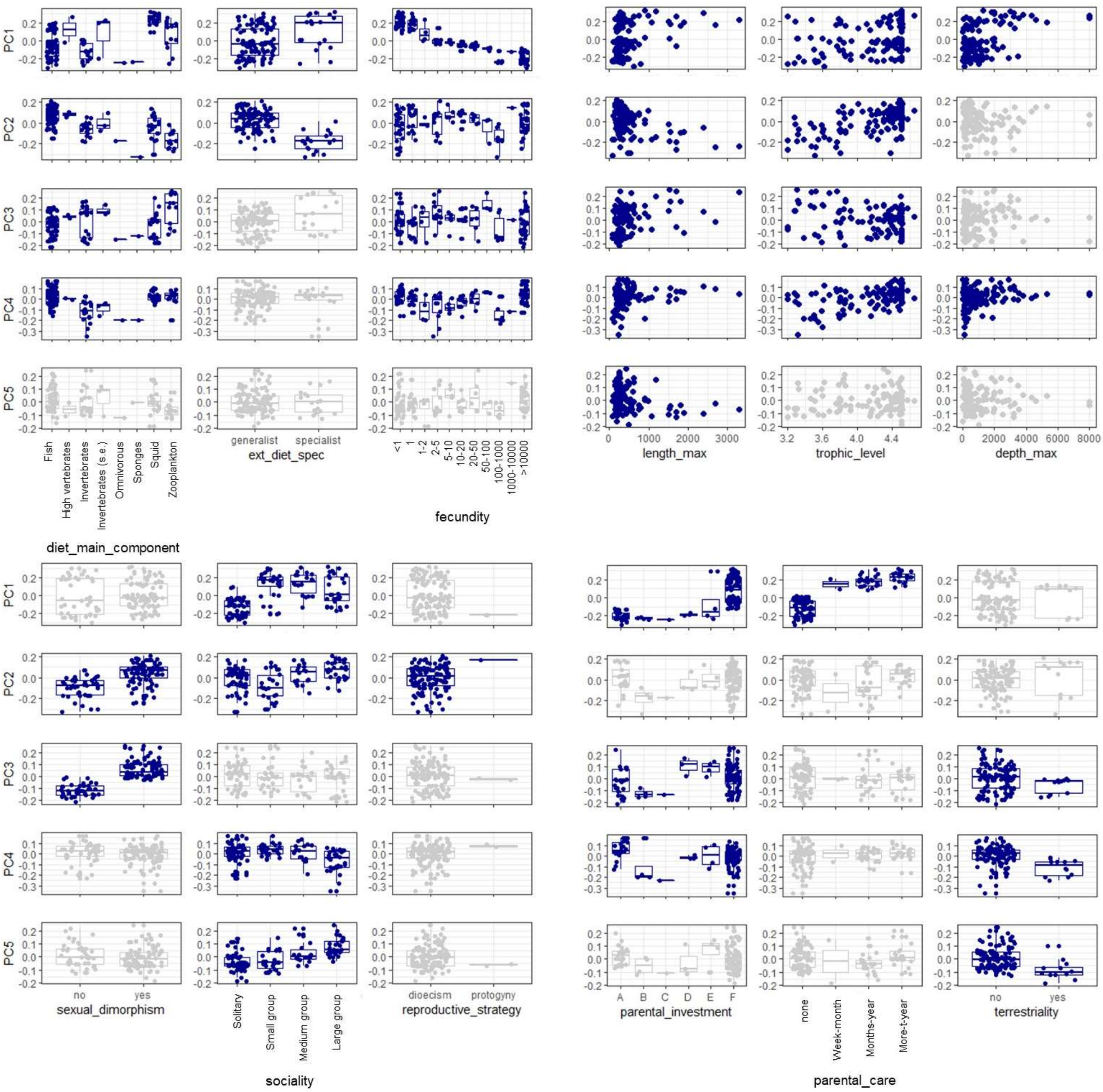


Figure S9. Relation between PCoA functional axes (PCo1 to PCo5) and traits. In blue the significant ones. PC1 is influenced by diet, diet_cleaned, and trophic level; PC2 is influenced by body_shape, water_column_position, length_com; PC3 by parental investment; PC4 by diet and body shape; PC5 by diet and water_column_position.



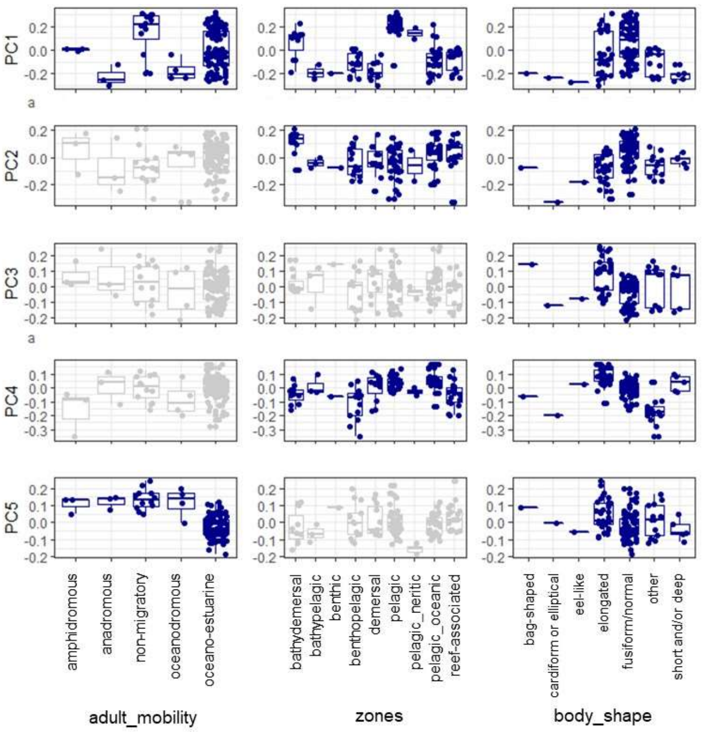

PC1
PC2
PC3
PC4
PC5
a
a
amphidromous
anadromous
non-migratory
oceanodromous
oceano-estuarine
bathydemersal
bathypelagic
benthic
benthopelagic
demersal
pelagic
pelagic_neritic
pelagic_oceanic
reef-associated
bag-shaped
cardiform or elliptical
eel-like
elongated
fusiform/normal
other
short and/or deep
adult_mobility
zones
body_shape

Table S5: Test correlation between PCoA functional axes (PCo1 to PCo5) and traits. In black the significant ones.

	trait	axis	test	stat	value	p.value
21	fecundity	PC1	Kruskal-Wallis	eta2	0.89	0
36	parental_care	PC1	Kruskal-Wallis	eta2	0.701	0
1	zones	PC1	Kruskal-Wallis	eta2	0.622	0
31	parental_investment	PC1	Kruskal-Wallis	eta2	0.561	0
21	sociality	PC1	Kruskal-Wallis	eta2	0.483	0
11	diet_main_component	PC1	Kruskal-Wallis	eta2	0.463	0
11	depth_max	PC1	Linear model	r2	0.189	0
6	body_shape	PC1	Kruskal-Wallis	eta2	0.188	0.0001
1	length_max	PC1	Linear model	r2	0.128	0
46	adult_mobility	PC1	Kruskal-Wallis	eta2	0.117	0.0011
16	ext_diet_spec	PC1	Kruskal-Wallis	eta2	0.057	0.0045
6	trophic_level	PC1	Linear model	r2	0.04	0.0245
12	diet_main_component	PC2	Kruskal-Wallis	eta2	0.445	0
17	sexual_dimorphism	PC2	Kruskal-Wallis	eta2	0.311	0
7	body_shape	PC2	Kruskal-Wallis	eta2	0.307	0
7	trophic_level	PC2	Linear model	r2	0.303	0
17	ext_diet_spec	PC2	Kruskal-Wallis	eta2	0.276	0
2	length_max	PC2	Linear model	r2	0.168	0
22	sociality	PC2	Kruskal-Wallis	eta2	0.166	0
2	zones	PC2	Kruskal-Wallis	eta2	0.155	0.0009
22	fecundity	PC2	Kruskal-Wallis	eta2	0.097	0.019
27	reproductive_strategy	PC2	Kruskal-Wallis	eta2	0.03	0.0301
18	sexual_dimorphism	PC3	Kruskal-Wallis	eta2	0.645	0
8	body_shape	PC3	Kruskal-Wallis	eta2	0.167	0.0002
3	length_max	PC3	Linear model	r2	0.11	0.0001
33	parental_investment	PC3	Kruskal-Wallis	eta2	0.106	0.0032
13	diet_main_component	PC3	Kruskal-Wallis	eta2	0.104	0.0069
23	fecundity	PC3	Kruskal-Wallis	eta2	0.089	0.0262
43	terrestriality	PC3	Kruskal-Wallis	eta2	0.047	0.0086
8	trophic_level	PC3	Linear model	r2	0.045	0.0166
9	body_shape	PC4	Kruskal-Wallis	eta2	0.472	0
4	zones	PC4	Kruskal-Wallis	eta2	0.32	0
24	fecundity	PC4	Kruskal-Wallis	eta2	0.266	0
14	diet_main_component	PC4	Kruskal-Wallis	eta2	0.245	0
9	trophic_level	PC4	Linear model	r2	0.21	0
44	terrestriality	PC4	Kruskal-Wallis	eta2	0.137	0
34	parental_investment	PC4	Kruskal-Wallis	eta2	0.125	0.0012
24	sociality	PC4	Kruskal-Wallis	eta2	0.114	0.0007
4	length_max	PC4	Linear model	r2	0.047	0.0147
14	depth_max	PC4	Linear model	r2	0.045	0.0171
50	adult_mobility	PC5	Kruskal-Wallis	eta2	0.35	0
25	sociality	PC5	Kruskal-Wallis	eta2	0.331	0
45	terrestriality	PC5	Kruskal-Wallis	eta2	0.099	0.0003
10	body_shape	PC5	Kruskal-Wallis	eta2	0.089	0.0104
5	length_max	PC5	Linear model	r2	0.051	0.0105

Supplementary Results

Figure S10. Diversity indices by ecoregions at year 2022 (baseline)

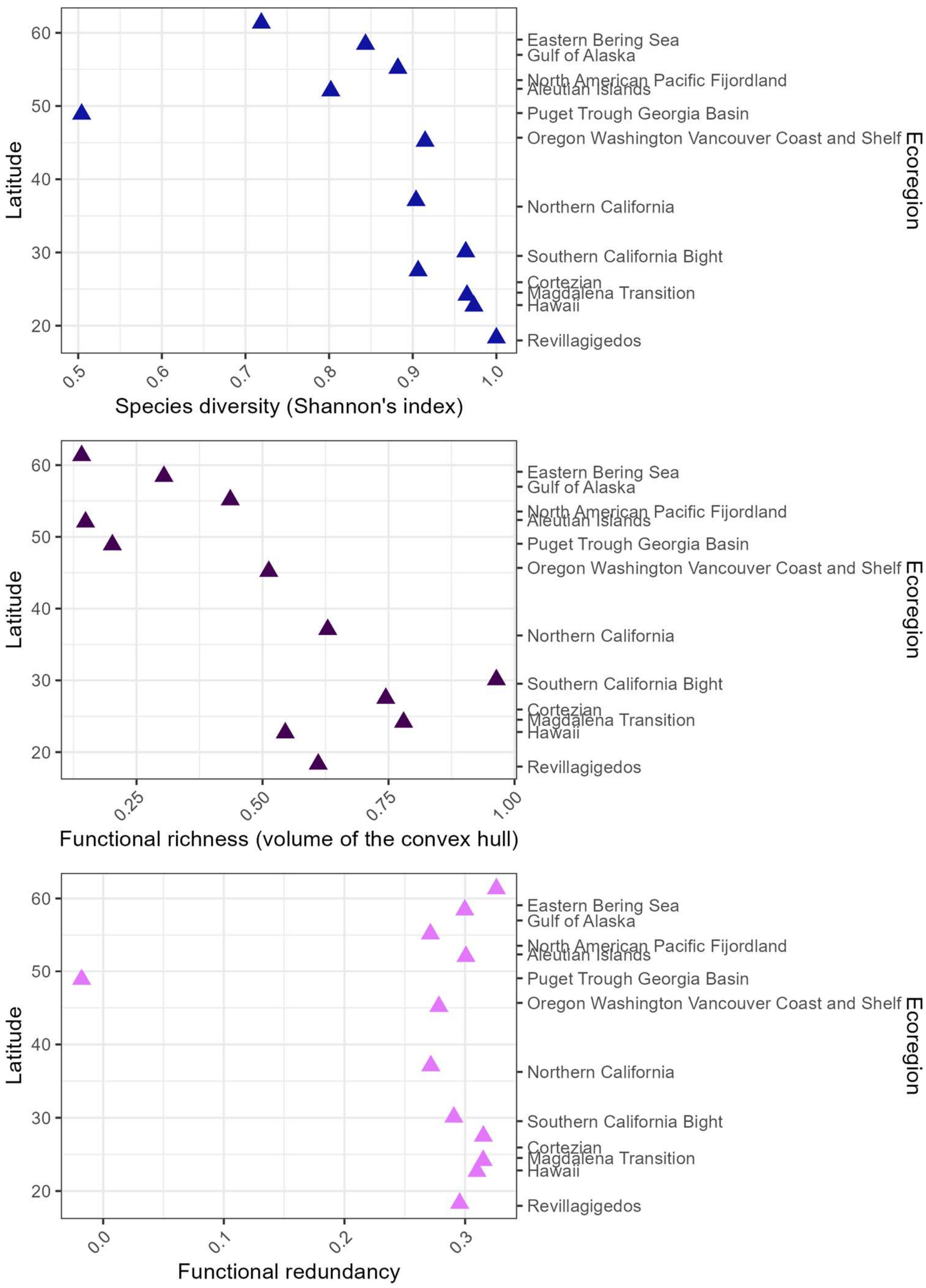


Table S6. Diversity indices percent change of ecoregions across Representative Concentration Pathways at years 2050 and 2100 from the baseline (year 2022).

No.	Ecoregions	Scenario	RCP 2.6	RCP 4.5		RCP 8.5	
		year	2100	2050	2100	2050	2100
Functional richness			%	%	%	%	%
1	Eastern Bering Sea		5.5	14.7	15.0	50.2	154.4
2	Gulf of Alaska		29.7	27.0	55.8	43.3	58.5
3	North American Pacific Fijordland		10.6	10.7	11.6	11.6	28.1
4	Aleutian Islands		32.5	41.6	49.1	49.3	164.3
5	Puget Trough Georgia Basin		9.7	-7.8	18.5	25.2	22.2
6	Oregon Washington Vancouver Coast and Shelf		0.7	0.7	0.7	0.9	23.4
7	Northern California		14.5	14.8	14.8	14.8	49.2
8	Southern California Bight		-0.3	-0.3	-0.3	0.0	-0.1
9	Cortezian		-2.5	-2.2	-2.5	-2.5	-8.5
10	Magdalena Transition		0.0	-2.4	-1.3	0.0	-3.8
11	Hawaii		2.0	0.6	0.6	-0.3	-7.7
12	Revillagigedos		-6.4	-6.1	-39.5	-9.4	-45.9
Species diversity							
1	Aleutian Islands		2.6	5.1	6.5	6.6	12.4
2	Eastern Bering Sea		2.7	3.5	3.9	7.7	11.2
3	Gulf of Alaska		2.6	3.1	4.5	4.3	8.2
4	North American Pacific Fijordland		2.8	1.6	1.9	2.4	1.0
5	Puget Trough Georgia Basin		13.0	17.1	12.4	9.6	4.5
6	Oregon Washington Vancouver Coast and Shelf		-0.2	0.4	0.2	0.2	1.3
7	Northern California		0.1	-0.3	0.2	-0.2	7.2
8	Southern California Bight		1.5	3.0	2.0	2.0	3.1
9	Cortezian		0.0	-0.2	-0.5	-0.3	-2.2
10	Magdalena Transition		1.0	1.1	-5.4	-2.7	-5.0
11	Revillagigedos		-1.6	-2.4	-7.1	-3.6	-18.6
12	Hawaii		-0.6	-0.1	-1.5	-2.3	-6.1
Functional richness			%	%	%	%	%
1	Eastern Bering Sea		5.5	14.7	15.0	50.2	154.4
2	Gulf of Alaska		29.7	27.0	55.8	43.3	58.5
3	North American Pacific Fijordland		10.6	10.7	11.6	11.6	28.1
4	Aleutian Islands		32.5	41.6	49.1	49.3	164.3
5	Puget Trough Georgia Basin		9.7	-7.8	18.5	25.2	22.2
6	Oregon Washington Vancouver Coast and Shelf		0.7	0.7	0.7	0.9	23.4
7	Northern California		14.5	14.8	14.8	14.8	49.2
8	Southern California Bight		-0.3	-0.3	-0.3	0.0	-0.1
9	Cortezian		-2.5	-2.2	-2.5	-2.5	-8.5
10	Magdalena Transition		0.0	-2.4	-1.3	0.0	-3.8
11	Hawaii		2.0	0.6	0.6	-0.3	-7.7
12	Revillagigedos		-6.4	-6.1	-39.5	-9.4	-45.9
Functional redundancy							
1	Eastern Bering Sea		-1.0	-4.5	-3.1	-1.4	-3.3
2	Gulf of Alaska		-4.7	-3.1	-5.2	-5.2	-5.2

3	North American Pacific Fijordland	4.9	-0.2	-1.7	0.1	-4.7
4	Aleutian Islands	-2.8	-1.3	-0.3	0.2	3.1
5	Puget Trough Georgia Basin	<-30	<-30	<-30	<-30	<-30
6	Oregon Washington Vancouver Coast and Shelf	0.0	-0.1	-1.0	-0.1	-3.0
7	Northern California	-1.7	-2.2	-1.7	-1.9	2.7
8	Southern California Bight	1.8	4.6	3.7	2.2	3.9
9	Cortezian	0.8	0.6	0.7	0.8	0.1
10	Magdalena Transition	0.2	1.3	-1.4	-0.1	-1.1
11	Hawaii	0.2	0.7	0.1	-0.5	-2.4
12	Revillagigedos	0.8	0.0	-2.8	-1.7	-2.7

Figure S11. Diversity indices percent change across Representative Concentration Pathways with respect to the baseline at year 2022.

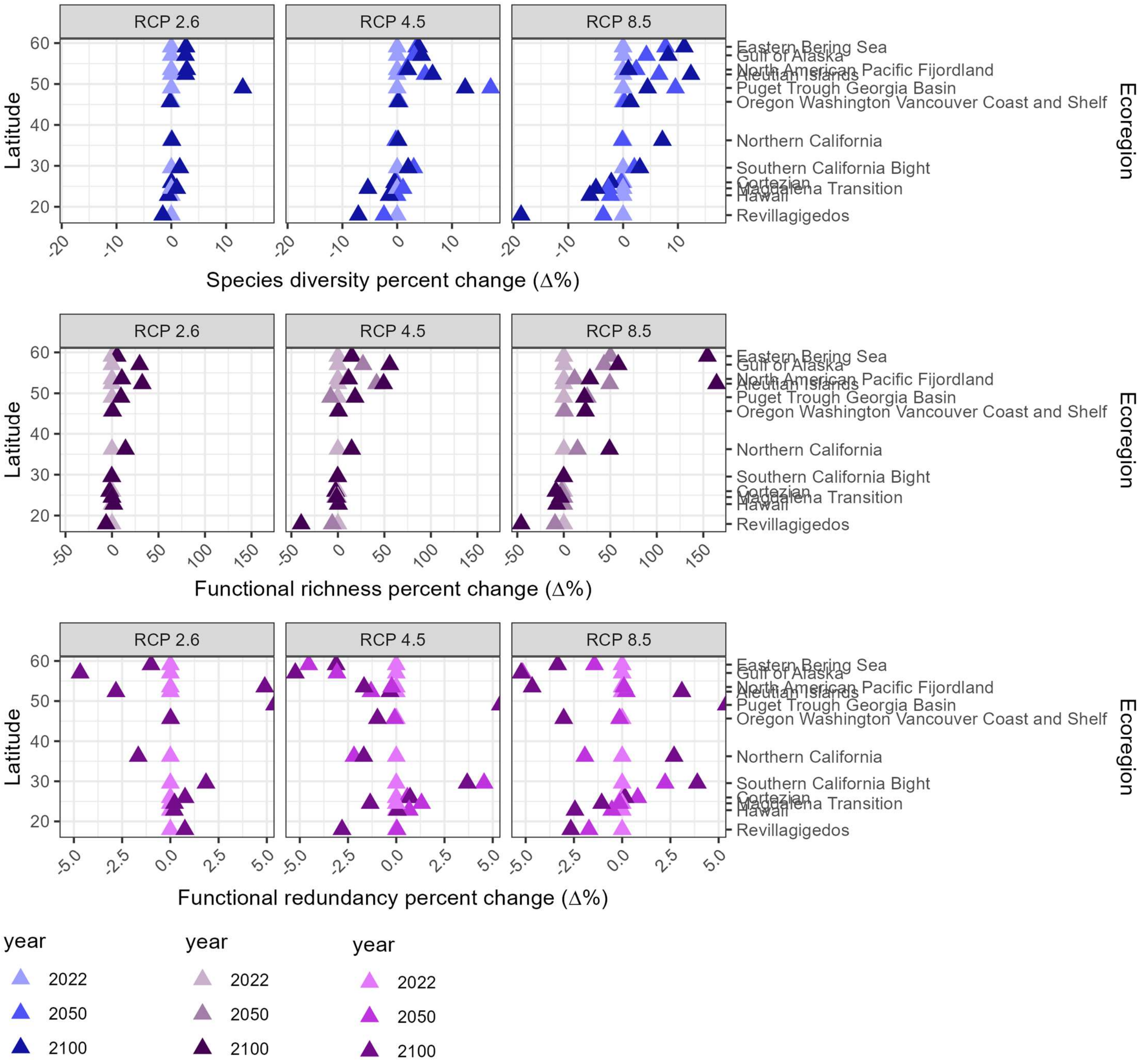


Figure S12. Identification of the megafauna species located in the functional space for the first two axis of the Principal Coordinate Analysis grouped by order and class.

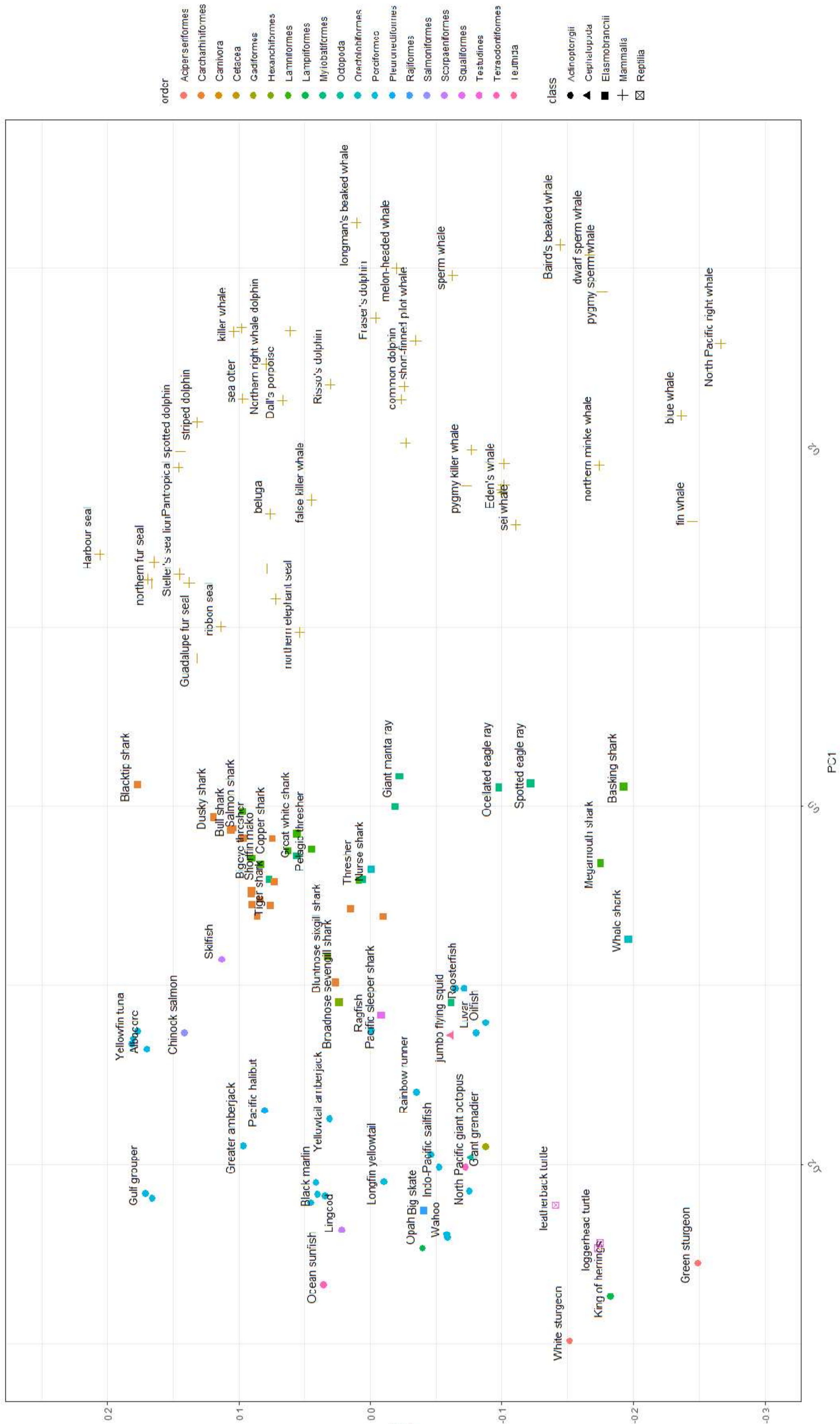


Fig. S13. Correlation between diversity indexes at ecoregional level and Sea Surface Temperature (SST) and latitude. We considered diversity indexes absolute values for each scenario (a,b,e) and percent change across scenarios (c,d,f); we considered the absolute SST values for each ecoregion as the mean temperature for each scenario (a,c), and the SST change across scenarios (b,d); for each ecoregion we considered the latitude centroid. Species diversity was positively correlated with SST (R = 0.67, p < 2.2e-16) and negatively correlated with latitude (R = -0.67, p < 3.7e-09); functional richness is positively correlated with SST (R = 0.68, p = 4.1e-11) and negatively correlated with latitude (R = -0.61, p < 1.8e-07). Interestingly, percent change of f. redundancy index is positively correlated with latitude (R=0.36, p=0.007), meaning that functional redundancy percent change decreases with latitude.

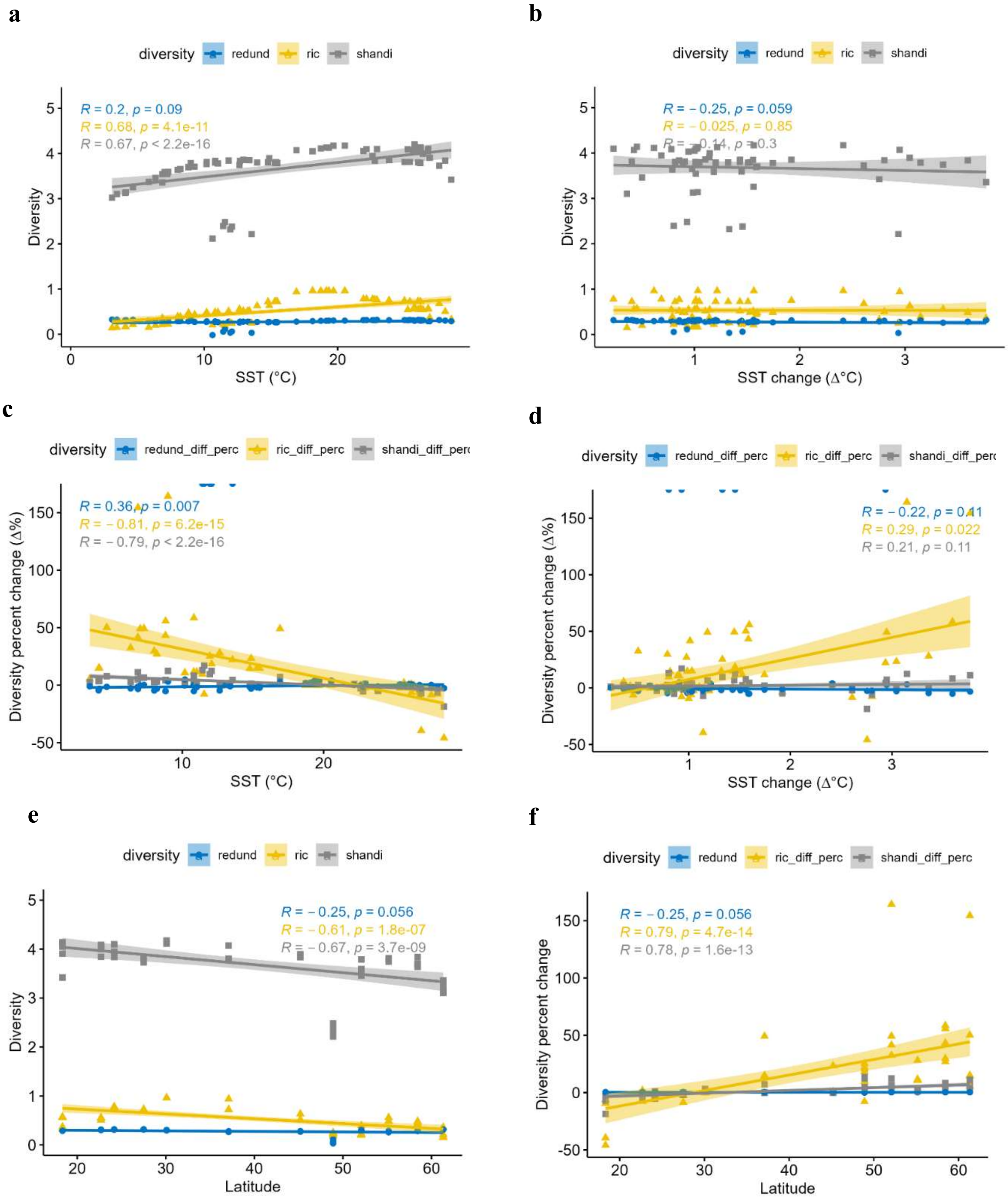


Fig. S14. Species diversity and functional richness with respect to Sea Surface Temperature (SST) and latitude. For each ecoregion we considered the latitude centroid.

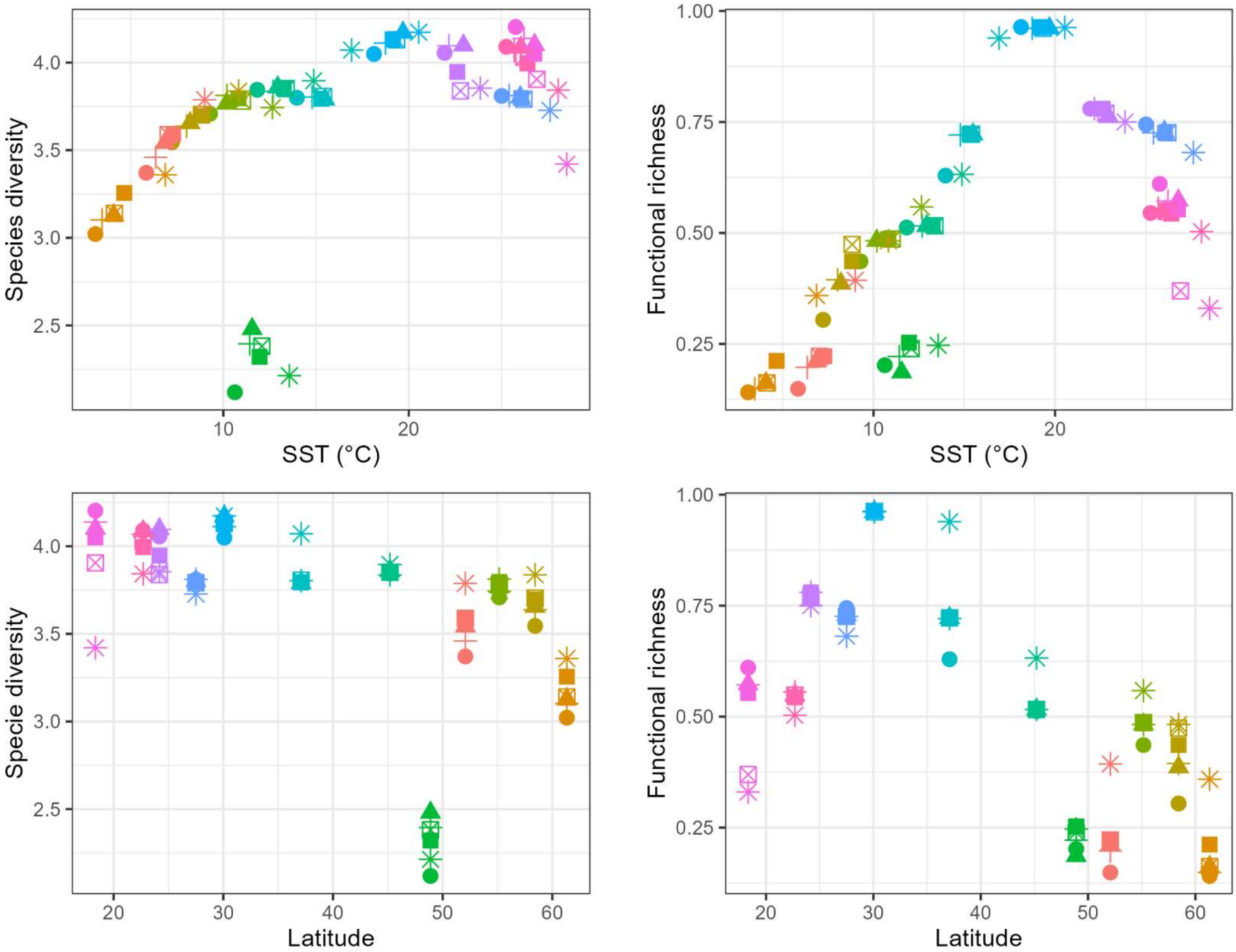


Table S7. Percent change of diversity indices by grid cells and year across Representative Concentration Pathways (RCP).

	2050		2100			
	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5	
	%	%	%	%	%	
Species diversity (Δ%)						
>5%	5.8	12.7	3.7	7.3	29.5	
0%< Δ <5%	47.2	41.1	41.4	44.4	22.3	
Δ = 0	0.0	0.0	0.0	0.0	0.0	
-5%<Δ<0%	33.6	29.8	41.8	26.6	16.9	
<-5%	13.4	16.4	13.1	21.7	31.3	
Functional richness (Δ%)						
>5%	38.2	41.3	27.4	39.3	50.4	
0%< Δ <5%	11.6	10.6	9.6	9.7	3.8	
Δ = 0	8.8	6.4	16.5	5.5	0.8	
-5%<Δ<0%	13.2	11.0	13.7	10.1	2.4	
<-5%	28.2	30.7	32.8	35.4	42.6	
Functional redundancy (Δ%)						*Interpretation*
>5%	16.8	18.9	15.9	24.3	38.1	index increases, so f.red. decreases
0%< Δ <5%	34.9	33.7	32.2	27.8	18.5	
Δ = 0	0.0	0.0	0.0	0.0	0.0	
-5%<Δ<0%	32.2	31.1	38.6	28.6	20.8	index decreases, so f.red. increases
<-5%	16.1	16.3	13.4	19.2	22.6	

Figure S15. Change of diversity indices by grid cells across latitude and Representative Concentration Pathways (RCP), considering grid cells across the case study and only for cells within ecoregions (coastal). Change in diversity indexes diverged when considering grid cells only within ecoregions (light gray) vs. also including open oceanic areas (dark gray). Changes diverged more strongly in the moderate scenario (RCP 2.6) than in the extreme one (RCP 8.5).

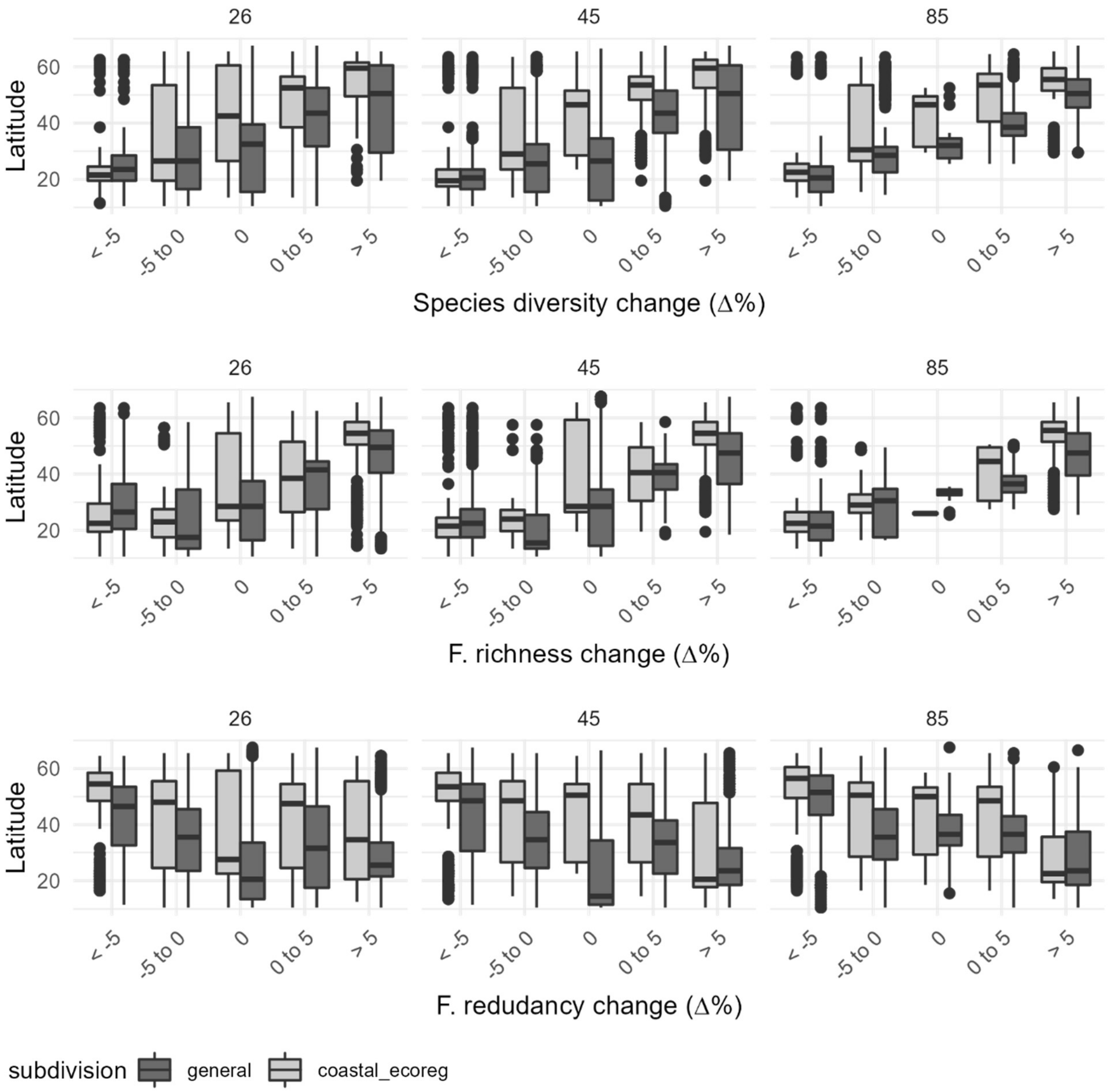


Table S8. Form of generalized additive models (GAM) and their relative explanatory power examining the effect of sea surface temperature (SST), depth, latitude (lat) and longitude (long), year and Representative Concentration Pathway (RCP) on diversity indexes, with R-squared (rsq) and the Akaike's information criterion (AIC).

Species diversity		
Variables	rsq	AIC
SST, lat&long	0.721467	10054.73
SST, lat&long, year&RCP	0.724099	9841.969
SST, lat&long, depth	0.743732	8152.63
SST, lat&long, depth, year&RCP	**0.746291**	**7927.424**
Functional richness		
Variables	rsq	AIC
SST, lat&long, year&RCP	0.68739	-58881
Lat&long, depth	0.700785	-59843.2
SST, lat&long, depth	0.792841	-68315.2
SST, lat&long, depth, year&RCP	**0.794757**	**-68523.4**
Functional redundancy		
Variables	rsq	AIC
SST, lat&long	0.616991	-76423.6
SST, lat&long, year&RCP	0.618109	-76485.6
SST, lat&long, depth	0.636523	-77615.5
SST, lat&long, depth, year&RCP	**0.637555**	**-77675.7**

Figure S16. Model fits. C Smoothed curves of the additive effects to the diversity index values for the individual environmental parameters in the GAM. Dotted lines represent 95% confidence intervals, marks along the lower axis represent a single observation. We compared the results of generalized additive models for species diversity (R-squared=0.7463, Dev. Explained=74.8%, RMSE=0.2860), functional richness (R-squared=0.7948, Dev. Explained=79.6%, RMSE=0.0540), and functional redundancy (R-squared=0.7948, Dev. Explained=79.6%, RMSE=0.0443) considering sea surface temperature, longitude and latitude, and depth as environmental variables, and year and scenario (RCP) as factors.

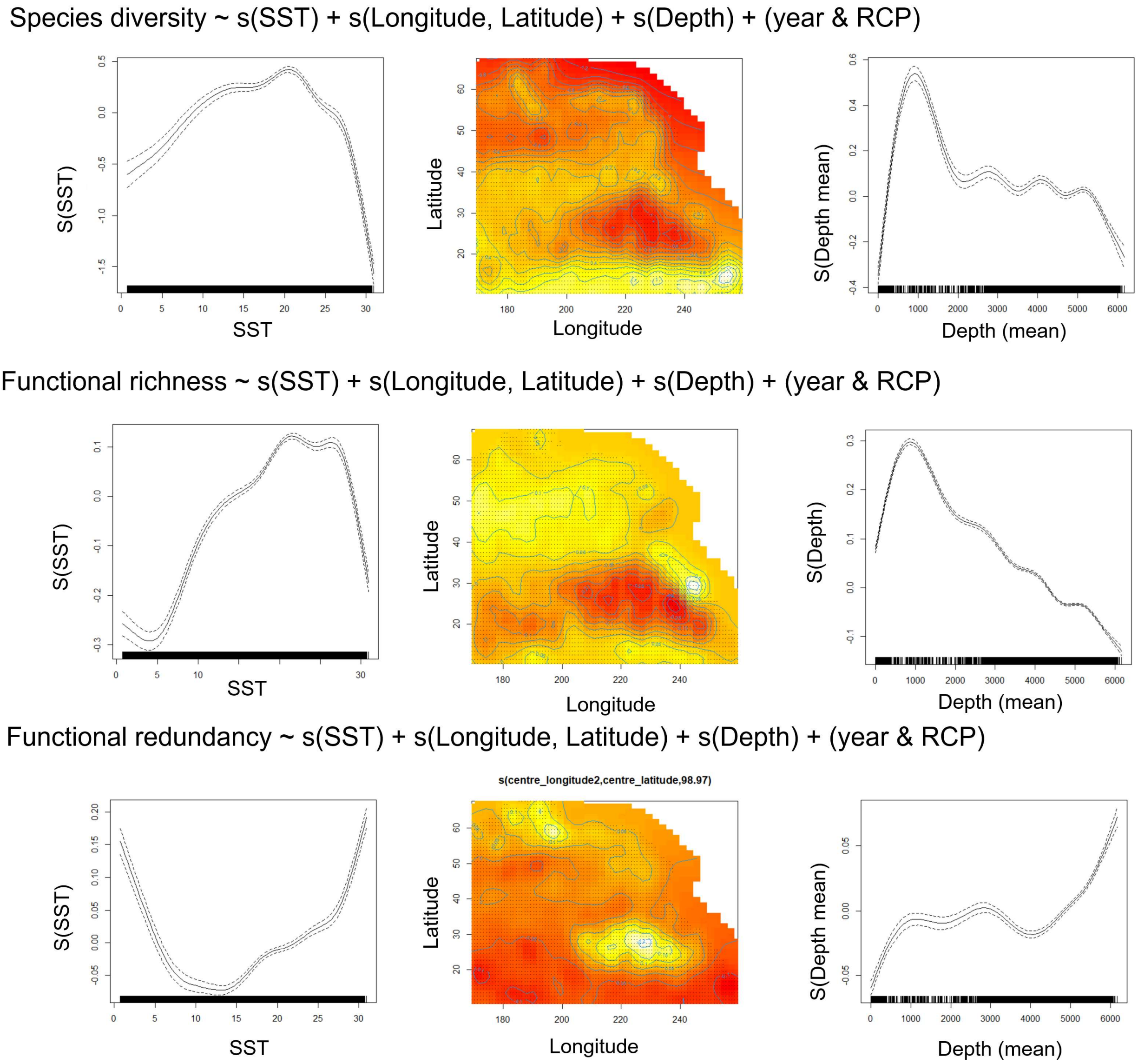
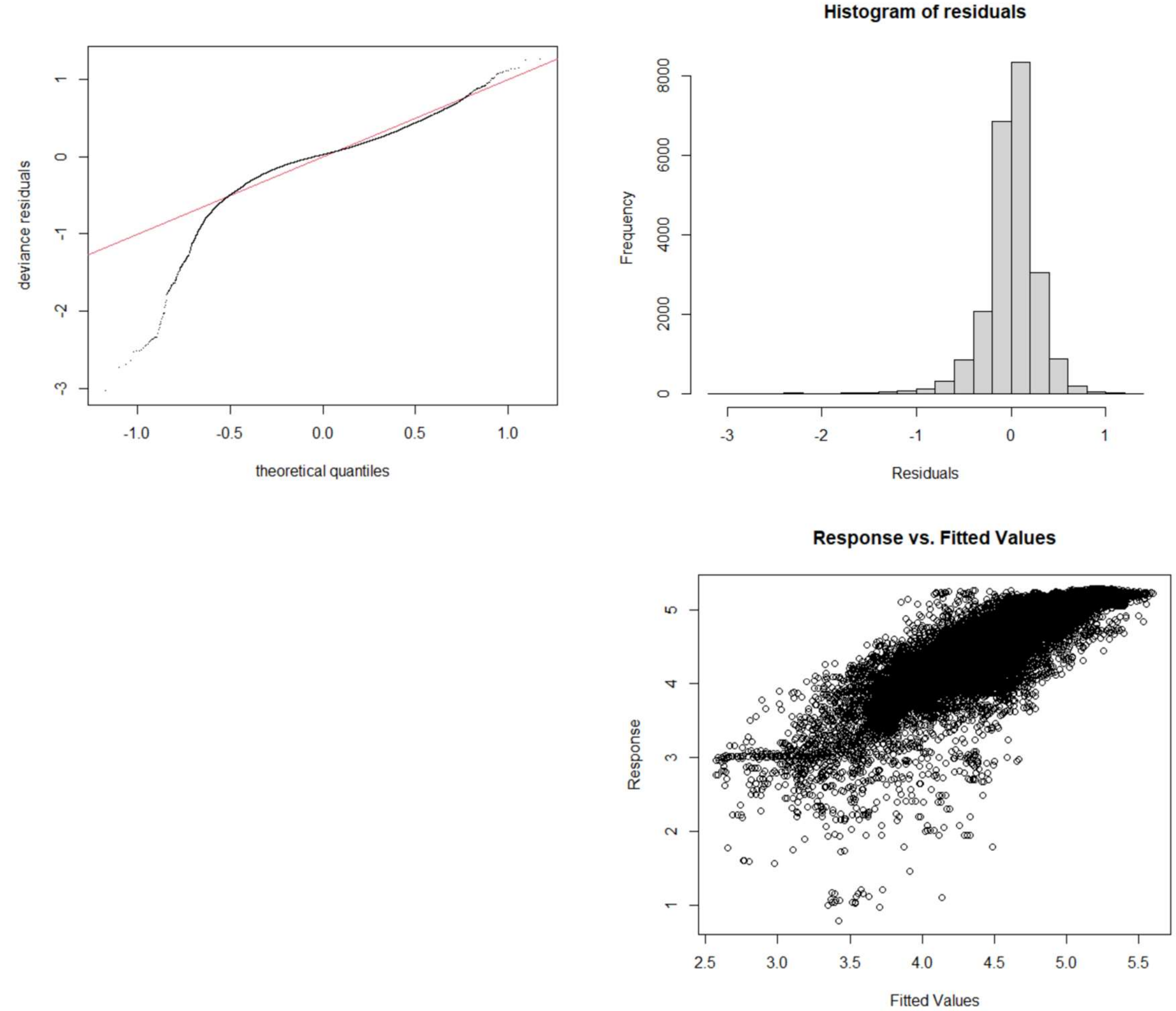


Figure S17 Model performance for the species diversity model. Model accuracy was characterized through the root mean squared error (RMSE)

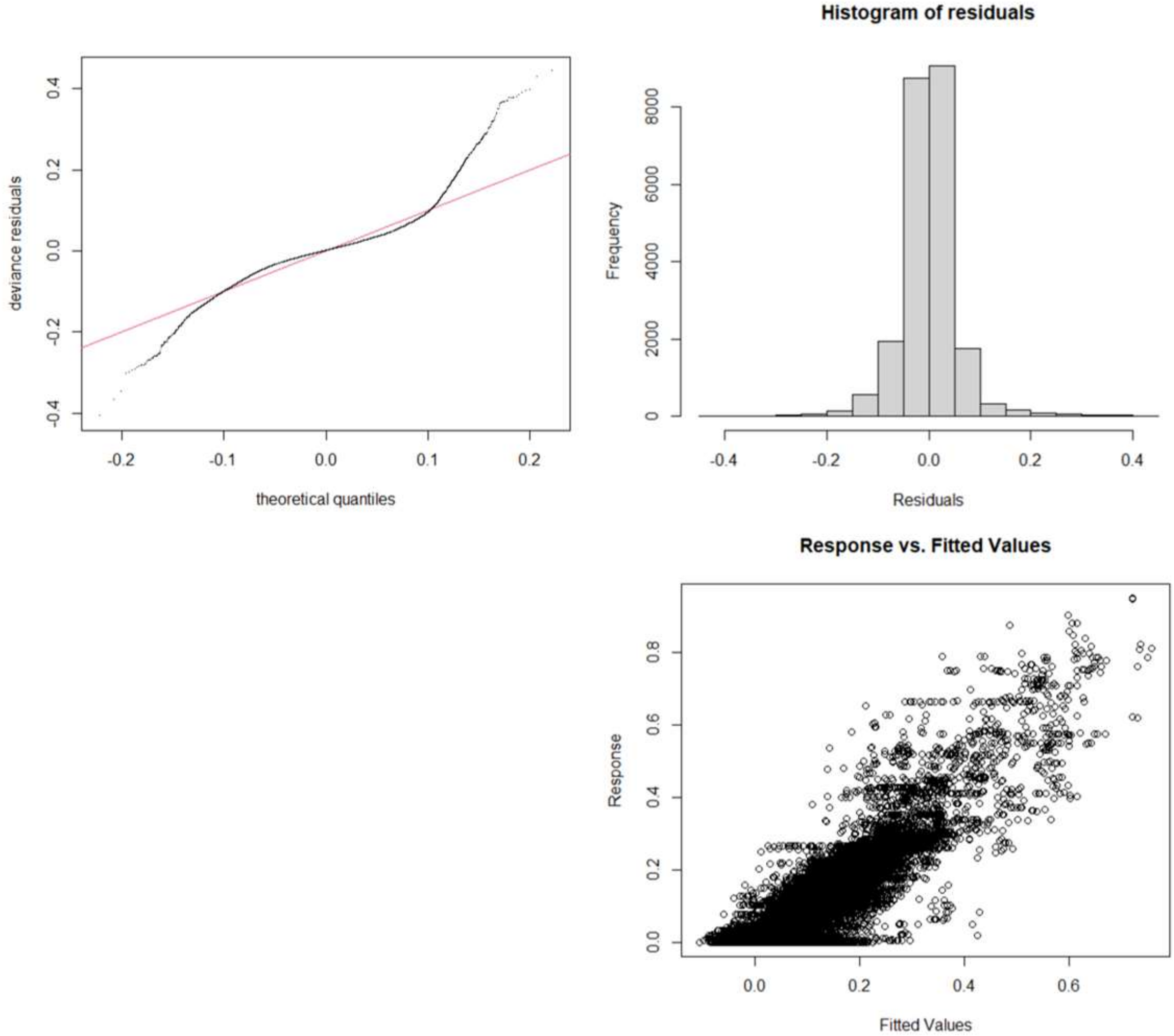
Model: Species diversity ~ s(SST) + s(Longitude, Latitude) + s(Depth) + (year & RCP)



R-squared=0.7463, Dev. Explained=74.8%, RMSE=0.2860

Figure S18. Model performance for the functional richness model. Model accuracy was characterized through the root mean squared error (RMSE).

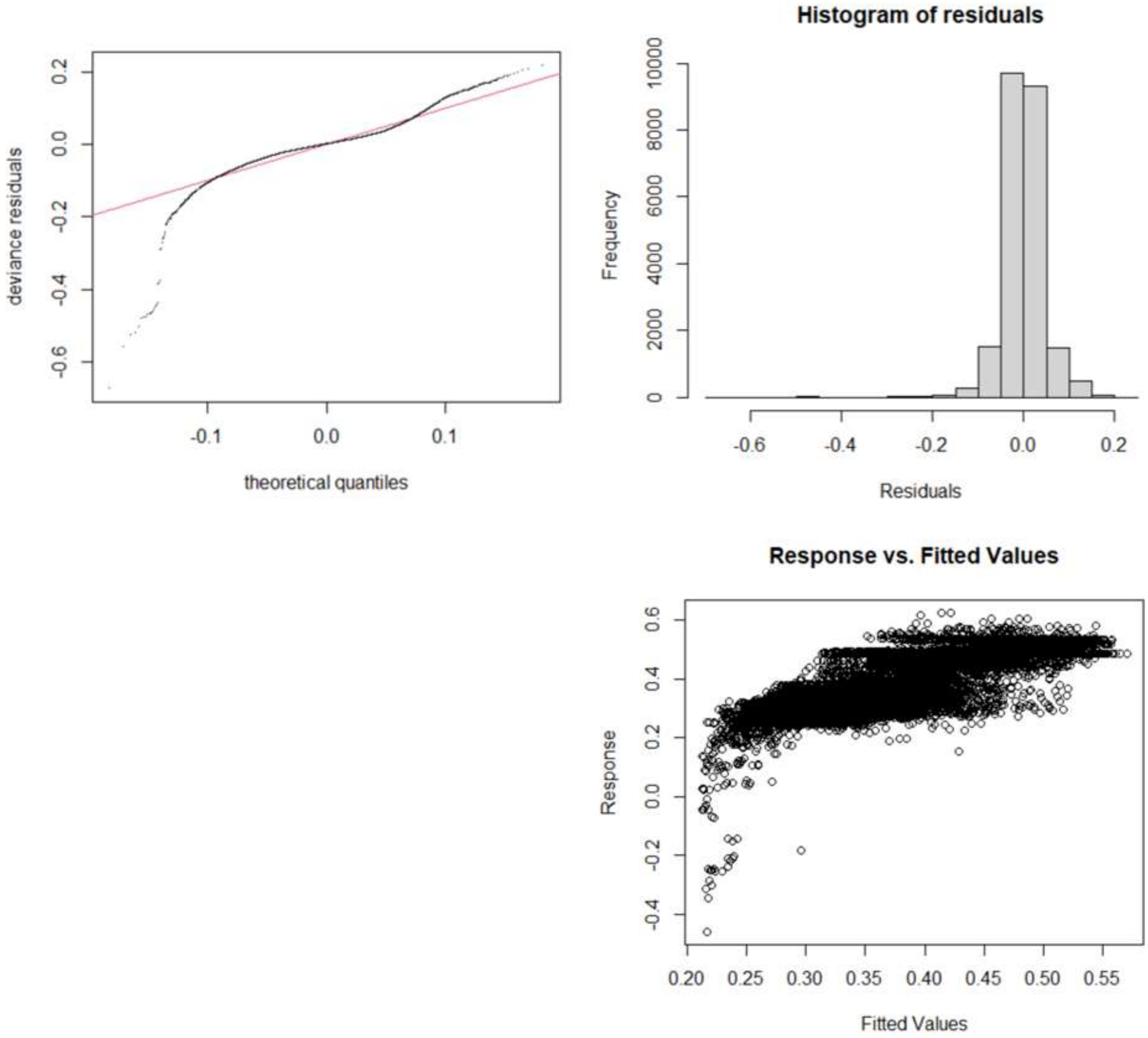
Model: Functional richness ~ s(SST) + s(Longitude, Latitude) + s(Depth) + (year & RCP)



R-squared=0.7948, Dev. Explained=79.6%, RMSE=0.0540

Figure S19. Model performance for the functional redundancy model. Model accuracy was characterized through the root mean squared error (RMSE).

Model: Functional redundancy ~ s(SST) + s(Longitude, Latitude) + s(Depth) + (year & RCP)



R-squared=0.638, Dev. Explained=63.9%, RMSE=0.0540

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