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The marine fish food web is globally connected

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Supplementary Materials for

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Fig. S1 | Distribution of the 13,916,517 Ocean Biogeographic System (OBIS) (*16*) occurrences (a) used for the construction of the 11,365 marine fish distribution maps species across the world and averaged across latitudes (b). The black bars on the chart represent the standard error of the mean. The blue line represents a GAM model fitted between the mean number of OBIS occurences (log) and the latitude (b; adjusted R^2 = 0.7, estimated degrees of freedom = 8.8) within shaded grey the 95% confidence limits. The coastline was defined by using the Global Self-consistent, Hierarchical, High-resolution Geography Database (*51*).

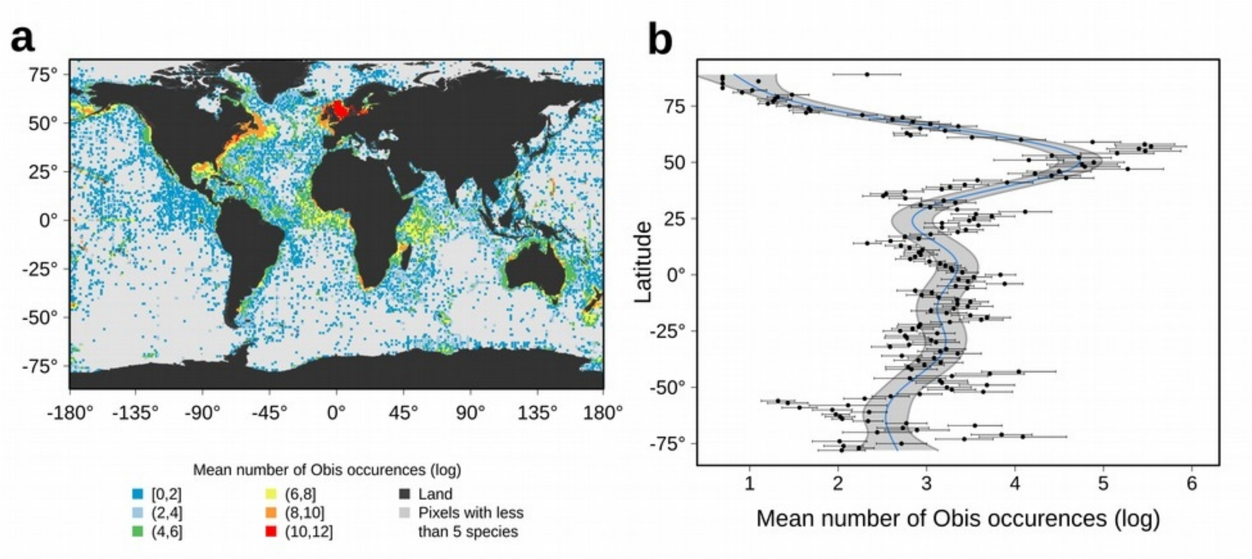


Fig S2 | Evaluation of the calibration process. To avoid any circularity, we evaluated the calibration by only keeping a single interaction par combination body sizes and predator present in the Barnes data set. When including all the interaction, the mean Boyce index value reached 0.64 (sd =0.07, n=999), and when we kept only unique combination of predator- prey body sizes (mean Boyce index = 0.55, sd = 0.08, n = 999).

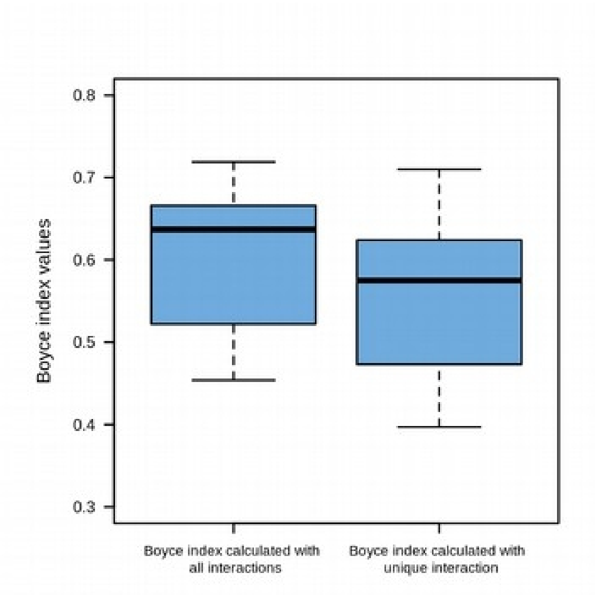
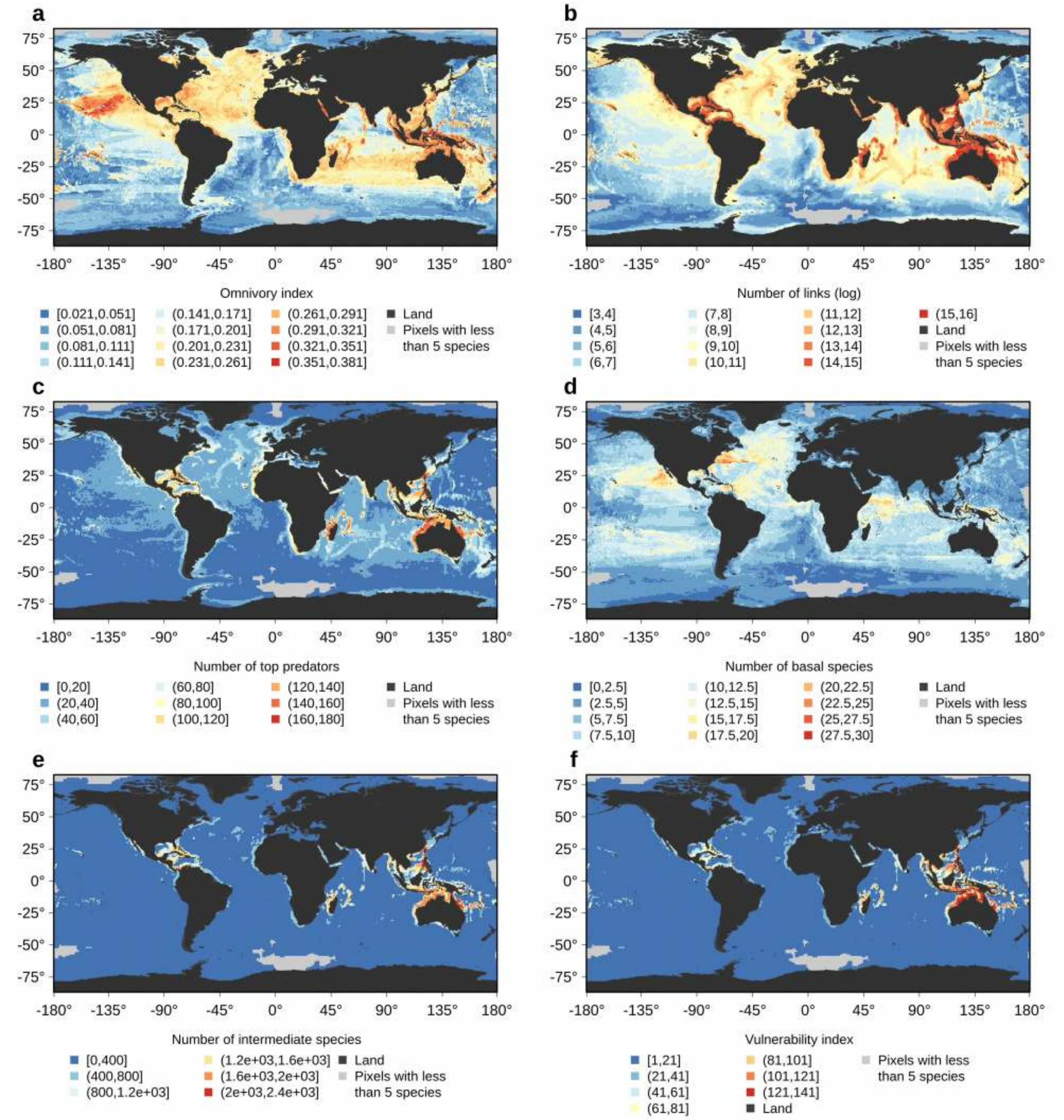


Fig. S3 | Maps of local food web indicators across the world ocean. The maps represent the distribution of, (a) omnivory index, (b) number of links, (c) number of top predators (d) number of basal species (e) number of intermediate species (f) vulnerability (mean number of consumer species per prey species), (g) generality (mean number of prey species per predator species), (h) modularity (i) percentage of shortest path length <3, (j) percentage of top predators (k) percentage of basal species and (l) percentage of intermediate species and for 11,365 fish species on a 1°×1° grid. The coastline was defined by using the Global Self-consistent, Hierarchical, High-resolution Geography Database (*51*).



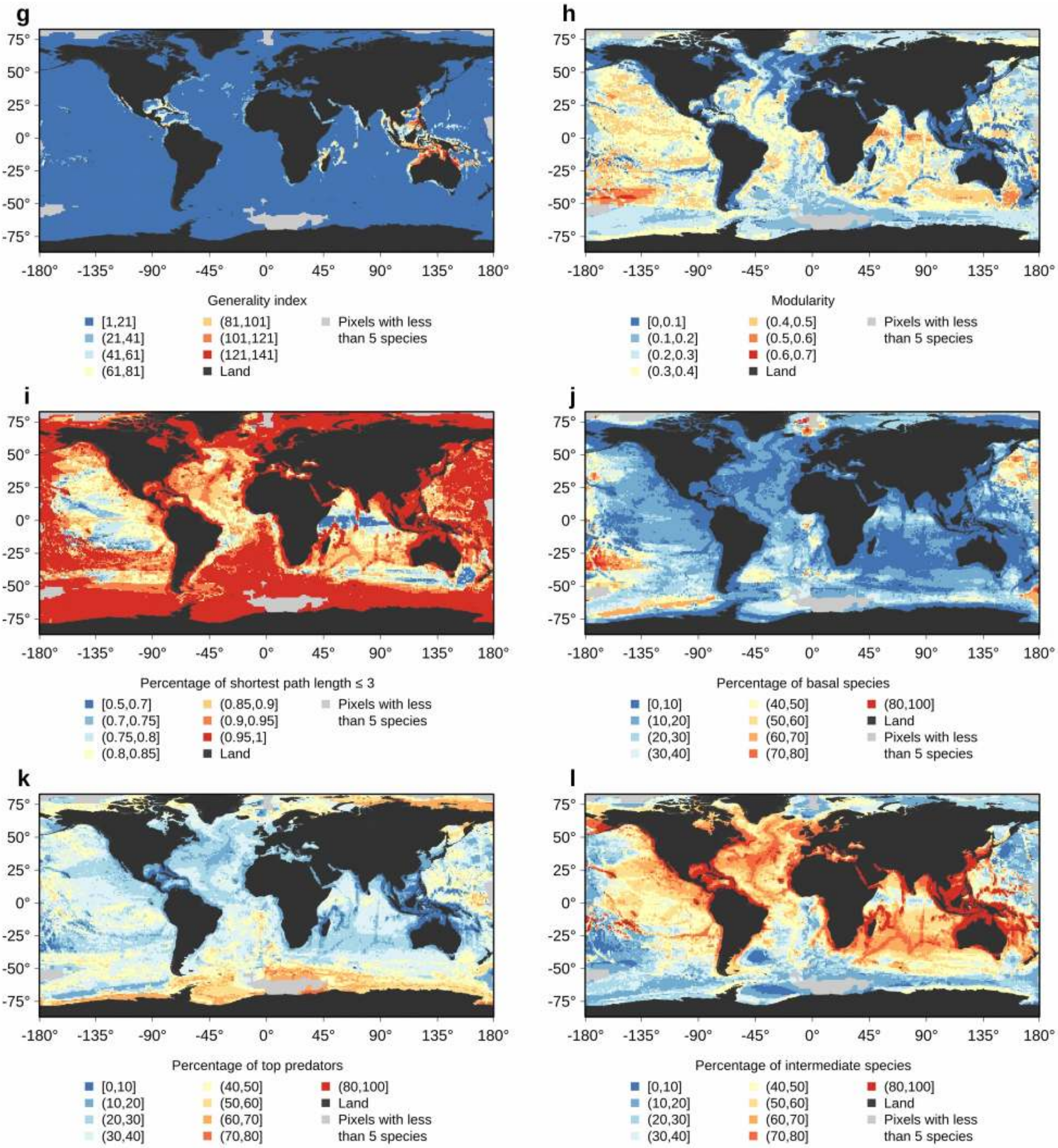

g
h
i
j
k
l
75°
50°
25°
0°
-25°
-50°
-75°
-180°
-135°
-90°
-45°
0°
45°
90°
135°
180°
Generality index
[1,21]
(21,41]
(41,61]
(61,81]
(81,101]
(101,121]
(121,141]
Land
Pixels with less than 5 species
Modularity
[0,0.1]
(0.1,0.2]
(0.2,0.3]
(0.3,0.4]
(0.4,0.5]
(0.5,0.6]
(0.6,0.7]
Land
Pixels with less than 5 species
Percentage of shortest path length ≤ 3
[0.5,0.7]
(0.7,0.75]
(0.75,0.8]
(0.8,0.85]
(0.85,0.9]
(0.9,0.95]
(0.95,1]
Land
Pixels with less than 5 species
Percentage of basal species
[0,10]
(10,20]
(20,30]
(30,40]
(40,50]
(50,60]
(60,70]
(70,80]
(80,100]
Land
Pixels with less than 5 species
Percentage of top predators
[0,10]
(10,20]
(20,30]
(30,40]
(40,50]
(50,60]
(60,70]
(70,80]
(80,100]
Land
Pixels with less than 5 species
Percentage of intermediate species
[0,10]
(10,20]
(20,30]
(30,40]
(40,50]
(50,60]
(60,70]
(70,80]
(80,100]
Land
Pixels with less than 5 species

Fig. S4 |Maps of environmental descriptors. The maps represent the distribution of (a) mean primary productivity, (b) mean sea surface temperature, (c) mean sea surface salinity and (d) distance from land. For more details about the environmental descriptors, see table S2. The coastline was defined by using the Global Self-consistent, Hierarchical, High-resolution Geography Database (*51*).

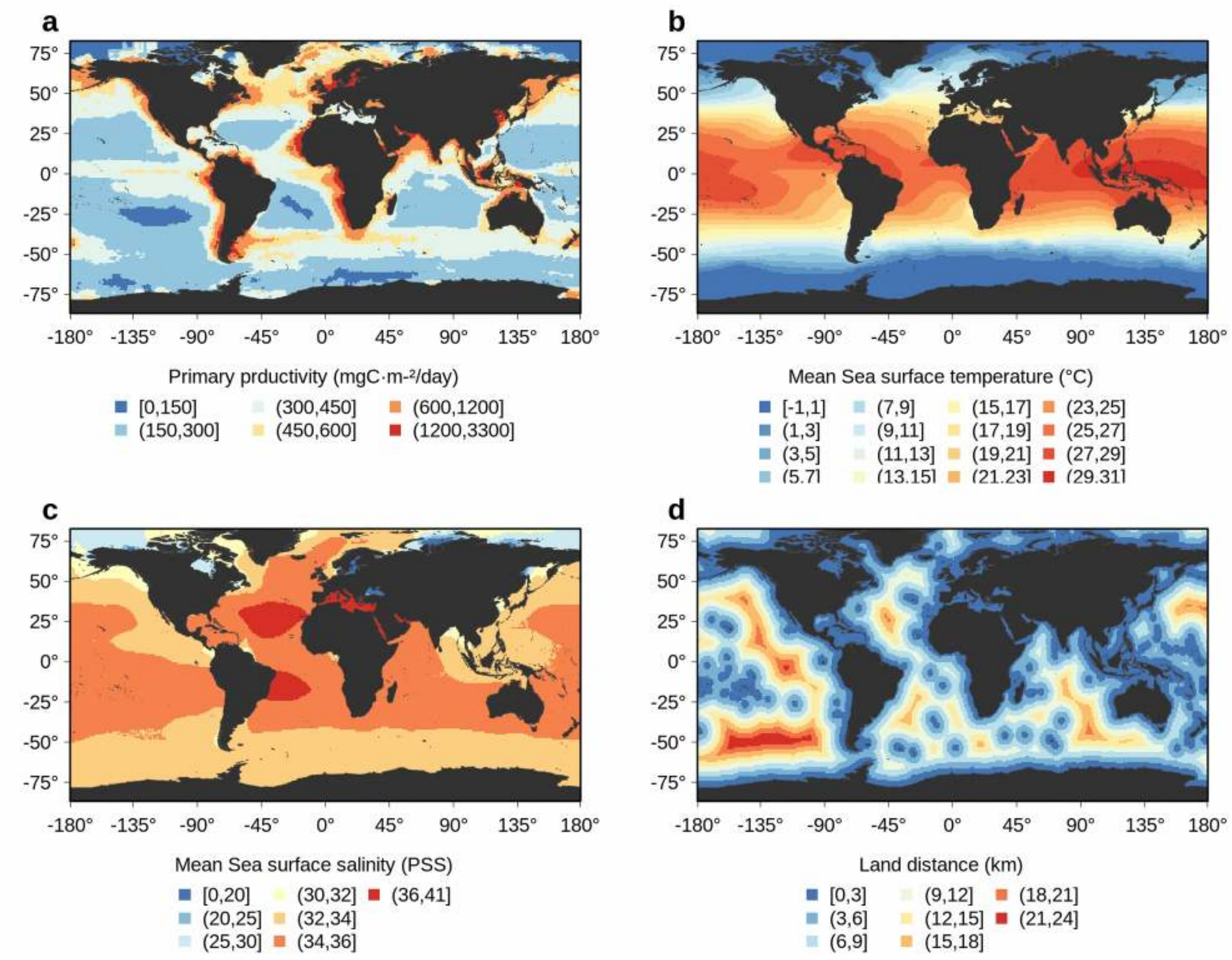


Fig. S5 | Partial spearman correlation matrix between estimated world trophic indicators and abiotic factors by excluding the effect of species richness. We added to this figure the spearman correlation between species richness and other indicators. The red colour indicates a significant negative correlation, while blue colours indicate a significant positive correlation between two trophic indicators. The colour gradient (from red to blue) indicates the magnitude of the correlation. White colour means that the correlation between indicators is not significant according to the Spearman correlation statistical test. (SST: Sea Surface Temperature; SSS: Sea Surface Salinity; Primary productivity; Distance to land). The coastline was defined by using the Global Self-consistent, Hierarchical, High-resolution Geography Database (*51*).

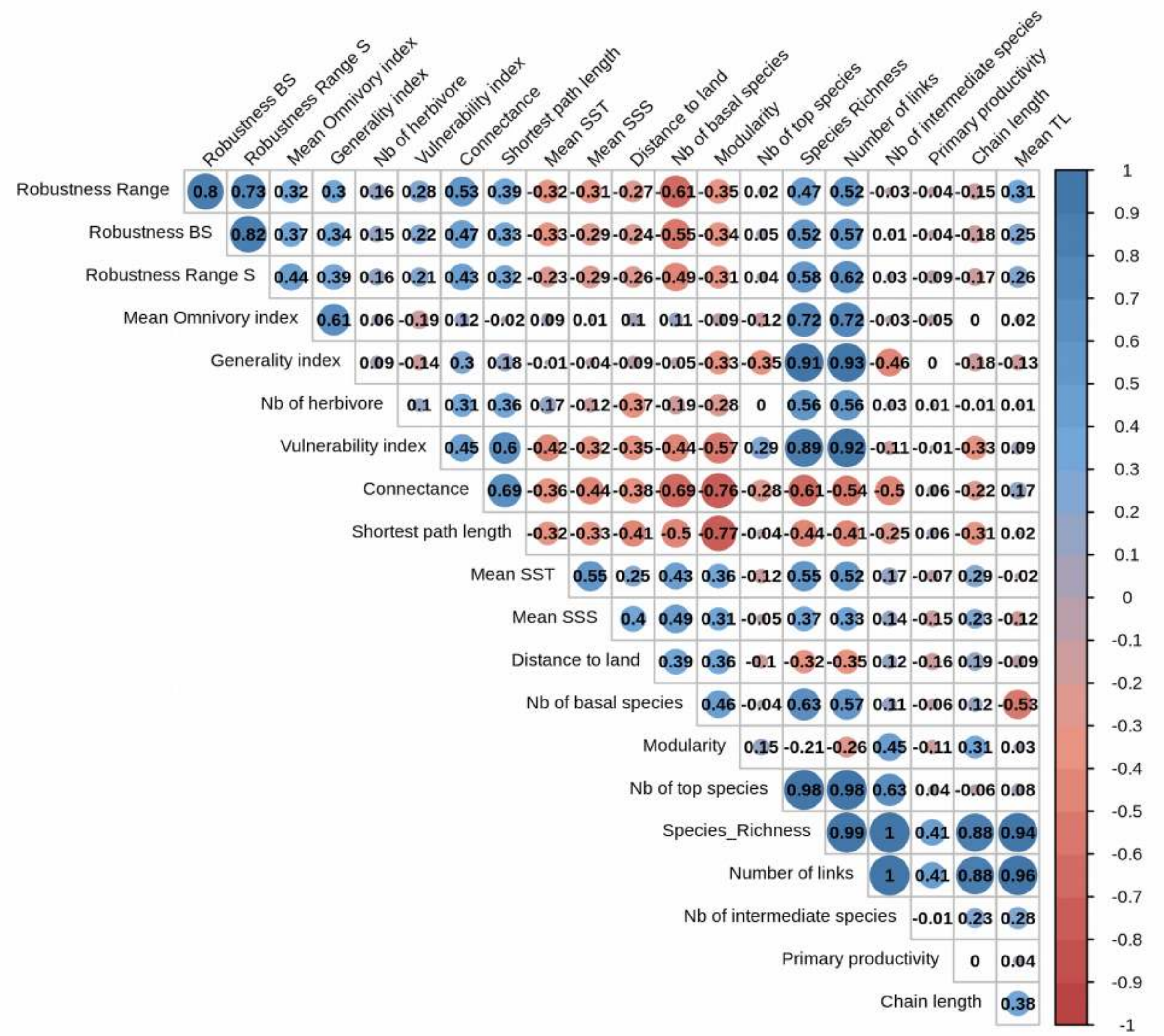


Fig. S6 | Spatial distribution of herbivorous species (a) on a 1° × 1° grid and (b) averaged across latitudes. The GAM models were fitted between the mean number of herbivorous species (b; adjusted R^2 = 0.85, edf =8.8), and latitude, within shaded grey the 95% confidence limits. The black bars on the chart represent the standard error of the mean. The coastline was defined by using the Global Self-consistent, Hierarchical, High-resolution Geography Database (*51*).

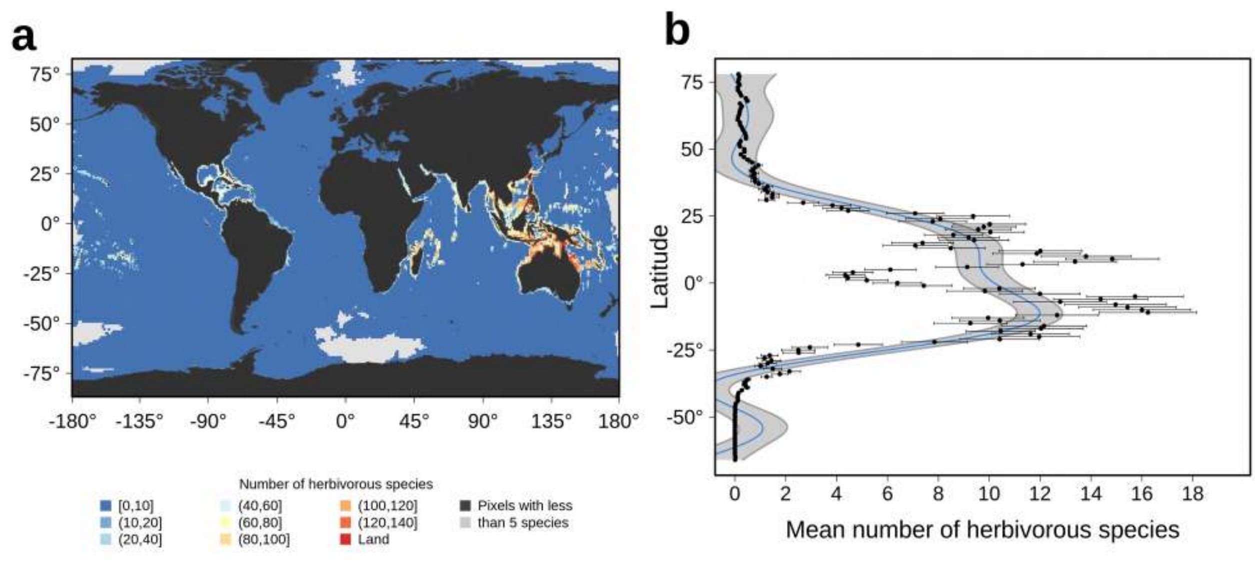


Fig. S7 | Map of local geometric mean body size (a) on a 1° × 1° grid and (b) averaged across latitudes. The GAM models were fitted between the mean number of herbivorous species (b; adjusted $R^2 = 0.96$, edf =8.9), and latitude, within shaded grey the 95% confidence limits. The black bars on the charts represent the standard error of the mean. The coastline was defined by using the Global Self-consistent, Hierarchical, High-resolution Geography Database (*51*).

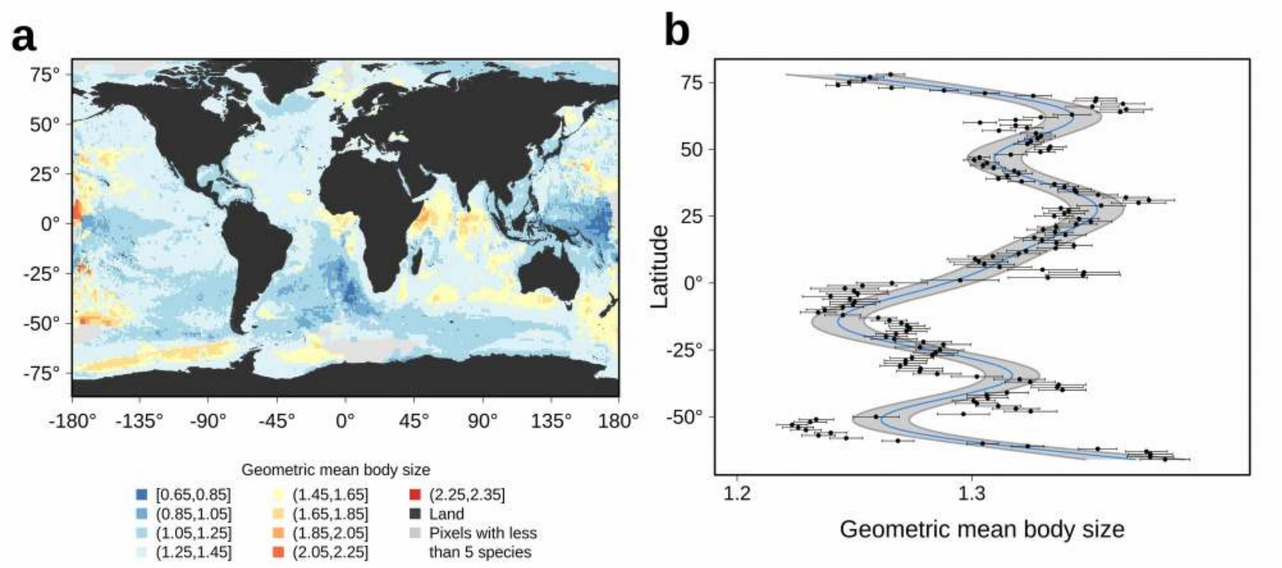


Fig. S8 | Spatial distribution of (a) the local food web robustness to random species extinctions and (b) its variance across the 99 scenarios. The coastline was defined by using the Global Self-consistent, Hierarchical, High-resolution Geography Database (*51*).

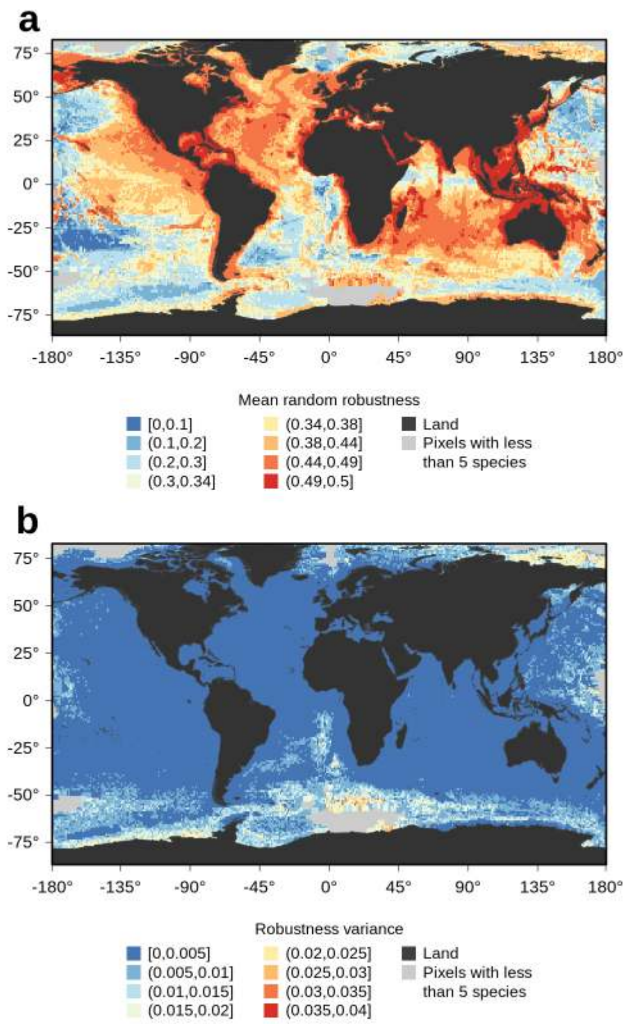


Fig. S9 | Representation of three different regression trees. (a) Relation between environmental factors (primary productivity, habitat, SST: sea surface temperature, salinity) and the robustness to species extinctions ordered by decreasing species body size. (b) Relation between environmental factors (primary productivity, distance from land, SST, salinity), species richness and the robustness to species extinctions ordered by decreasing species body size. The variable distance from land was transformed in a categorical variable, i.e. cells with a depth between 0-200m were identified as coastal while the others as open ocean. (c) Relation between internal structure networks indicators and the robustness to species extinctions ordered by decreasing species body size. (d) Relation between internal structure networks indicators, species richness and the robustness to species extinctions ordered by decreasing species body size. We substituted the number of links by the species richness because these variables are highly correlated.

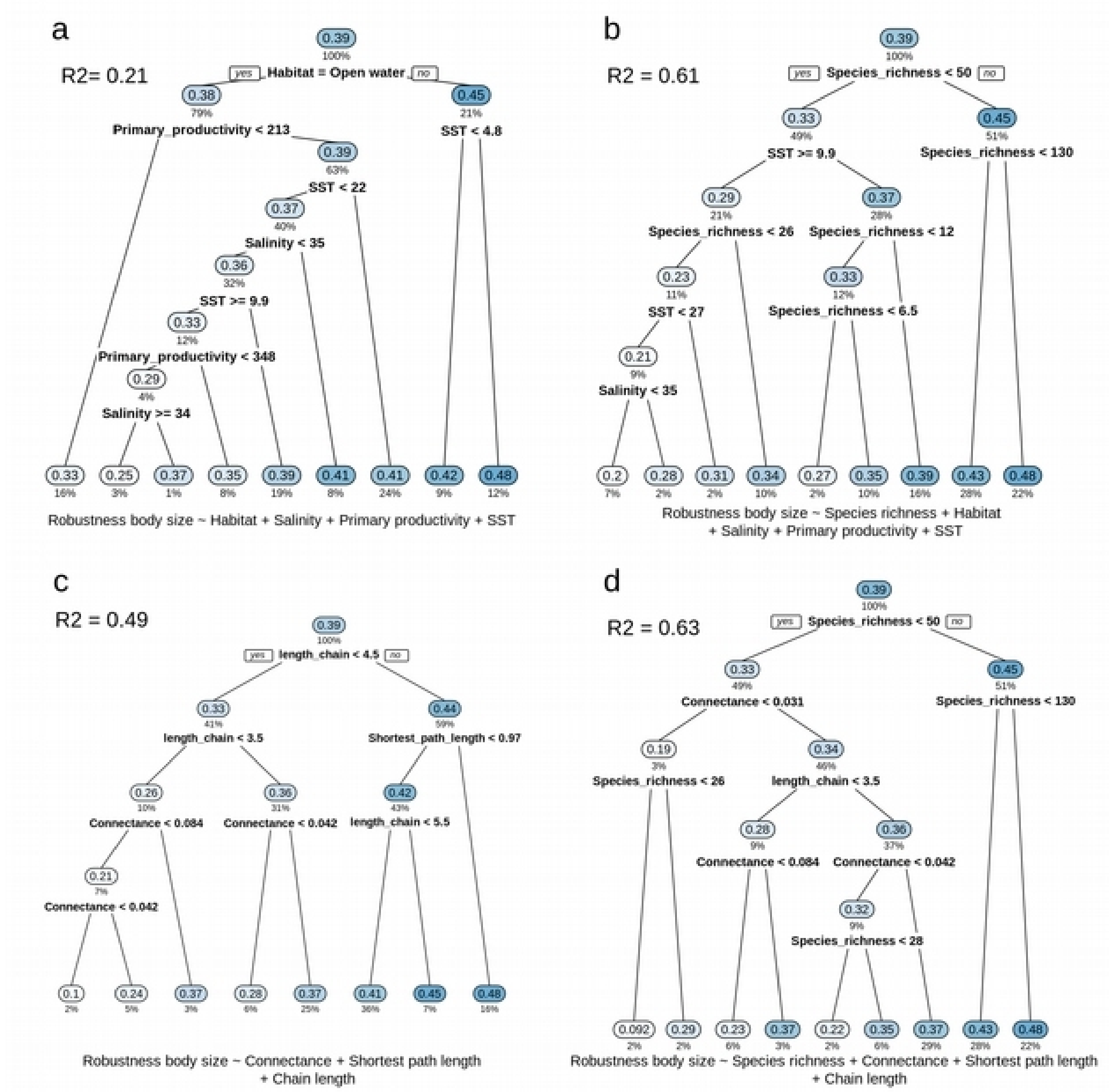
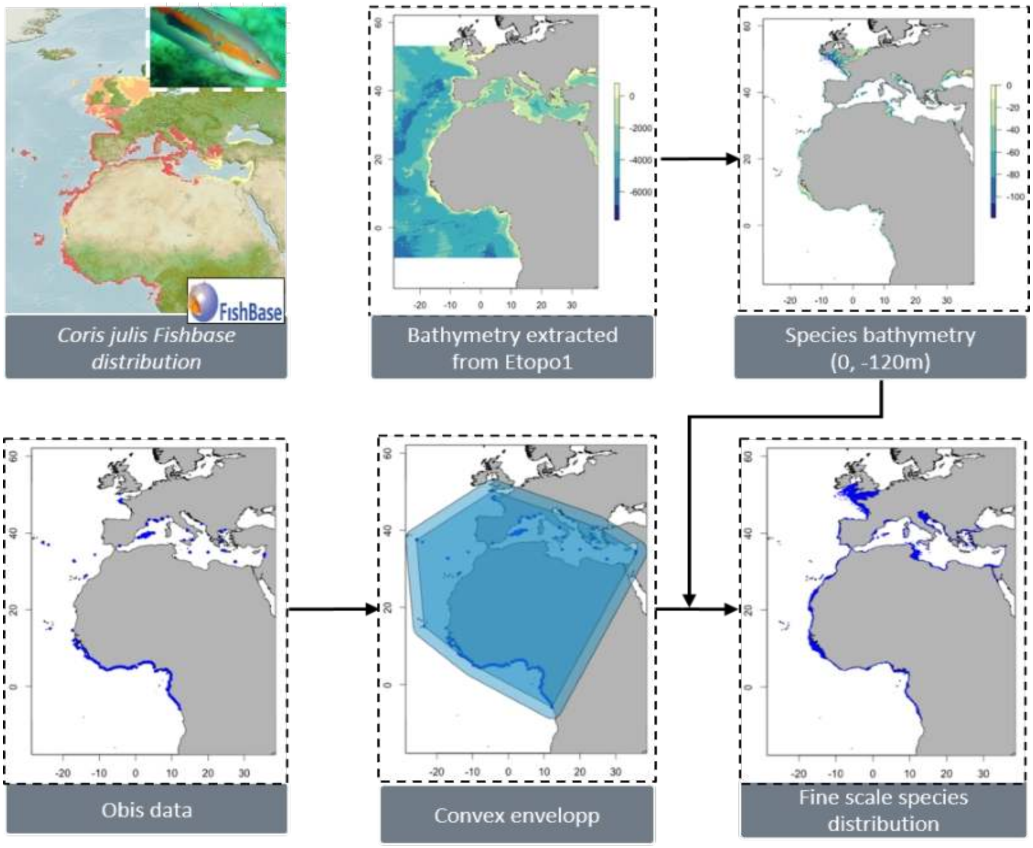


Fig S10 | Transformations conducted on the Ocean Biogeographic System OBIS data to obtain the fine scale species distribution. Here we use the distribution of the Mediterranean rainbow wrasse (*Coris julis*) as an example. Species data were obtained from the Ocean Biogeographic Information System (OBIS, http://www.iobis.org) on 08/27/2014. We reconstructed distribution maps for each species, defined as the convex polygon surrounding the area where each species was observed (see for details Fig. S3). The resulting polygon was divided into four parts across the world to integrate possible discontinuity between the two hemispheres and the Atlantic and Pacific Oceans. Then we refined each species distribution map by removing areas where maximal depths fell outside the minimum or maximum known depth range of the species (*1*). Bathymetry data were taken from ETOPO1 *(2)*. Finally, we aggregated fish distributions on a 1° resolution grid covering all oceans. All the data are freely available at https://figshare.com/s/c9ca229cc1f3548f8b5c. The coastline was defined by using the Global Self-consistent, Hierarchical, High-resolution Geography Database (*51*).



1. Froese, R. & Pauly., D. Fishbase. FishBase World Wide Web electronic publication (2015). Available at: www.fishbase.org.
2. Amante, C. and B.W. Eakins. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA. (2009).

Table S1. Information on the 56 biogeochemical provinces (*39*).

Province numbers	Province codes	Short provinces description	Climatic biomes
1	BPLR	Polar - Boreal Polar Province (POLR)	Polar
2	ARCT	Polar - Atlantic Arctic Province	Polar
3	SARC	Polar - Atlantic Subarctic Province	Polar
4	NADR	Westerlies - N. Atlantic Drift Province (WWDR)	Temperate
5	GFST	Westerlies - Gulf Stream Province	Subtropical
6	NASTW	Westerlies - N. Atlantic Subtropical Gyral Province (West) (STGW)	Subtropical
7	NATR	Trades - N. Atlantic Tropical Gyral Province (TRPG)	Tropical
8	WTRA	Trades - Western Tropical Atlantic Province	Equatorial
9	ETRA	Trades - Eastern Tropical Atlantic Province	Equatorial
10	SATL	Trades - South Atlantic Gyral Province (SATG)	Tropical
11	NECS	Coastal - NE Atlantic Shelves Province	Temperate
12	CNRY	Coastal - Canary Coastal Province (EACB)	Equatorial
13	GUIN	Coastal - Guinea Current Coastal Province	Tropical
14	GUIA	Coastal - Guianas Coastal Province	Equatorial
15	NWCS	Coastal - NW Atlantic Shelves Province	Temperate
16	MEDI	Westerlies - Mediterranean Sea, Black Sea Province	Subtropical
17	CARB	Trades - Caribbean Province	Tropical
18	NASTE	Westerlies - N. Atlantic Subtropical Gyral Province (East) (STGE)	Subtropical
19	BRAZ	Coastal - Brazil Current Coastal Province	Tropical
20	FKLD	Coastal - SW Atlantic Shelves Province	Temperate
21	BENG	Coastal - Benguela Current Coastal Province	Subtropical
22	MONS	Trades - Indian Monsoon Gyres Province	Tropical
23	ISSG	Trades - Indian S. Subtropical Gyre Province	Subtropical
24	EAFR	Coastal - E. Africa Coastal Province	Tropical
25	REDS	Coastal - Red Sea, Persian Gulf Province	Tropical
26	ARAB	Coastal - NW Arabian Upwelling Province	Tropical
27	INDE	Coastal - E. India Coastal Province	Tropical
28	INDW	Coastal - W. India Coastal Province	Tropical
29	AUSW	Coastal - Australia-Indonesia Coastal Province	Subtropical
30	BERS	Polar - N. Pacific Epicontinental Province	Polar
31	PSAE	Westerlies - Pacific Subarctic Gyres Province (East)	Temperate
32	PSAW	Westerlies - Pacific Subarctic Gyres Province (West)	Temperate
33	KURO	Westerlies - Kuroshio Current Province	Subtropical
34	NPPF	Westerlies - N. Pacific Polar Front Province	Subtropical
35	NPSW	Westerlies - N. Pacific Subtropical Gyre Province (West)	Tropical
36	TASM	Westerlies - Tasman Sea Province	Temperate
37	SPSG	Westerlies - S. Pacific Subtropical Gyre Province	Subtropical
38	NPTG	Trades - N. Pacific Tropical Gyre Province	Tropical
39	PNEC	Trades - N. Pacific Equatorial Countercurrent Province	Equatorial
40	PEQD	Trades - Pacific Equatorial Divergence Province	Equatorial
41	WARM	Trades - W. Pacific Warm Pool Province	Equatorial
42	ARCH	Trades - Archipelagic Deep Basins Province	Equatorial

43	ALSK	Coastal - Alaska Downwelling Coastal Province	Temperate
44	CCAL	Coastal - California Upwelling Coastal Province	Subtropical
45	CAMR	Coastal - Central American Coastal Province	Equatorial
46	CHIL	Coastal - Chile-Peru Current Coastal Province	Tropical
47	CHIN	Coastal - China Sea Coastal Province	Subtropical
48	SUND	Coastal - Sunda-Arafura Shelves Province	Equatorial
49	AUSE	Coastal - East Australian Coastal Province	Subtropical
50	NEWZ	Coastal - New Zealand Coastal Province	Temperate
51	SSTC	Westerlies - S. Subtropical Convergence Province	Subtropical
52	SANT	Westerlies - Subantarctic Province	Polar
53	ANTA	Polar - Antarctic Province	Polar
54	APLR	Polar - Austral Polar Province	Polar
55	NPSE	Northeast Pacific subtropical	Subtropical
56	OCAL	California current	Subtropical

Table S2 | Environmental variable descriptions

Layers	Description	Unit	Type	Spatial Resolution	Temporal Range	Derivatives	Source	Primary Data Source	URL
Land distance	Distance (km) to the nearest land cell (water cells only) calculated using Euclidean distance formula using ArcGIS. Values represented in floating point integer.	km	-	5 arcmin	-	-	-	-	http://gmed.auckland.ac.nz/layersd.html
Temperature	Sea surface temperature is the temperature of the water at the ocean surface. This parameter indicates the temperature of the topmost meter of the ocean water column.	°C	Monthly climatolog y	5 arcmin (9.2 km)	2002 - 2009	Mean	Bio-Oracle	1	http://oceancolor.gsfc.nasa.gov/
Salinity	Salinity indicates the dissolved salt content in the ocean surface.	PSS	In situ measure: WOD 2009	1°×1°	1961-2009	Mean	Bio-Oracle	2	http://www.nodc.noaa.gov/
Primary productivity	Proportion of annual primary production in a cell. See reference for details about the productivity calculation methods.	$mgC \cdot m^{-2} \cdot$/ day/ cell	Annual climatolog y	5 arcmin (9 km)	-	Mean	Aquamaps HCAF v4	3, 4, 5	http://www.aquamaps.org/download/main.php and http://www.seaaroundus.org/doc/saup_manual.htm#3

1. Feldman, G.C., C.R. McClain, N. Kuring (ed.), S.W. Bailey (ed.). 2006. Sea-viewing Wide Field-of-View Sensor (SeaWIFS) Level-3 Standard Mapped Images: Chlorophyll-a Mean Concentration Annual and Seasonal Climatologies. NASA Goddard Space Flight Center
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3. Bouvet, M., Hoepffner, N. & Dowell, M. D. Parameterization of a spectral solar irradiance model for the global ocean using multiple satellite sensors. *J. Geophys. Res. Ocean.* **107,** 8-1-8–18 (2002).
4. Hoepffner, N., Sturm, B., Finenko, Z. & Larkin, D. Depth-integrated primary production in the eastern tropical and subtropical North Atlantic basin from ocean colour imagery. *Int. J. Remote Sens.* **20,** 1435–1456 (1999).
5. Longhurst, A., Sathyendranath, S., Platt, T. & Caverhill, C. An estimate of global primary production in the ocean from satellite radiometer data. *J. Plankton Res.* **17,** 1245–1271 (1995).

Table S3.Spearman correlations between the four sequential removal scenarios. The body size scenario corresponds to the removing of species by decreasing species body size. The largest range size scenario corresponds to species extinctions ordered by decreasing species range size. The smallest range size scenario corresponds to species extinctions ordered by increasing species range size. The random scenario was obtained by removing the species randomly (99 random deletion sequences initiated for each web). All correlations were significant ($P < 0.001$).

	Body size scenario	Largest range size scenario	Smallest range size scenario	Random scenario
Body size scenario	1	0.86	0.88	0.88
Largest range size scenario	0.86	1	0.82	0.86
Smallest range size scenario	0.88	0.82	1	0.93
Random scenario	0.88	0.86	0.93	1

Table S4 | Wilcoxon rank tests performed between mean coastal and open water indicators. Values for robustness referred to the sequential removal scenario of the largest-bodied size species (Rob BS), the smallest-bodied size species (Rob Range small) and the species with the largest range (Rob Range). SST referred to the Sea Surface Temperature and the SSS referred to the Sea Surface Salinity.

Indicators	**Coastal Mean**	**Coastal sd**	**Open water Mean**	**Open water sd**	***p-value***
Rob BS	0.45	0.06	0.38	0.1	< 0.001
Rob Range	0.46	0.06	0.38	0.1	< 0.001
Rob Range small	0.46	0.06	0.38	0.11	< 0.001
Species richness	366.95	499.35	66.10	120.11	< 0.001
Path length	4.97	0.92	4.22	1.15	< 0.001
Number of links	21,404.58	48,048.7	824	5910.34	< 0.001
Connectance	0.06	0.03	0.09	0.13	< 0.001
Modularity	0.13	0.12	0.28	0.11	< 0.001
Omnivory index	0.17	0.08	0.16	0.08	< 0.001
Generality	20.05	29.09	3.34	5.43	< 0.001
Primary productivity	545.35	426.79	314.79	166.74	< 0.001
SST	11.7	11.91	14.1	10.83	< 0.001
SSS	32	4.36	34	1.65	< 0.001

Table S5 | Results of generalized linear models with a Gaussian distribution for continuous explicated variables and quasi-Poisson distribution for discretionary explicated variables. We included as predictors the coastal or open ocean factor and the species richness. The sign of the t-statistic indicate which mean is greater (open water versus coastal) and the p-value of the factor terms indicate if the difference is significative accounting for the species richness. Finaly, we performed a Moran's I test on the residual of the glm model to test the spatial autocorrelation.

Connectance			**Generality**		
	Estimate	t value		Estimate	t value
Intercept	0.083	53.02***	Intercept	1.66	231.81***
Open ocean	0.018	11.41***	Open ocean	-0.62	-78.07***
Species richness	-6.07e-05	-26.03***	Species richness	0.0019	359.89***
	Expected	Observed		Expected	Observed
Moran's I	-2.32e-05	0.15***	Moran's I	-2.32e-05	0.079***
Link			**Modularity**		
	Estimate	t value		Estimate	t value
Intercept	7.65	696.02***	Intercept	0.19	134.10***
Open ocean	-1.23	-86.37***	Open ocean	0.10	68.73***
Species richness	0.0026	384.57***	Species richness	-0.00016	-75.01***
	Expected	Observed		Expected	Observed
Moran's I	-2.32e-05	0.066***	Moran's I	-2.32e-05	0.078***
Omnivory index			**Path length**		
	Estimate	t value		Estimate	t value
Intercept	-2.04	-315***	Intercept	1.45	467.65***
Open ocean	0.17	25.29***	Open ocean	-0.038	-11.75***
Species richness	0.00065	90.14***	Species richness	0.00036	92.07***
	Expected	Observed		Expected	Observed
Moran's I	-2.32e-05	0.12***	Moran's I	-2.32e-05	0.14***
Robustness body size			**Robustness range**		
	Estimate	t value		Estimate	t value
Intercept	0.41	330.85***	Intercept	0.42	342***
Open ocean	-0.04	-31.16***	Open ocean	-0.047	-36.76***
Species richness	0.0001	55.41***	Species richness	9.87e-05	53.27***
	Expected	Observed		Expected	Observed
Moran's I	-2.49e-05	0.11***	Moran's I	-2.49e-05	0.10***
Robustness small range					
	Estimate	t value			
Intercept	0.41	314.97***			
Open ocean	-0.045	-33.43***			
Species richness	0.00012	58.56***			
	Expected	Observed			
Moran's I	-2.49e-05	0.12***			