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Supplementary information

Protecting the global ocean for biodiversity, food and climate

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Protecting the global ocean for biodiversity, food and climate

Supplementary Information

Enric Sala, Juan Mayorga, Darcy Bradley, Reniel B. Cabral, Trisha B. Atwood, Arnaud Auber, William Cheung, Christopher Costello, Francesco Ferretti, Alan M. Friedlander, Steven D. Gaines, Cristina Garilao, Whitney Goodell, Benjamin S. Halpern, Kristin Kaschner, Kathleen Kesner-Reyes, Fabien Leprieur, Jennifer McGowan, Lance E. Morgan, David Mouillot, Juliano Palacios-Abrantes, Hugh P. Possingham, Kristin D. Rechberger, Boris Worm, Jane Lubchenco

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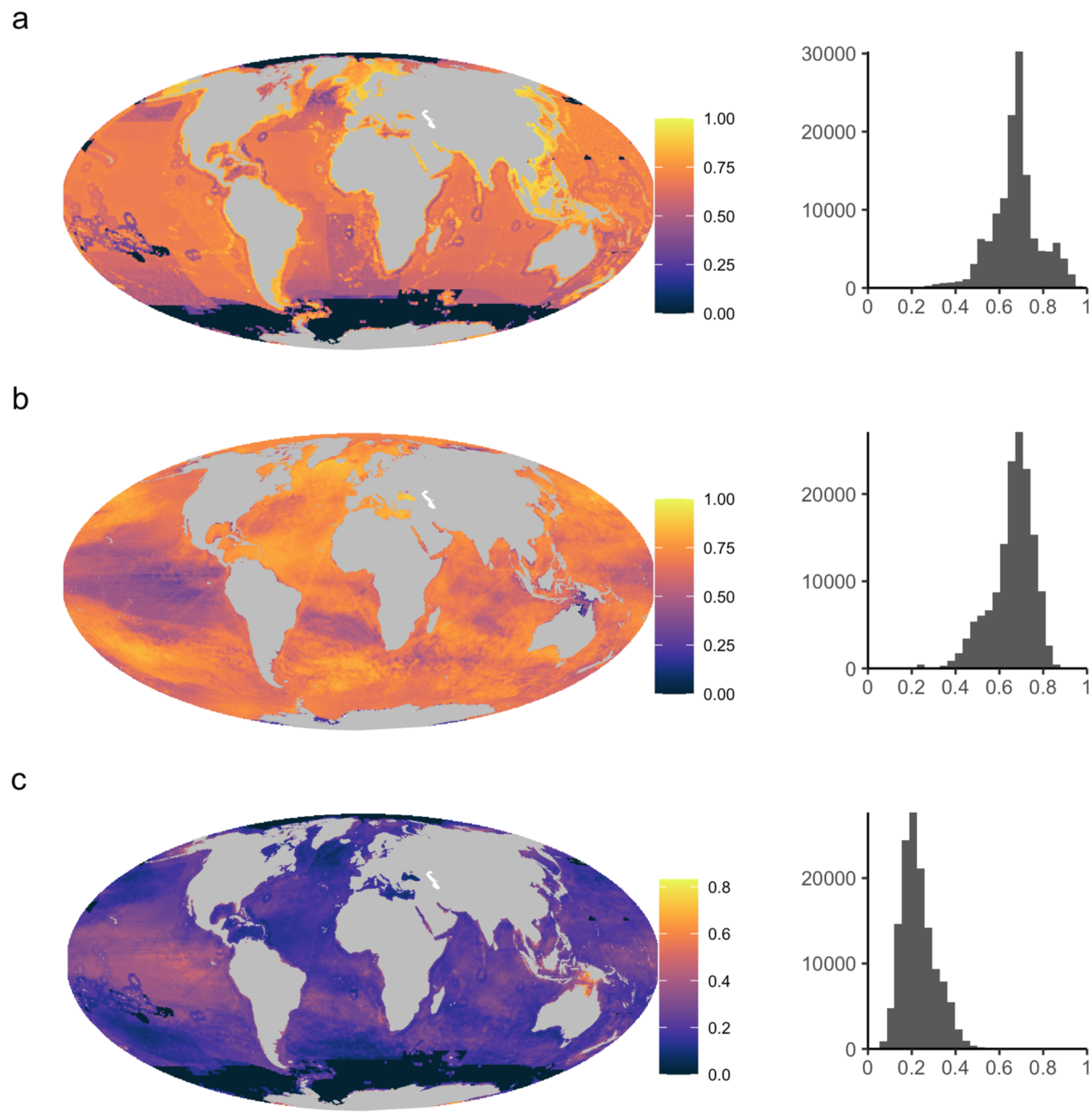
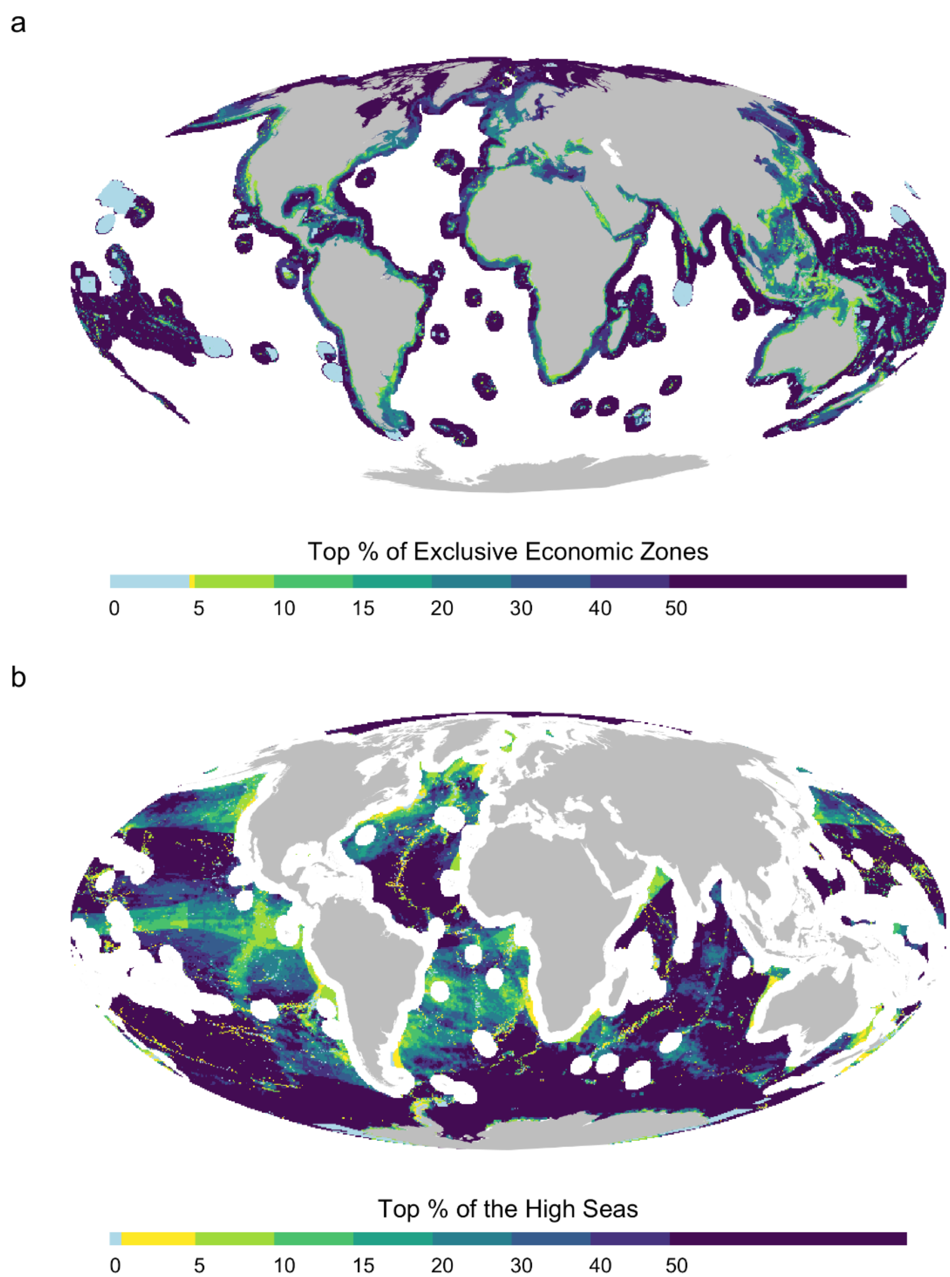


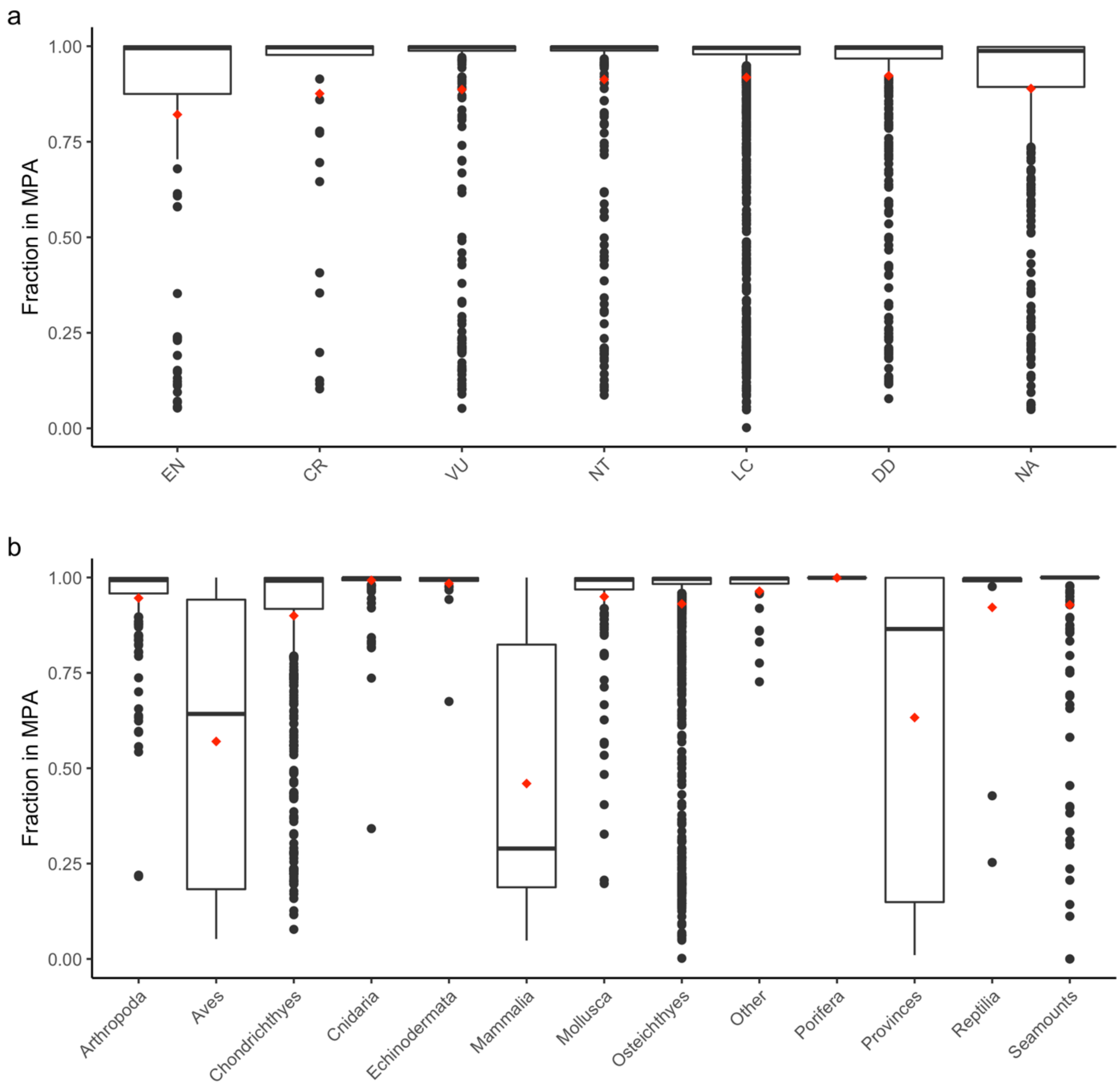
Supplementary Figure 1. Human impacts on marine biodiversity.

Values correspond to the relative fraction of the suitable habitat in a pixel that is at risk of being lost as a result of a) abatable and b) un-abatable impacts. Abatable impacts include artisanal fishing and commercial fishing classified in: pelagic high-bycatch, pelagic low-bycatch, demersal destructive, demersal non-destructive high bycatch, and demersal non-destructive low bycatch1. Un-abatable impacts by MPAs include sea surface temperature, light pollution, organic and nutrient pollution, ocean acidification, shipping, and sea-level rise. Panel c represents the difference made by protection expressed as a fraction of current habitat suitability. Areas in darker yellow represent places where abatable impacts are relatively high and un-abatable impacts are relatively low, making them attractive for MPAs.



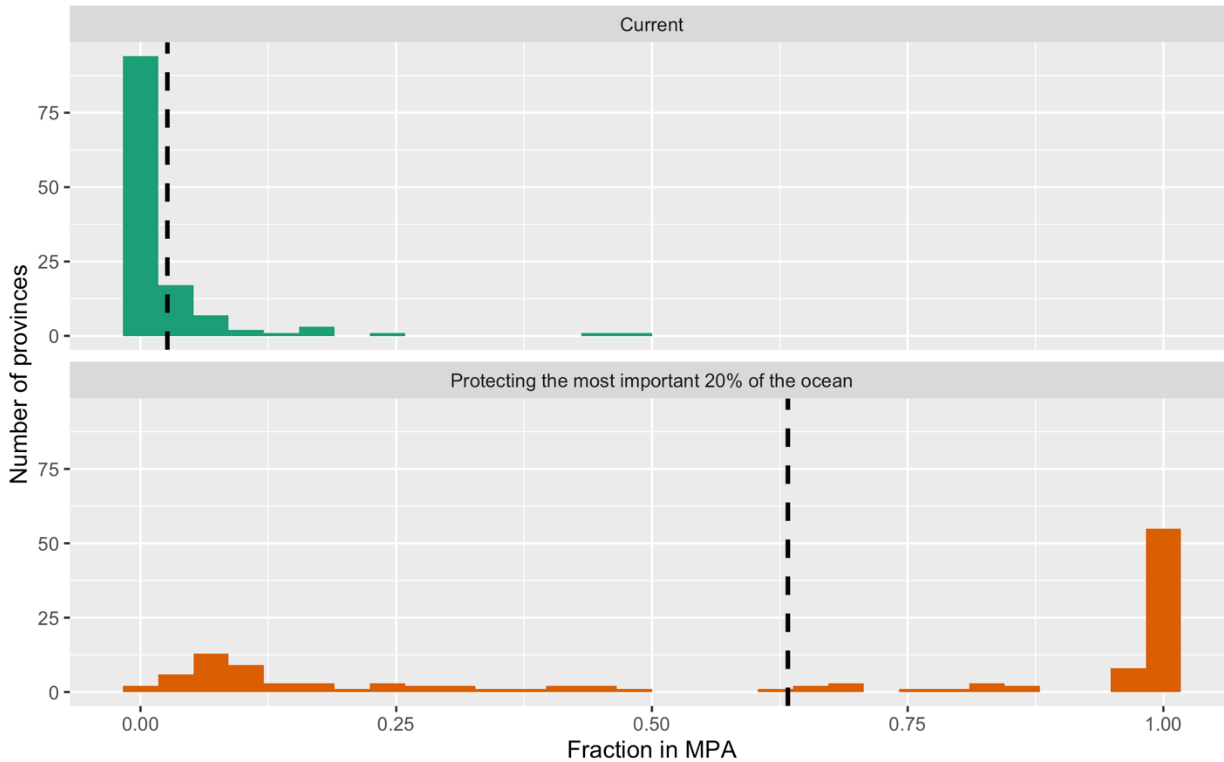
Supplementary Figure 2. Global biodiversity conservation priorities within Exclusive Economic Zones (a) and in the High Seas (b).

The values correspond to the global ranking (Fig. 1a) but are rescaled to represent the most important areas for the high seas and exclusive economic zones.



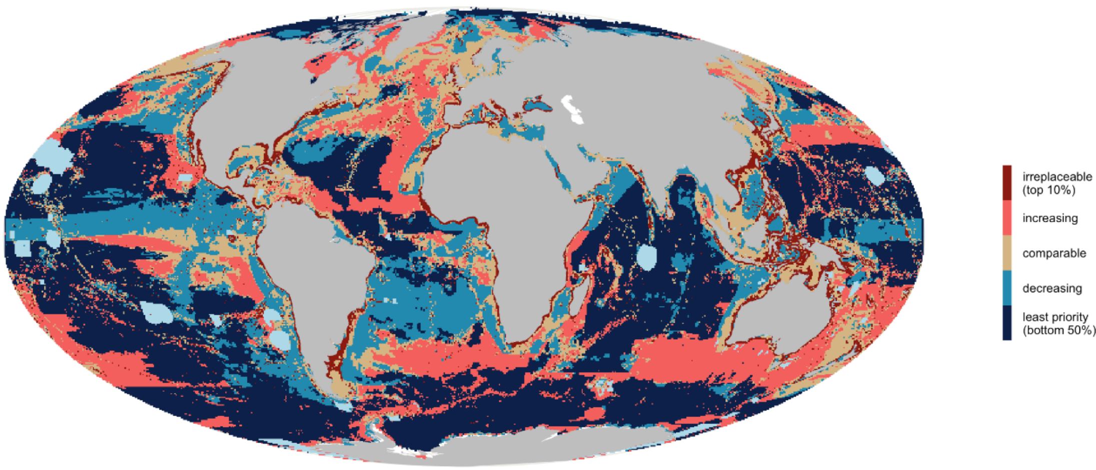
Supplementary Figure 3. Representation levels within the top 20% priority areas for biodiversity conservation

For species in each IUCN category (a) and per feature group (b). Red diamonds represent group means and cross bars correspond to group medians. EN: Endangered, CR: Critically Endangered, VU: Vulnerable, NT: Near Threatened, LC: Least Concern, DD: Data Deficient, NA: No data.



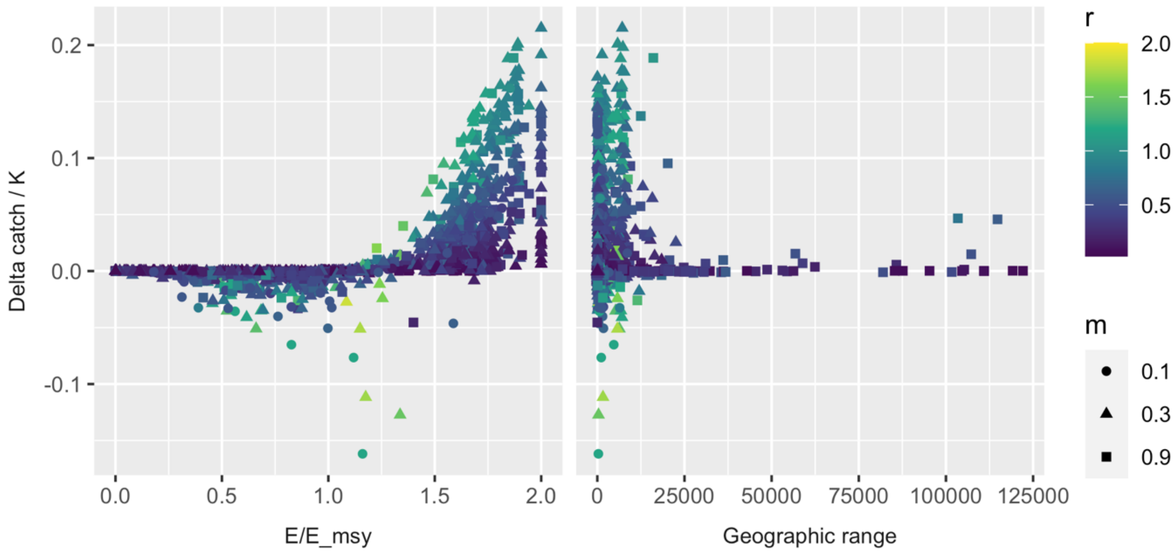
Supplementary Figure 4. Biogeographic representation in today's MPAs and within the top 20% priority areas for biodiversity conservation

Distributions of the current representation levels of pelagic, coastal, abyssal, and bathyal biogeographic provinces (green) and representation levels within the top 20% priority areas (orange). Vertical dashed lines represent group means.



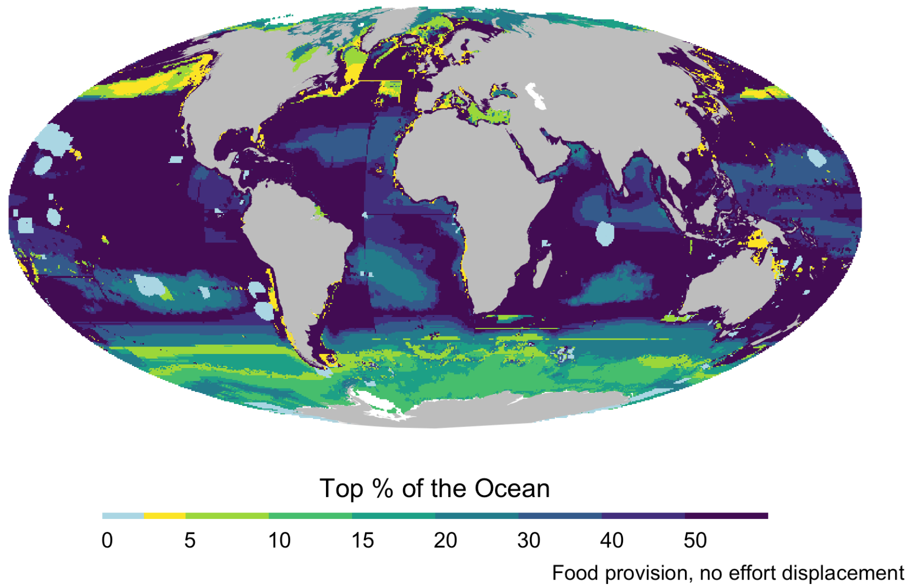
Supplementary Figure 5. Change in global biodiversity priorities in 2050

Changes in the global biodiversity conservation priorities as a result from planning for the future (2050, IPCC SRES A2 emissions scenario) compared to planning for today. "Irreplaceable" are areas in the top 10% priorities for biodiversity protection today and in 2050. "Comparable" are areas neither irreplaceable nor "least priority" (<5% difference in priority between now and 2050). Current protected areas shown in light blue.



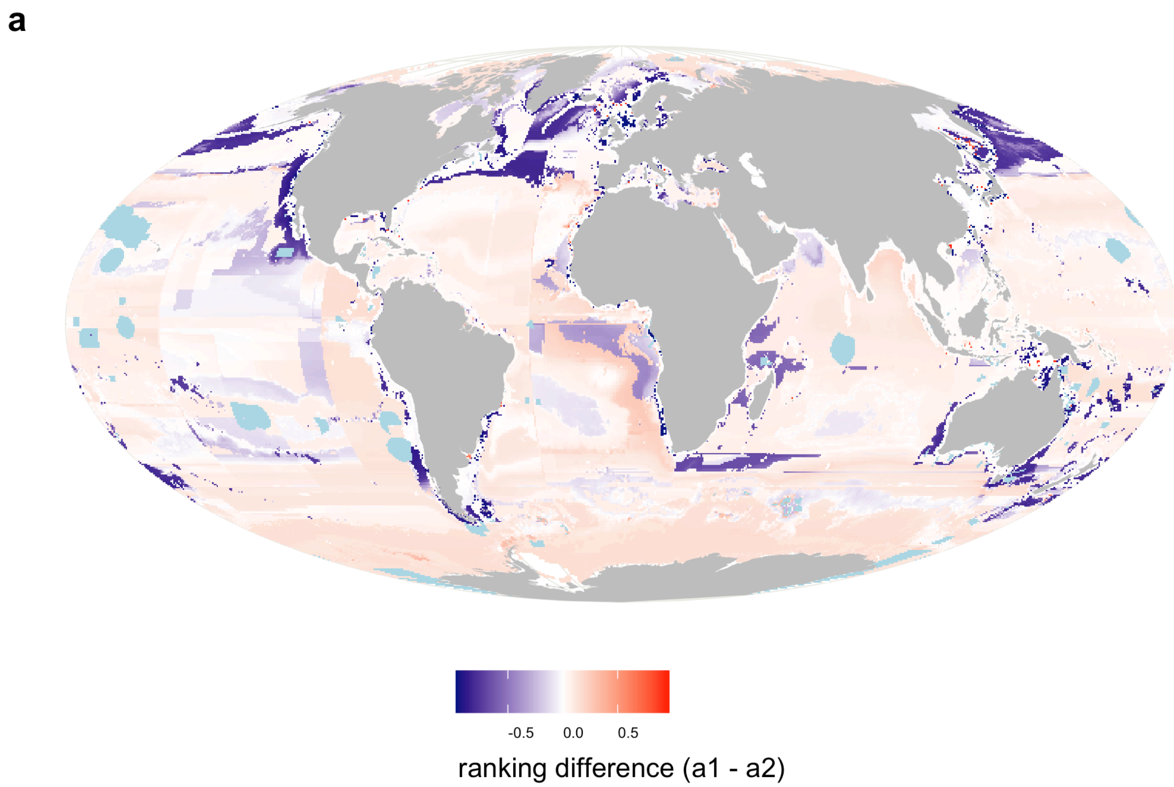
Supplementary Figure 6. Change in catch per stock at top 10% of ocean protected.

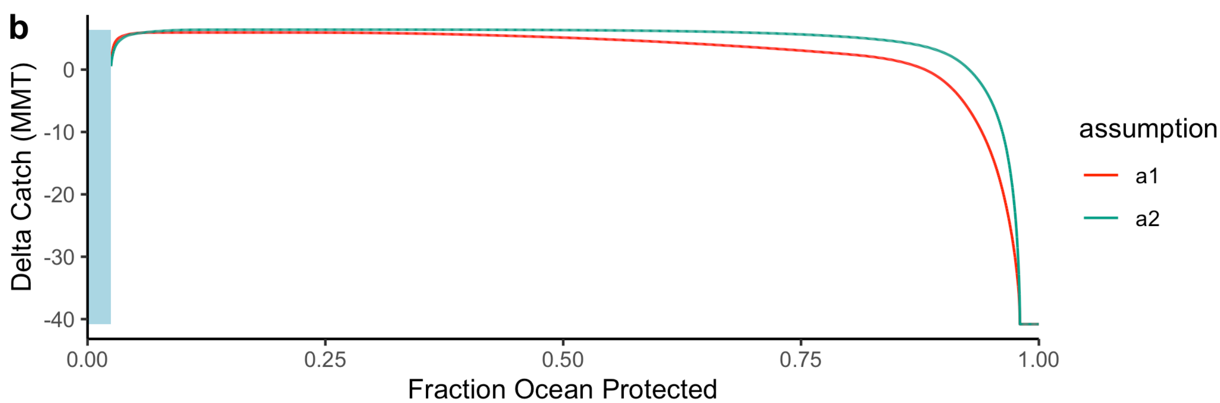
Each point corresponds to the change in catch per stock, normalized by carrying capacity, at the optimal 10% of the ocean protected. The results highlight that the food provisioning model prioritizes overexploited stocks ($E/E_{msy} > 1$; left panel) and those with relatively small range size (number of pixels, right panel).



Supplementary Figure 7. Global priorities for food provisioning under a no effort redistribution model.

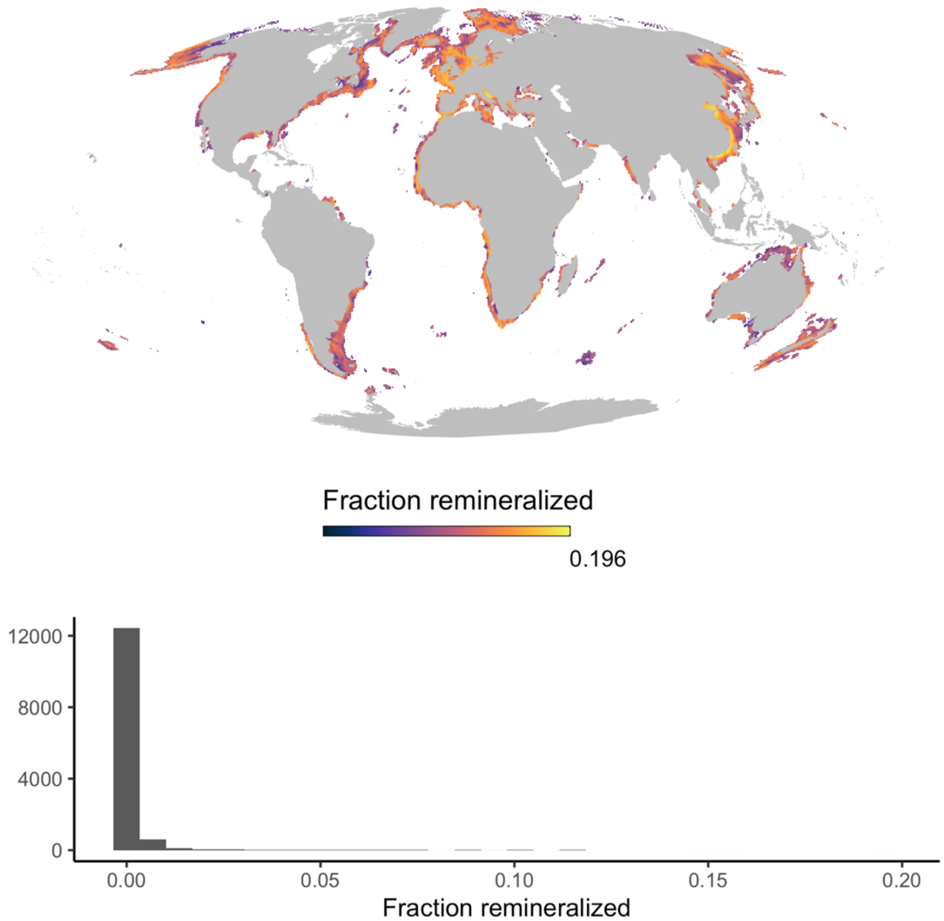
Optimal conservation strategy to maximize food provisioning benefits assuming that fishing effort inside MPAs vanishes after protection.





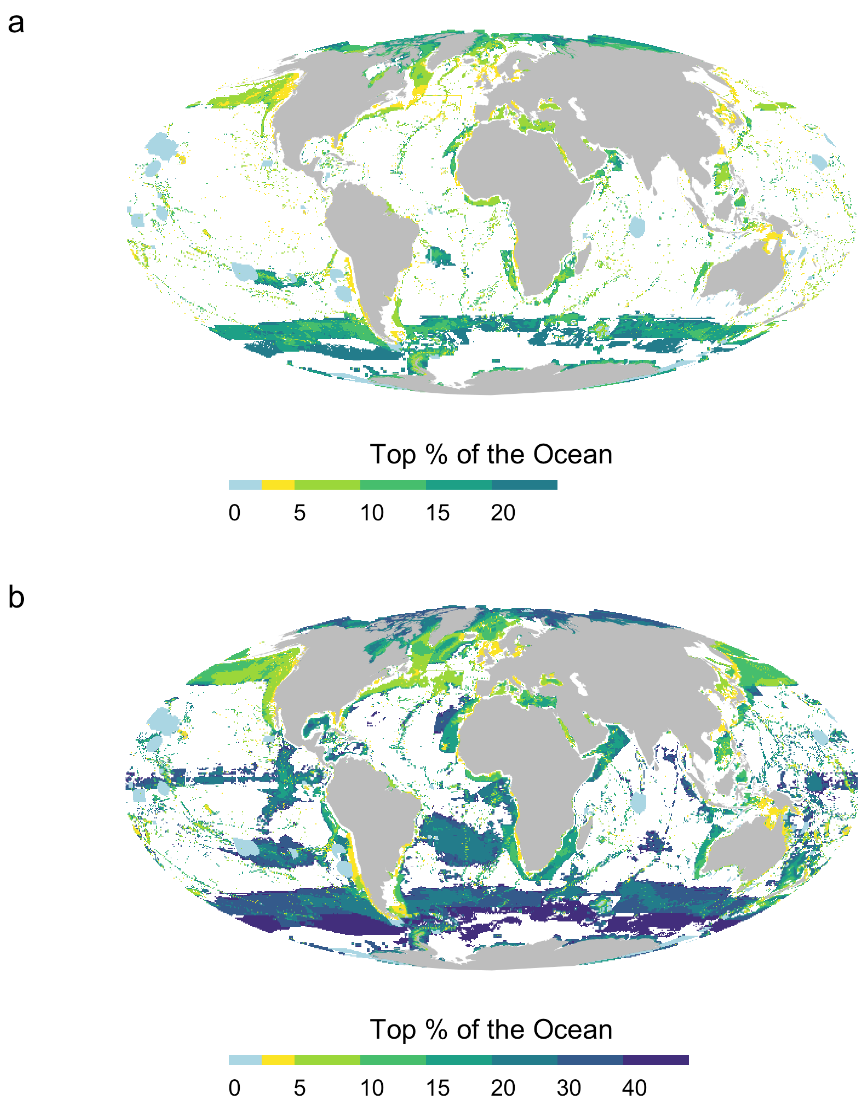
Supplementary Figure 8. Differences in global conservation priorities for food provisioning across alternative effort redistribution models.

Difference in ranking (a) between the no effort redistribution (a1) and the full effort redistribution models (a2). Blue areas would decrease in priority under the no effort redistribution model. Delta catch accumulation curves for each effort redistribution model (b). The blue bar denotes the current 2.5% of the global ocean in fully protected areas.



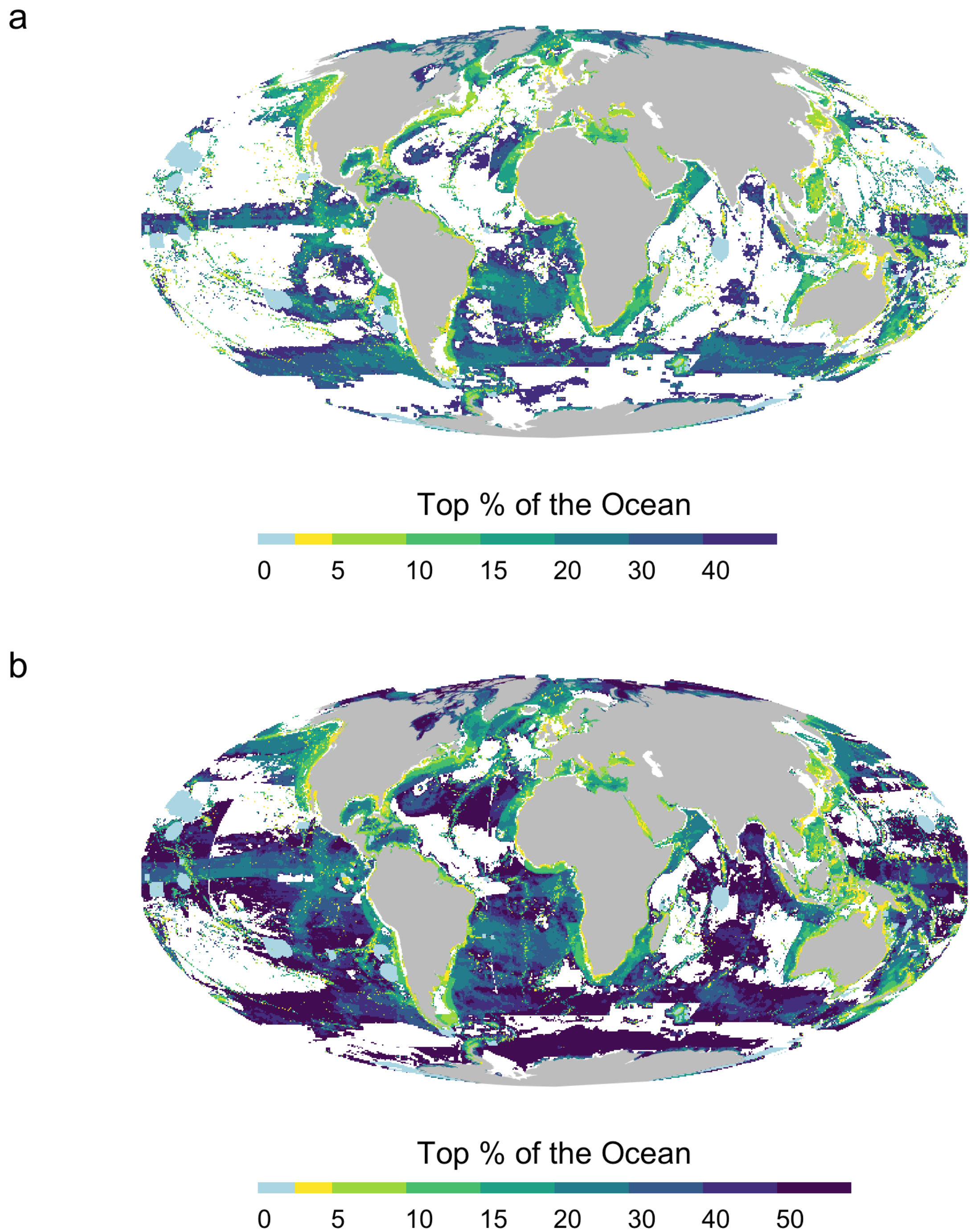
Supplementary Figure 9. Impacts to sedimentary carbon stocks

Values correspond to the fraction of the sedimentary carbon stock that is at risk of being lost in each pixel as a result of abatable impacts (i.e. bottom trawling). These areas represent places where MPAs can be most effective to minimize risk of sediment carbon disturbance. Color scale has been log-transformed for visualization purposes.



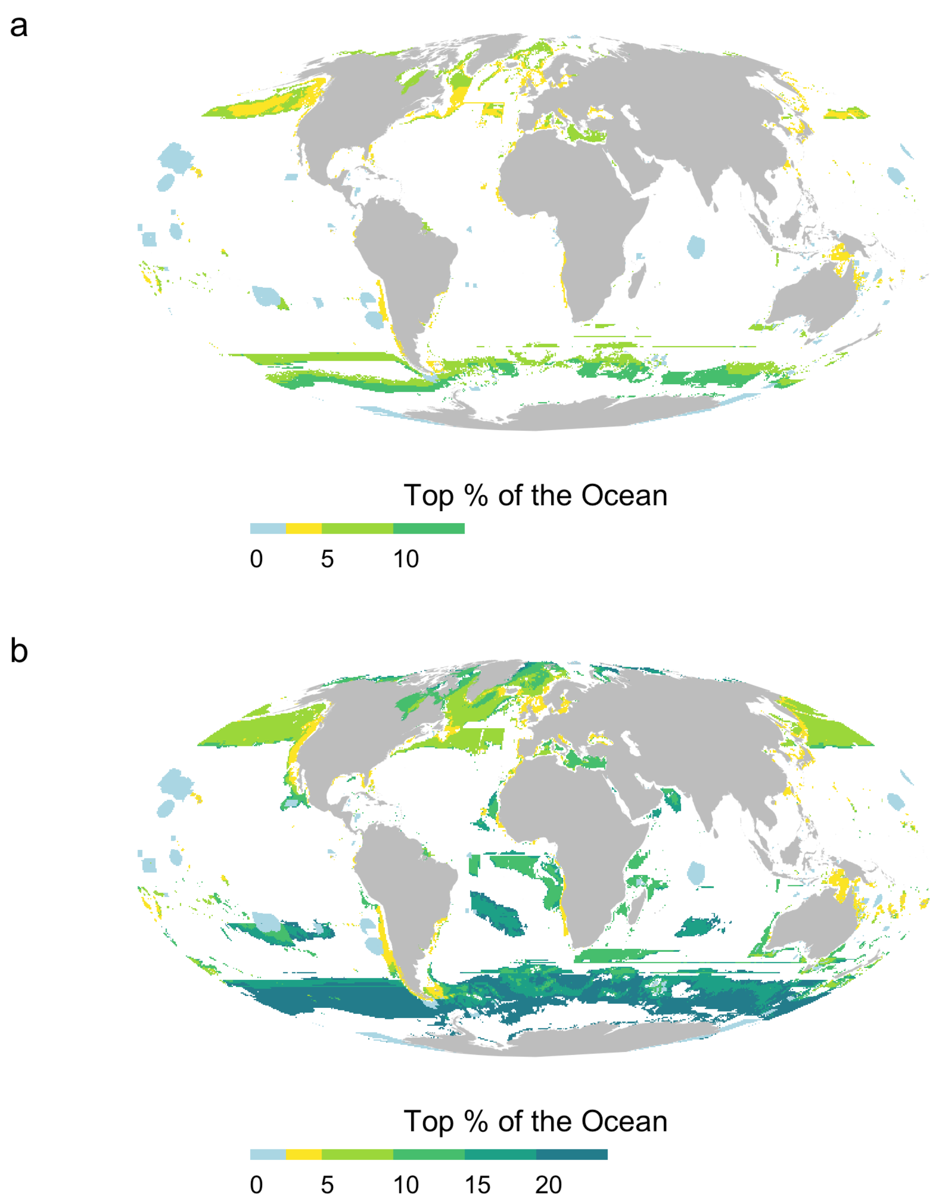
Supplementary Figure 10. Optimal conservation strategy from a multi-objective prioritization with equal preference for biodiversity and food provisioning.

Assuming fishing effort disappears (a), this strategy calls for protecting 24% of the ocean, achieving 57% of the biodiversity benefits, 20% of the carbon benefit, and 86% of the food benefits. Assuming full fishing effort redistribution (b), this strategy calls for protecting 45% of the ocean, achieving 71% of the biodiversity benefits, 29% of the carbon benefit and 92% of the food benefits. Existing highly and fully protected MPAs shown in light blue.



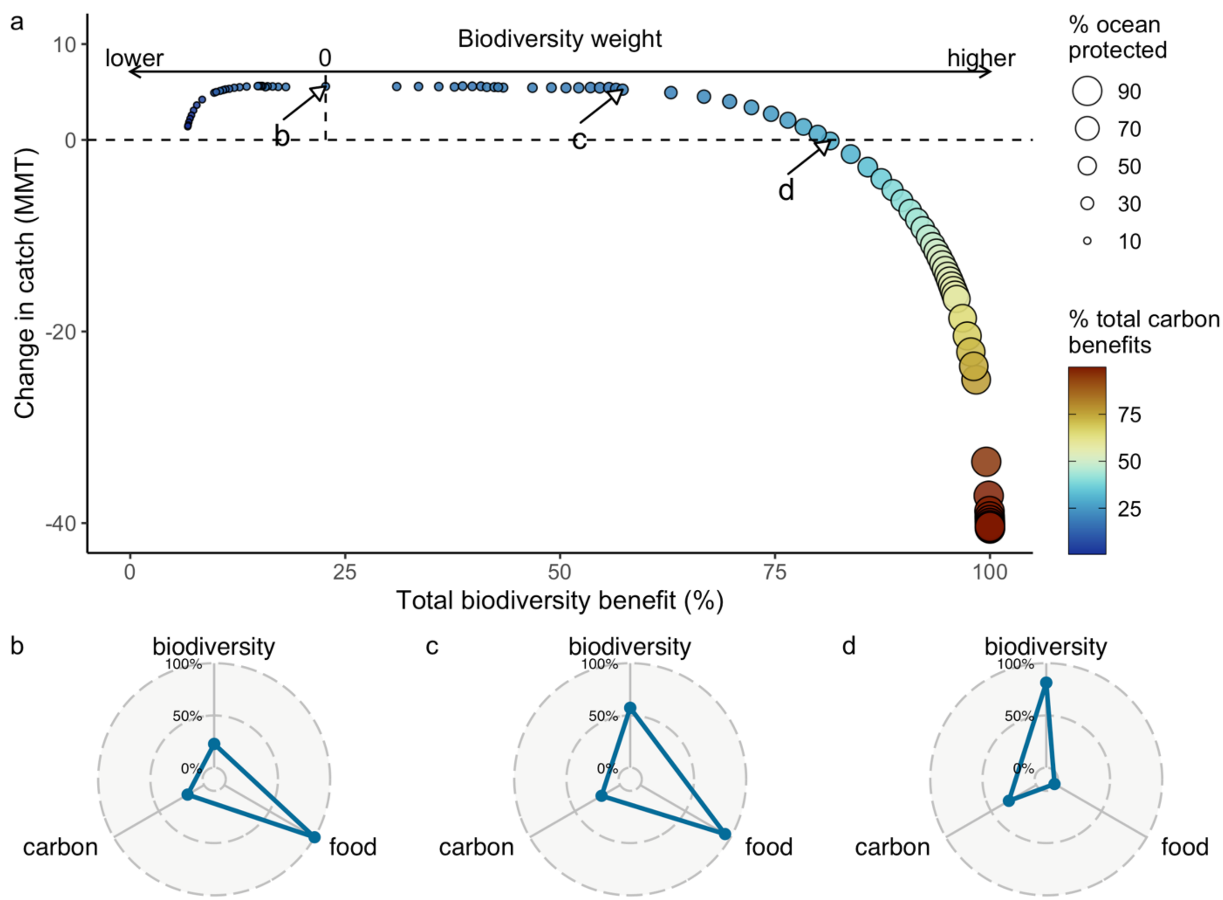
Supplementary Figure 11. Optimal conservation strategies with a strong preference for biodiversity.

Assuming fishing effort disappears (a), this strategy calls for protecting 48% of the ocean, achieving 81% of the biodiversity benefits and 30% of the carbon benefit with no change in future fish catch. Assuming full fishing effort redistribution (b), this strategy calls for protecting 71% of the ocean, achieving 91% of the biodiversity benefits and 48% of the carbon benefit with no change in future fish catch. Existing highly and fully protected MPAs shown in light blue.



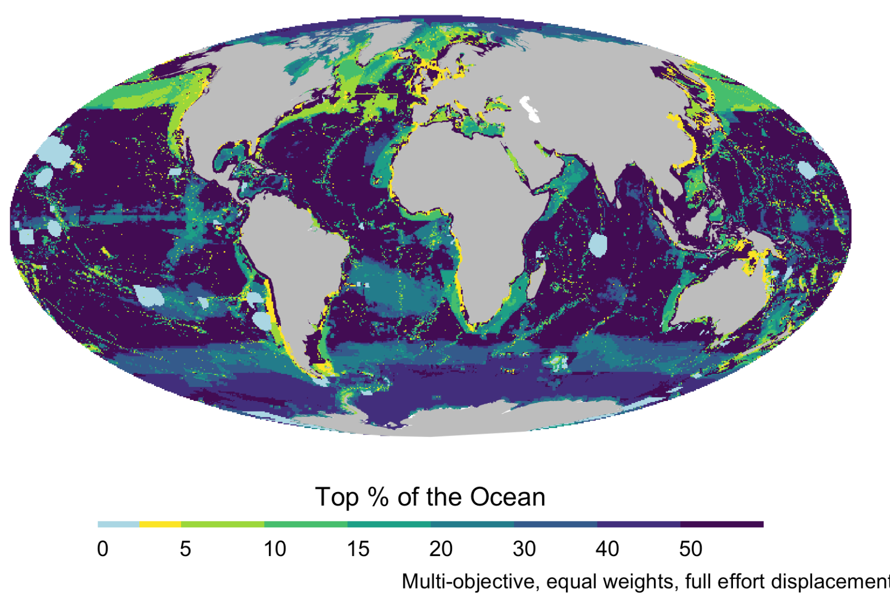
Supplementary Figure 12. Optimal conservation strategy from a multi-objective prioritization with zero weight placed on biodiversity

Assuming fishing effort disappears (a), this strategy calls for protecting 12% of the ocean, yielding maximum food provisioning benefits, 23% of the biodiversity benefits and 18% of the carbon benefit. Assuming full fishing effort redistribution (b), this strategy calls for protecting 28% of the ocean, yielding maximum food provisioning benefits, 35% of the biodiversity benefits and 27% of the carbon benefits. Existing highly and fully protected MPAs shown in light blue.



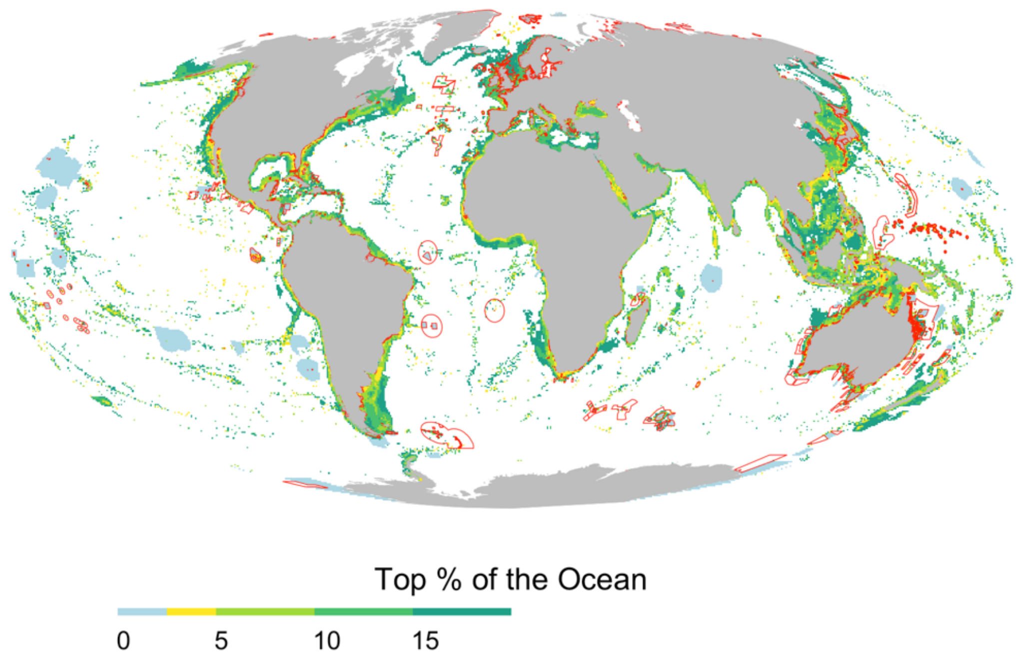
Supplementary Figure 13. Prioritizing multiple objectives assuming no fishing effort redistribution.

Each point represents the spatial configuration that maximizes the net benefits of protection for an assigned weight (i.e. preference) to biodiversity in a joint biodiversity-food provisioning prioritization, under the assumption that fishing effort on a stock from an area designated for protection disappears following protection (a). Carbon was treated as a co-benefit (weight = 0). Optimal conservation strategy if biodiversity is given a weight of zero (b). This scenario achieves 100% of the potential fisheries benefit by protecting the 12% top priority of the ocean and achieves 23% of biodiversity benefits, and 18% of carbon benefits. Optimal conservation strategy if biodiversity is given the same weight as food provisioning (c). This scenario protects 24% of the ocean, yielding 86% of the maximum food benefits, 57% of biodiversity benefits, and 20% of carbon benefits. Optimal conservation with strong biodiversity preference (10× food provisioning weight) (d). This scenario achieves 81% of the biodiversity benefit at the least cost to future fisheries yields and achieves 30% of the carbon benefit by protecting 48% of the global ocean.



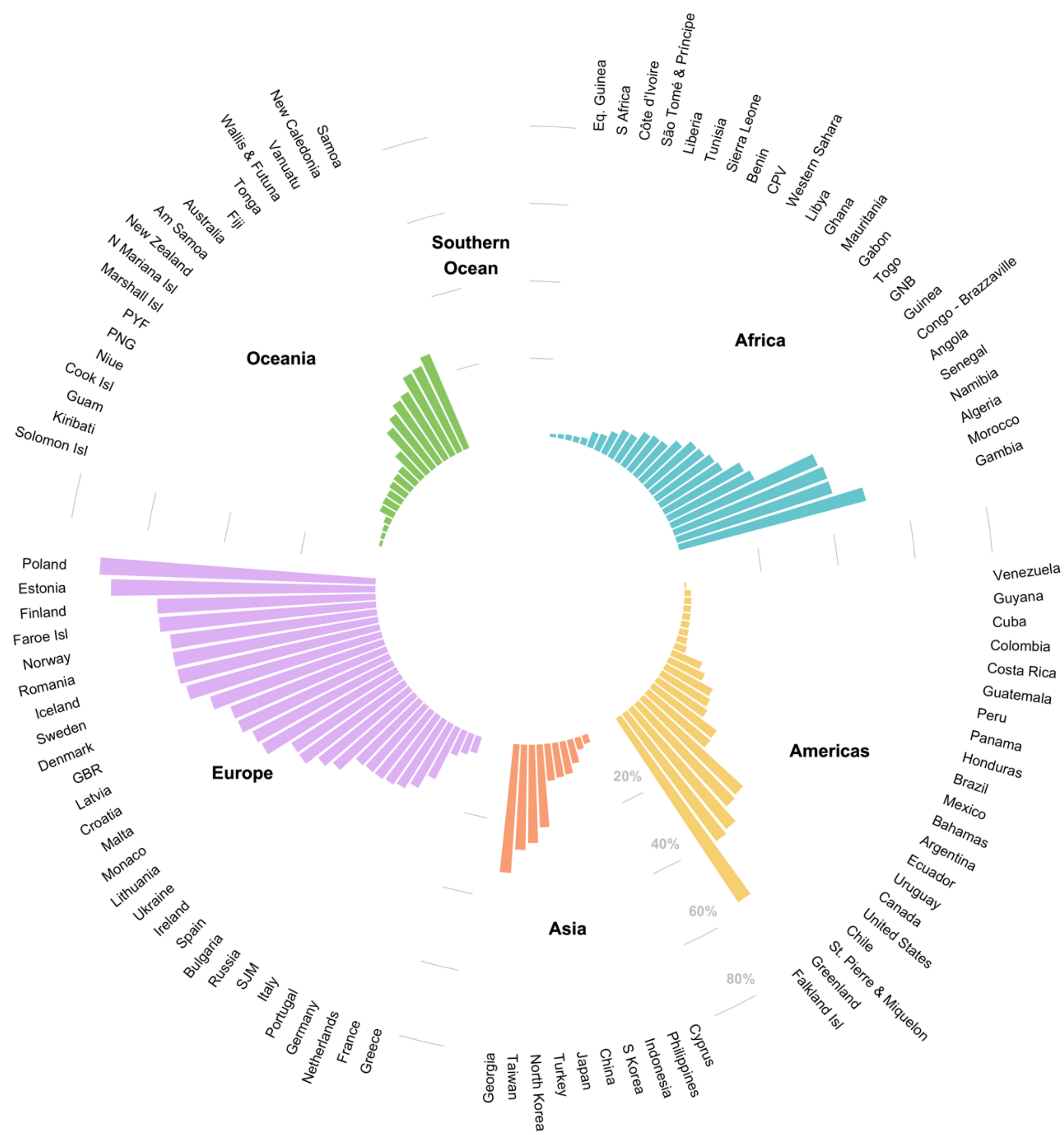
Supplementary Figure 14. Optimal conservation strategy from a multi-objective prioritization with equal preference for biodiversity, food provisioning, and carbon

This scenario assumes redistribution of fishing effort after protection. The colour scale denotes percent priority.



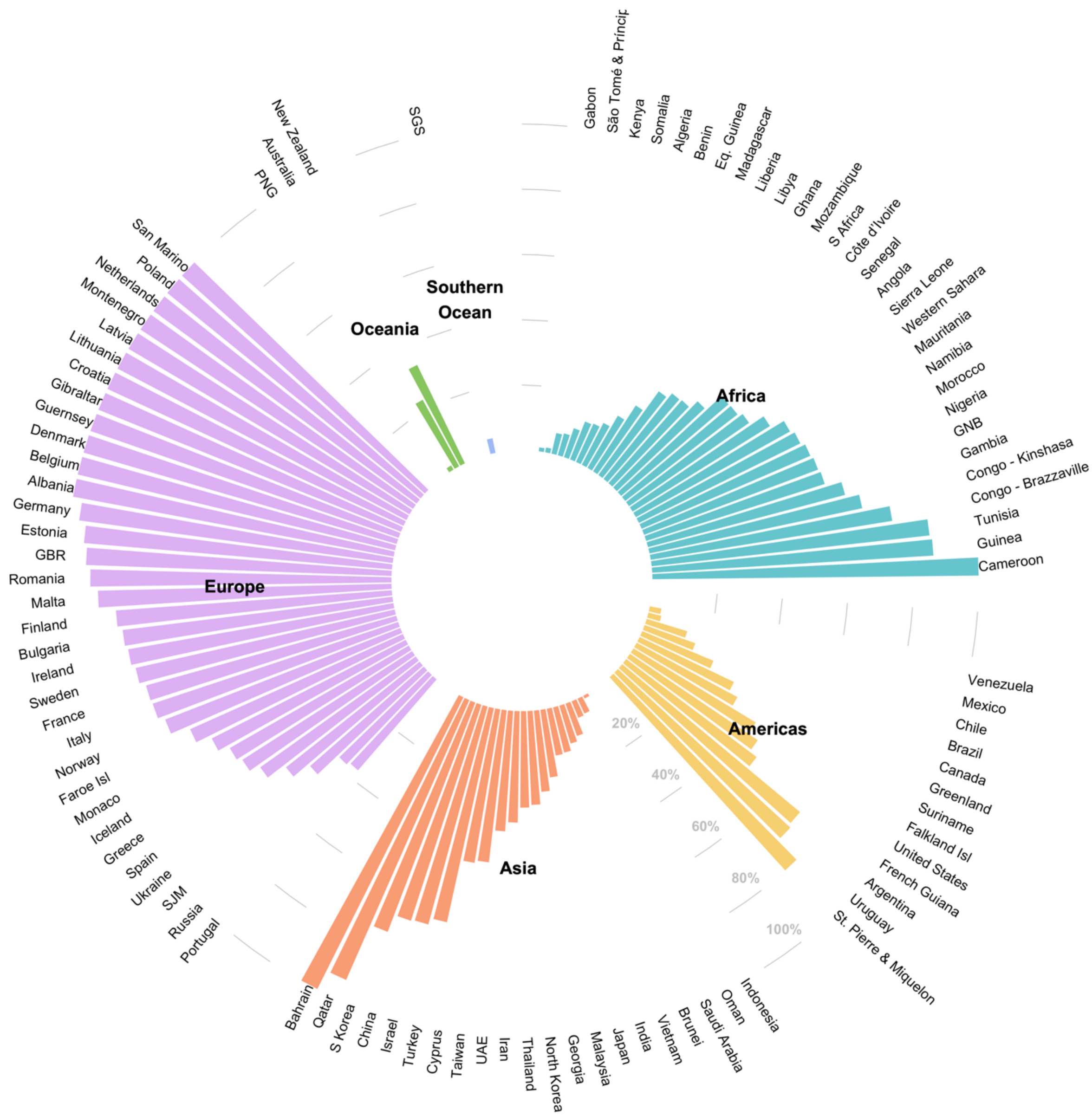
Supplementary Figure 15. Opportunities for strengthening the current level of ocean protection.

Blue polygons are highly-fully protected MPAs. Red circles indicate MPAs that are currently lightly- and minimally-protected according to the MPA Guide classification[2]. The coloured areas correspond to the 20% top priorities for biodiversity conservation.



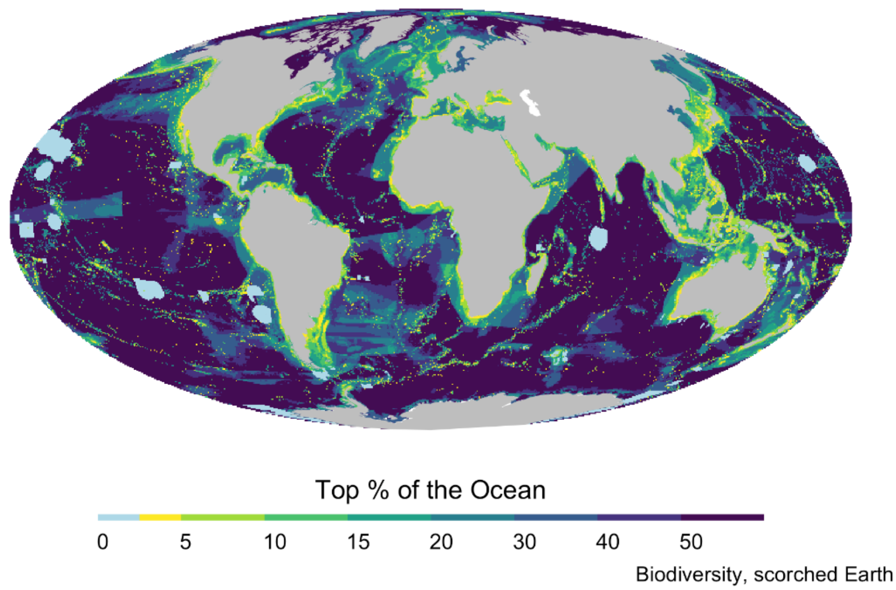
Supplementary Figure 16. National contributions to maximize food provision

Values correspond to the percentage of each territory or country's exclusive economic zone within the most important 10% of the ocean to boost food provisioning. Values are in addition to current protection levels. Shown here are the top 100 countries and territories in terms of the net gain in catch accrued from their exclusive economic zone.

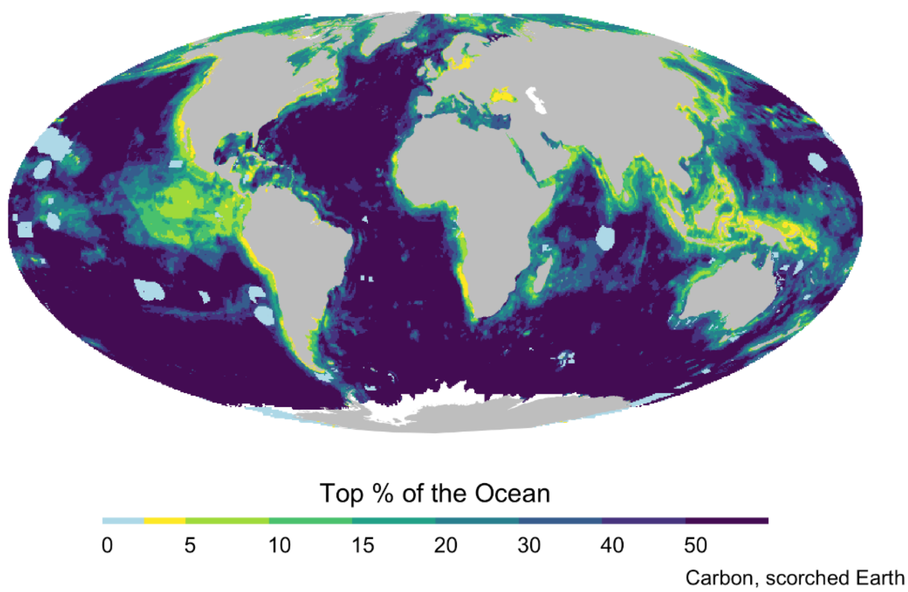


Supplementary Figure 17. National contributions to safeguard carbon stocks

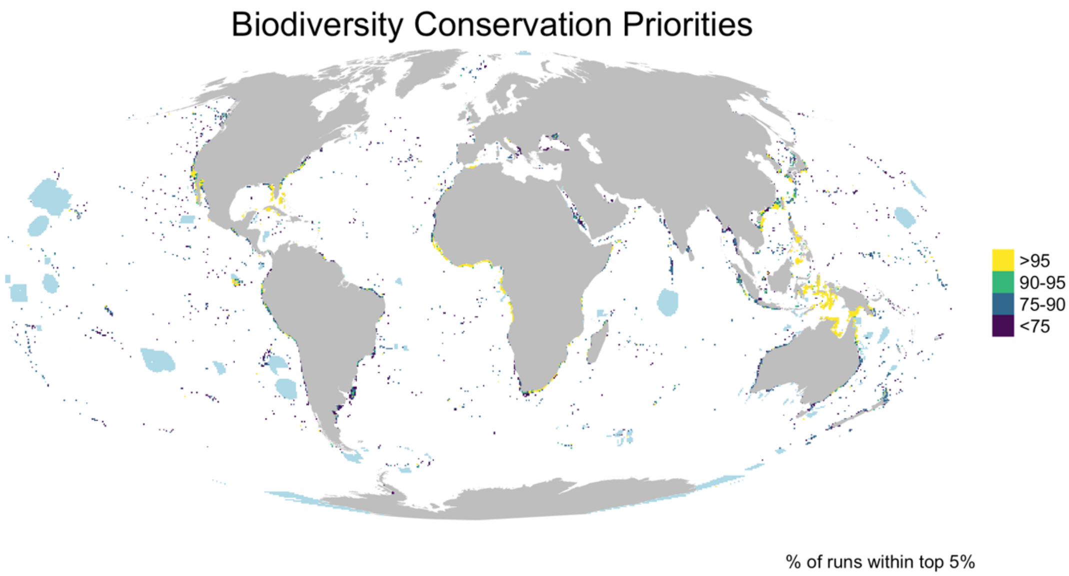
Values correspond to the percentage of each territory or country's exclusive economic zone within the most important 10% of the ocean to safeguard carbon stocks. Values are in addition to current protection levels. Shown here are the top 100 countries and territories in terms of the gains in carbon benefits accrued from their exclusive economic zone.



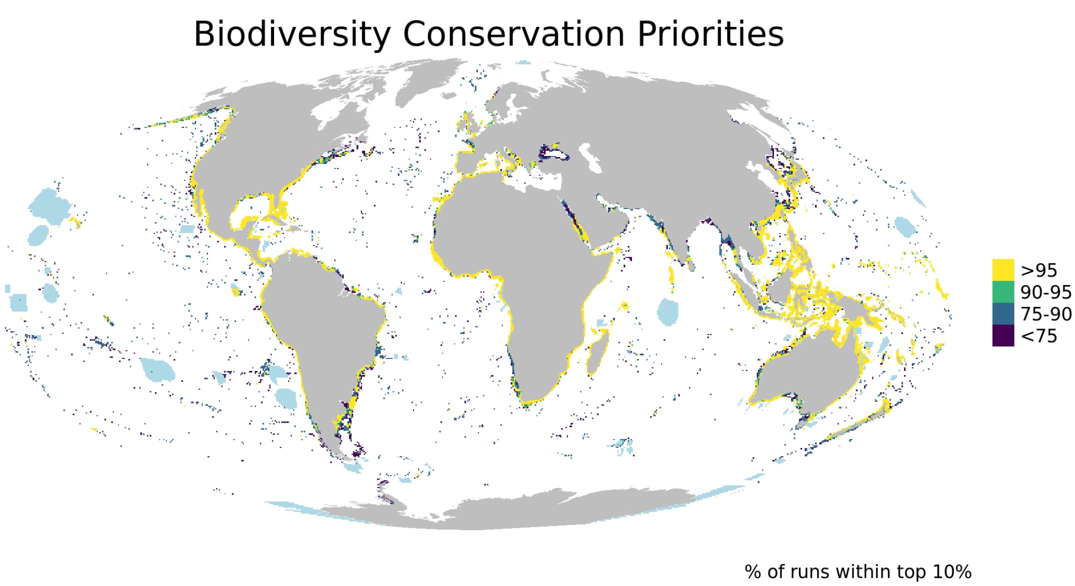
Supplementary Figure 18. Biodiversity conservation priorities in a "Scorched-Earth" scenario.



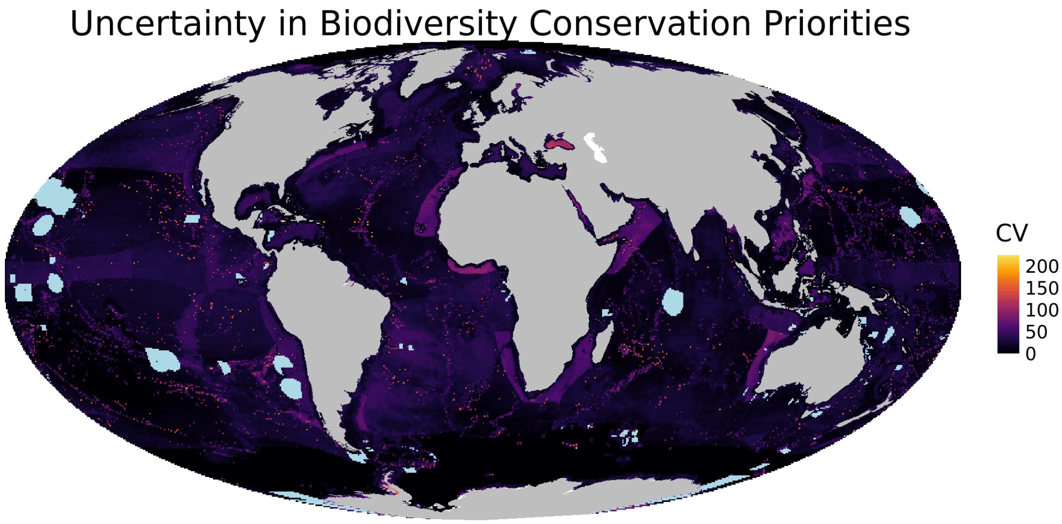
Supplementary Figure 19. Carbon conservation priorities in a "Scorched-Earth" scenario.



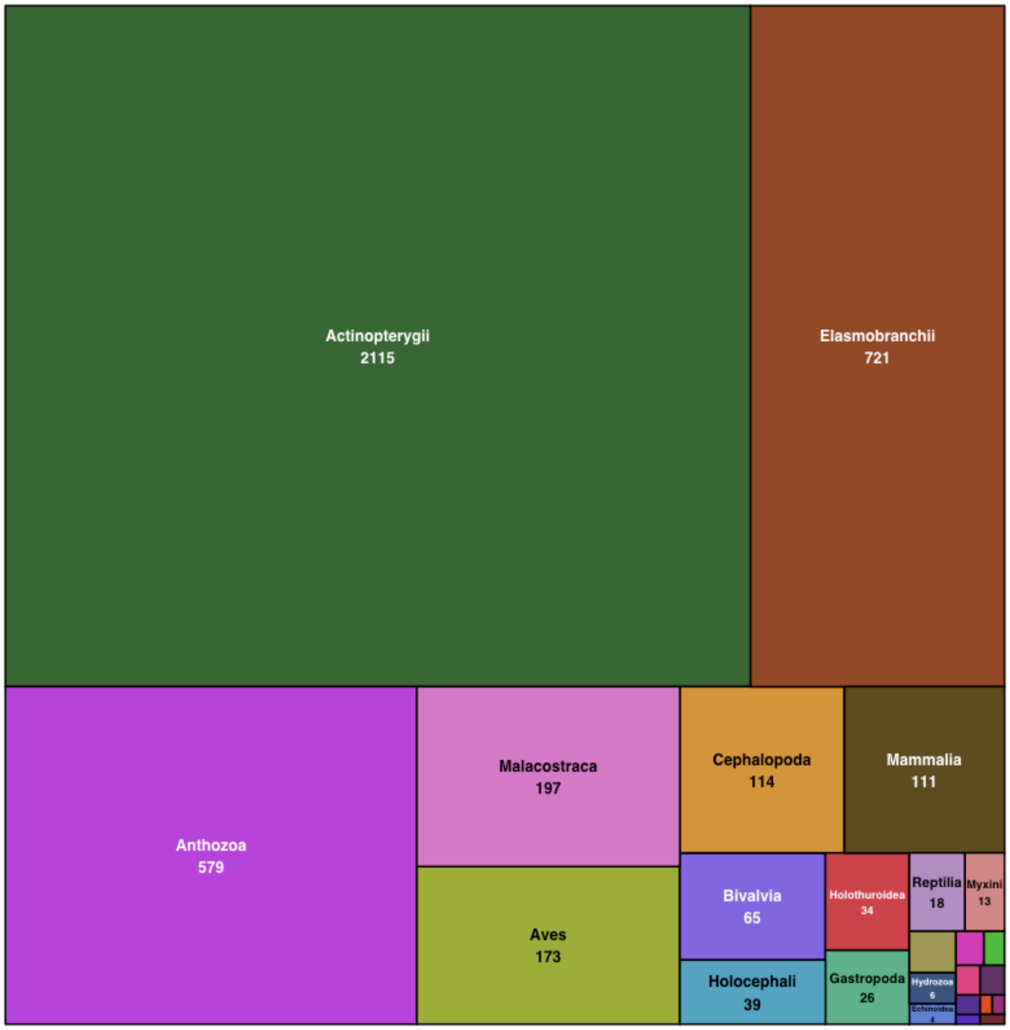
Supplementary Figure 20. Uncertainty in biodiversity priorities: percent iterations in top 5%



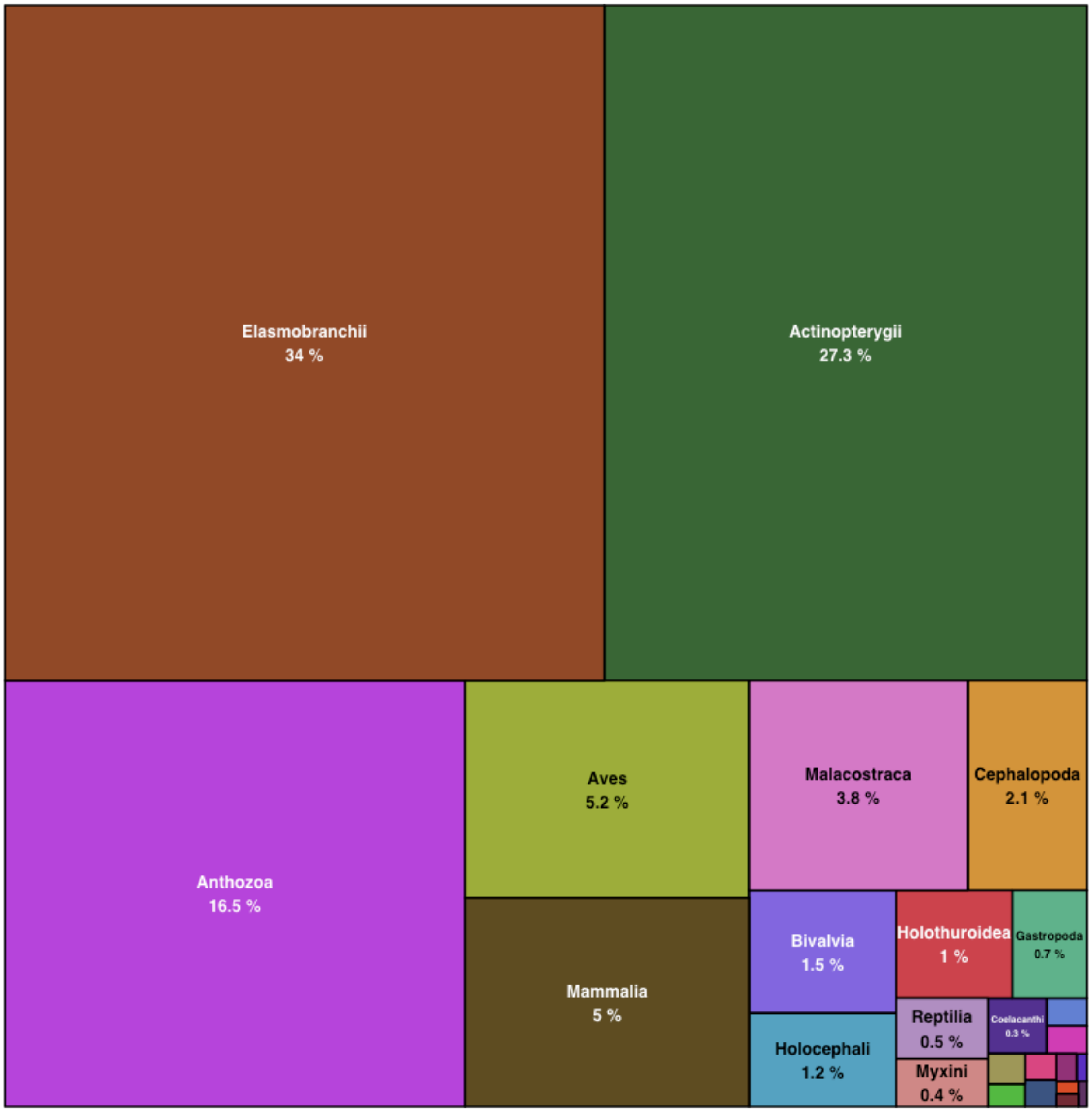
Supplementary Figure 21. Uncertainty in biodiversity priorities: % iterations in top 10%



Supplementary Figure 22. Uncertainty in biodiversity priorities: coefficient of variation in the top 5%

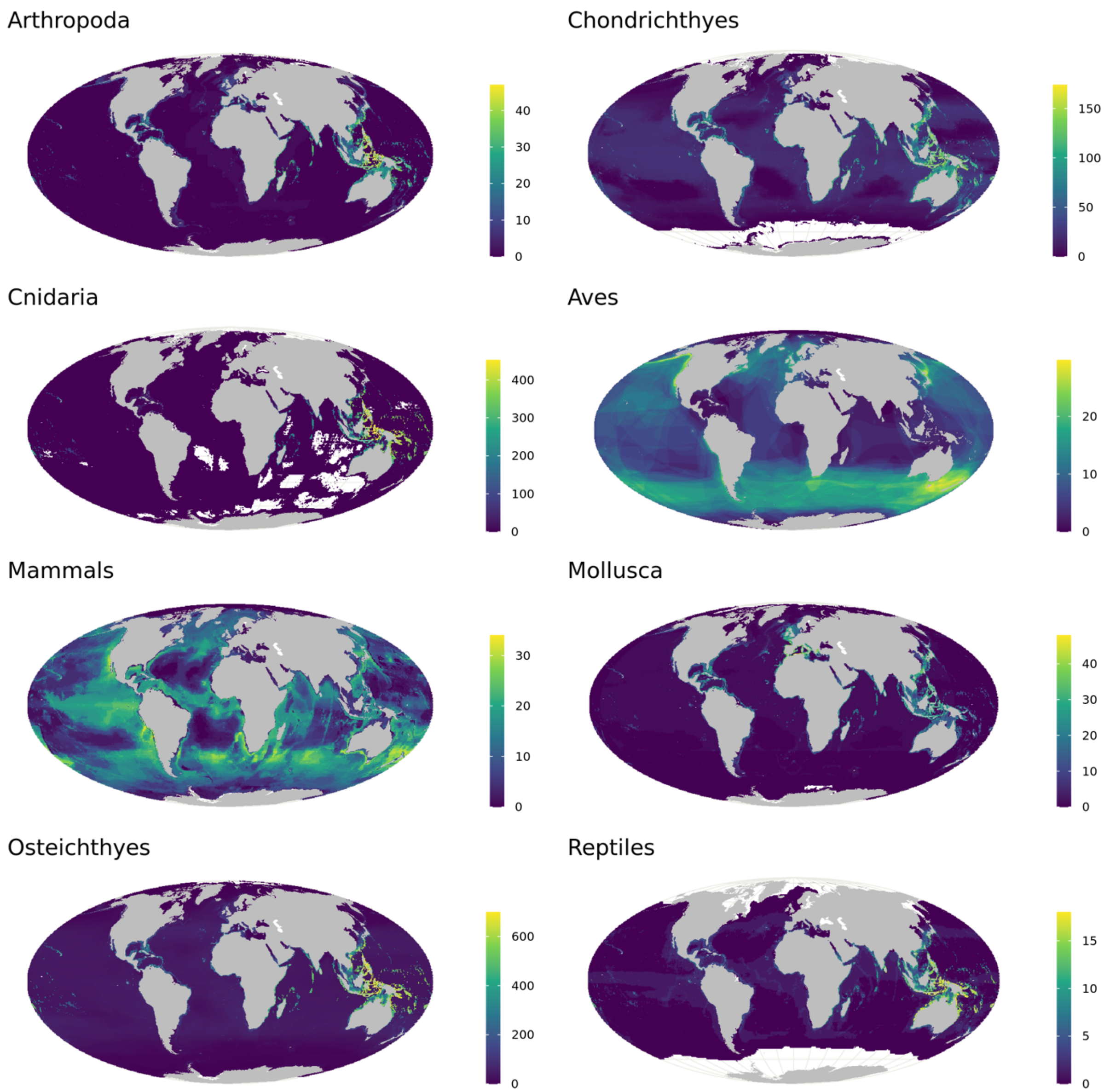


Supplementary Figure 23. Number of species included in the analysis by taxonomic class



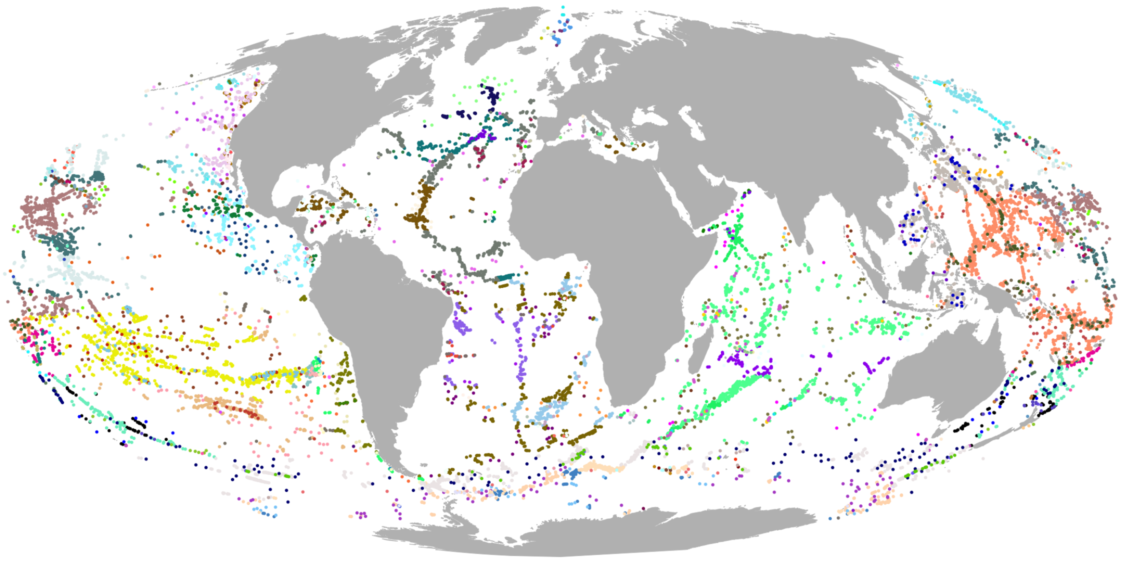
Supplementary Figure 24. Aggregate weight of species per taxonomic class

Values correspond to the relative importance of each taxonomic class and area function of the number of species, as well as their extinction risk and functional and evolutionary distinctiveness.

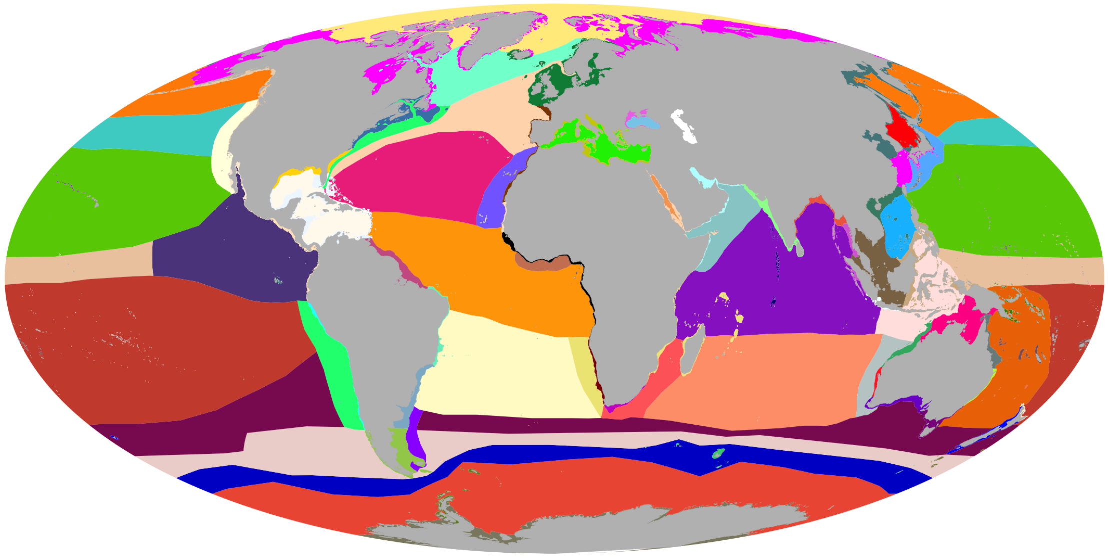


Supplementary Figure 25. Patterns of species richness by major taxonomic class

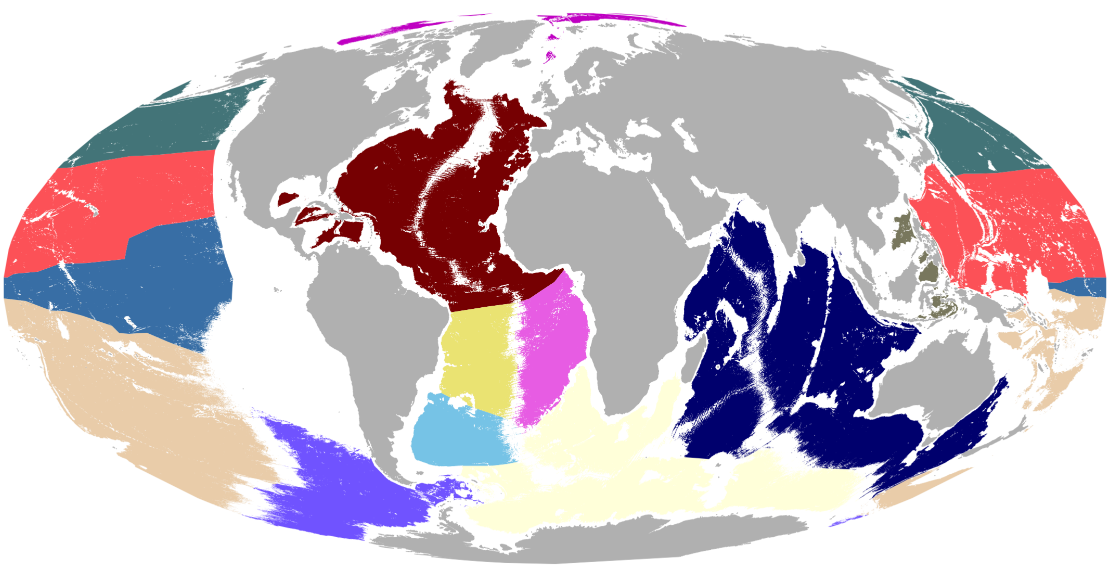
These maps are for illustration purposes. We did not use species richness in our analyses, but the distribution of each of 4,242 species that would likely be affected (mostly benefited) by protection[3].



Supplementary Figure 26. Global distribution of bathyal seamounts classified into 194 distinct classes[4]**.**

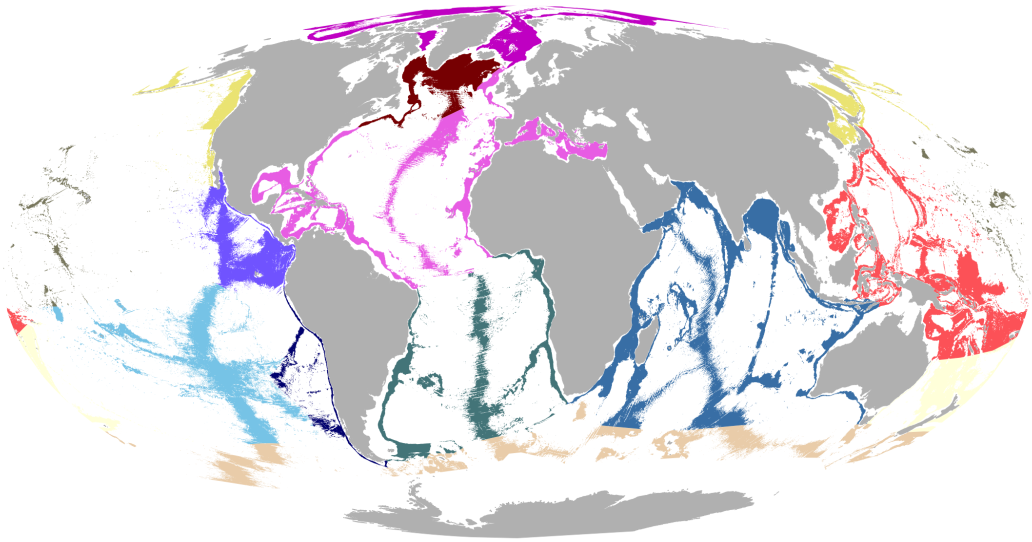


Supplementary Figure 27. Pelagic and coastal biogeographic provinces of the global ocean. Every colour represents a different province. For detailed information on provinces see Spalding et al. (2007, 2012)[5,6]



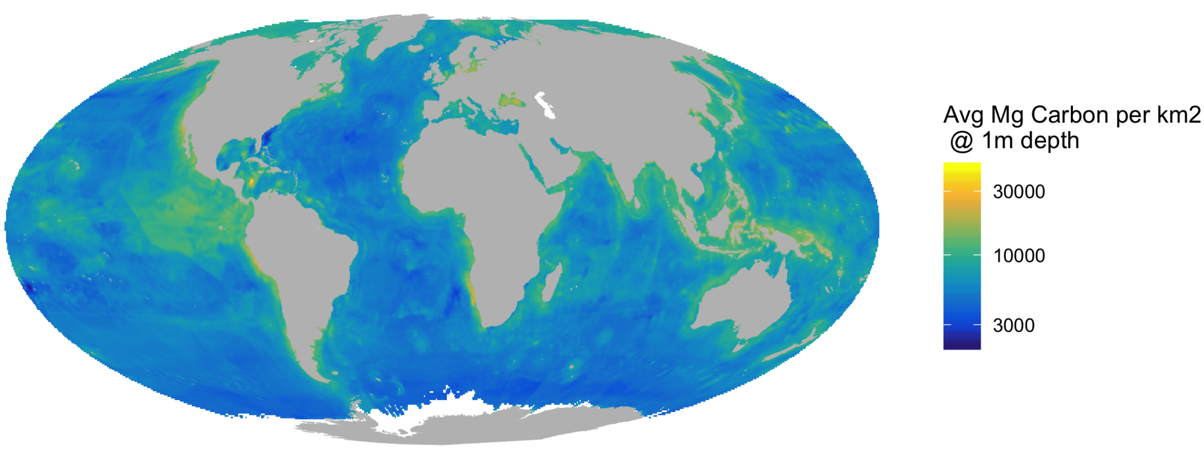
Supplementary Figure 28. Abyssal biogeographic provinces of the global ocean

Every colour represents a different province. For detailed information on provinces see Watling (2013).

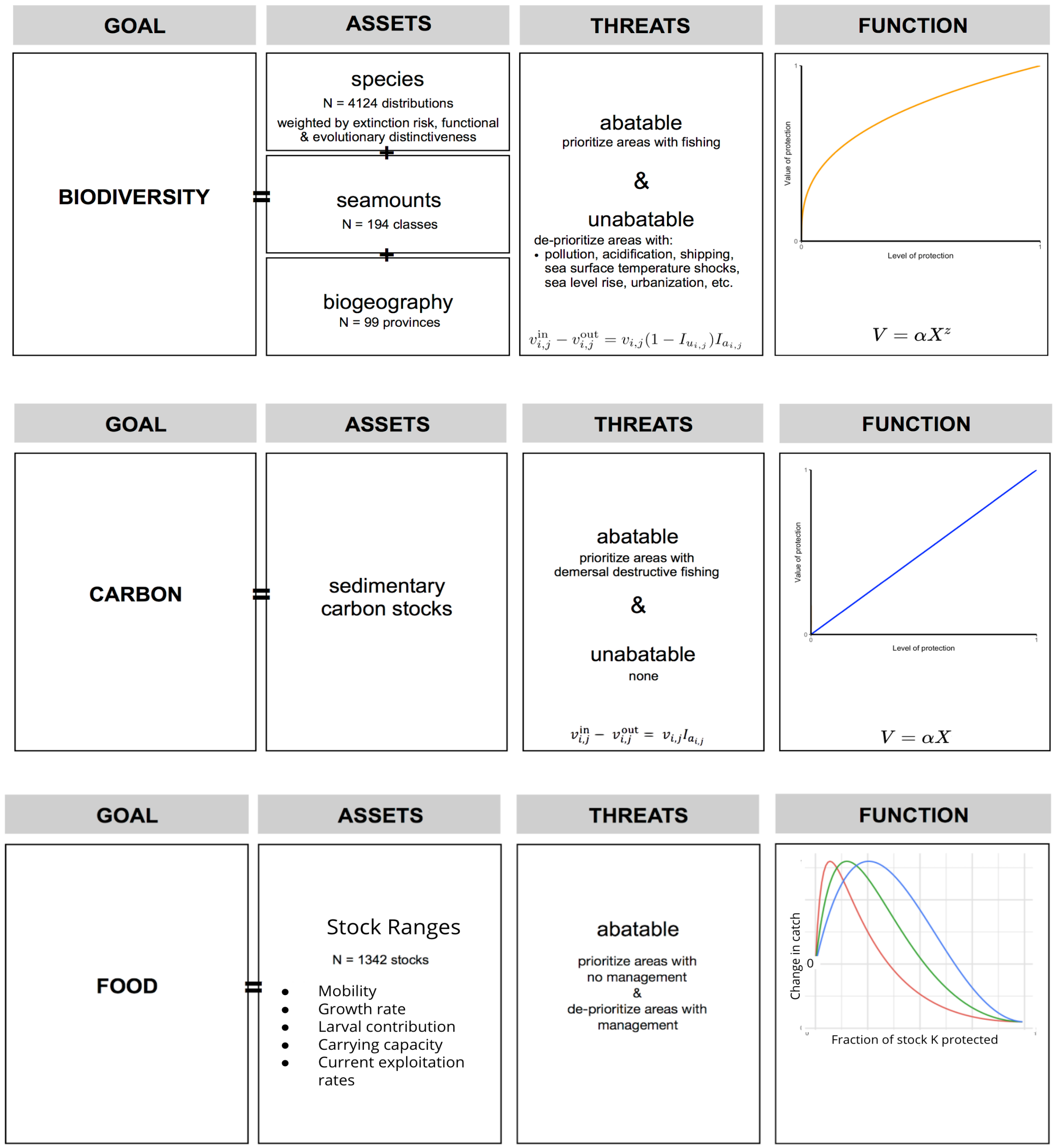


Supplementary Figure 29. Bathyal biogeographic provinces of the global ocean

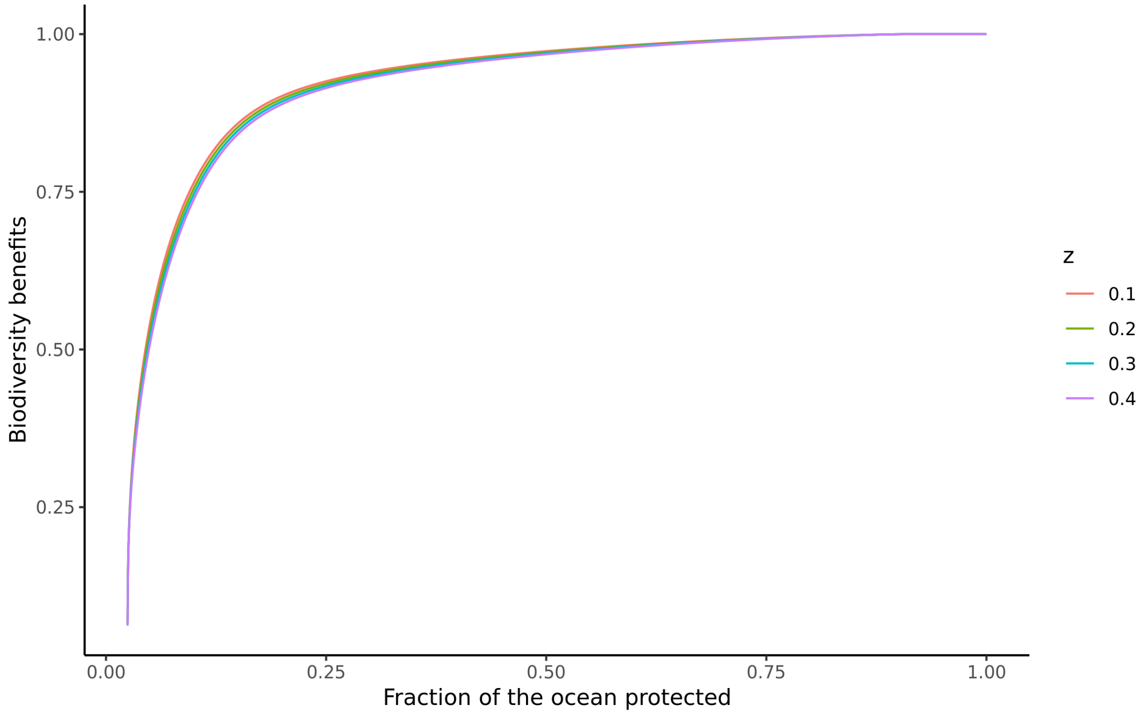
Every colour represents a different province. For detailed information on provinces see Watling (2013)[7]



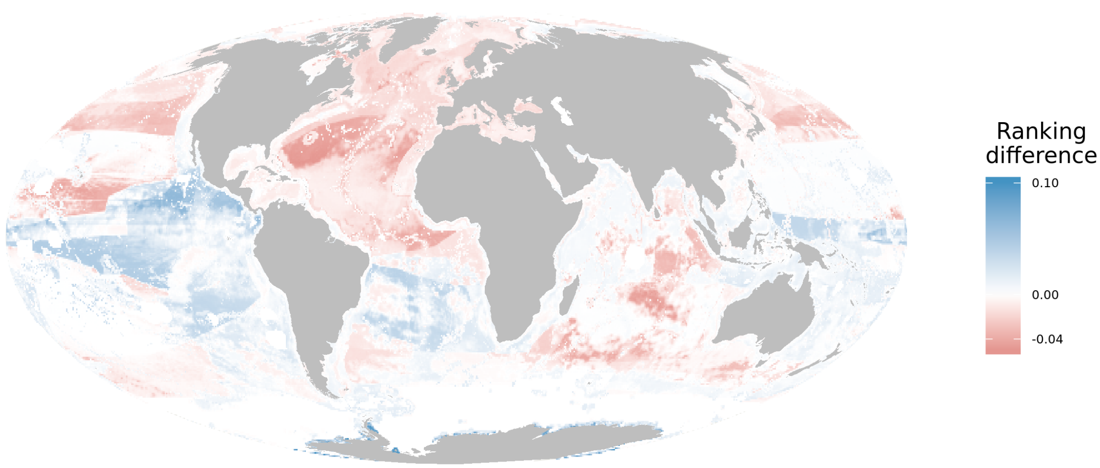
Supplementary Figure 30. Global distribution of marine sedimentary carbon stocks



Supplementary Figure 31. Conceptual diagram of each prioritization model.

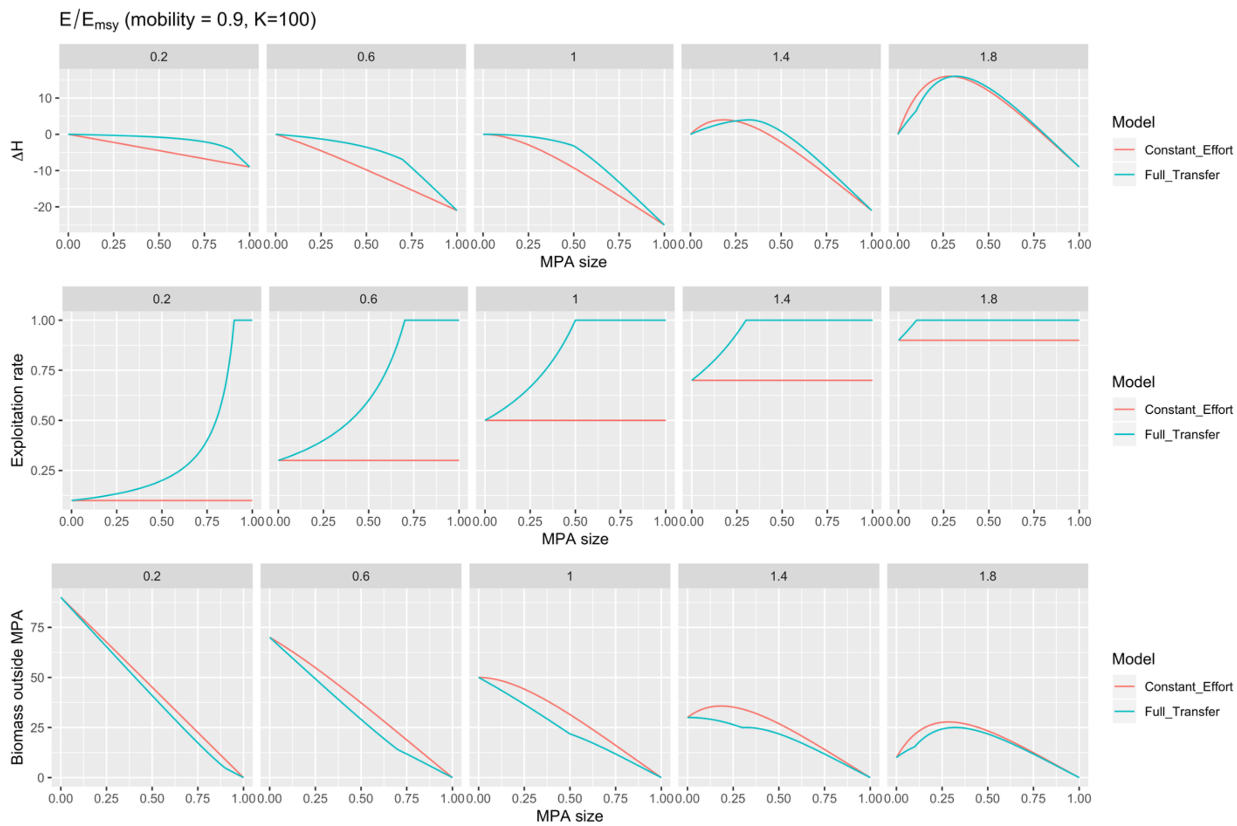


Supplementary Figure 32. Sensitivity of the biodiversity benefit curve to the z parameter.



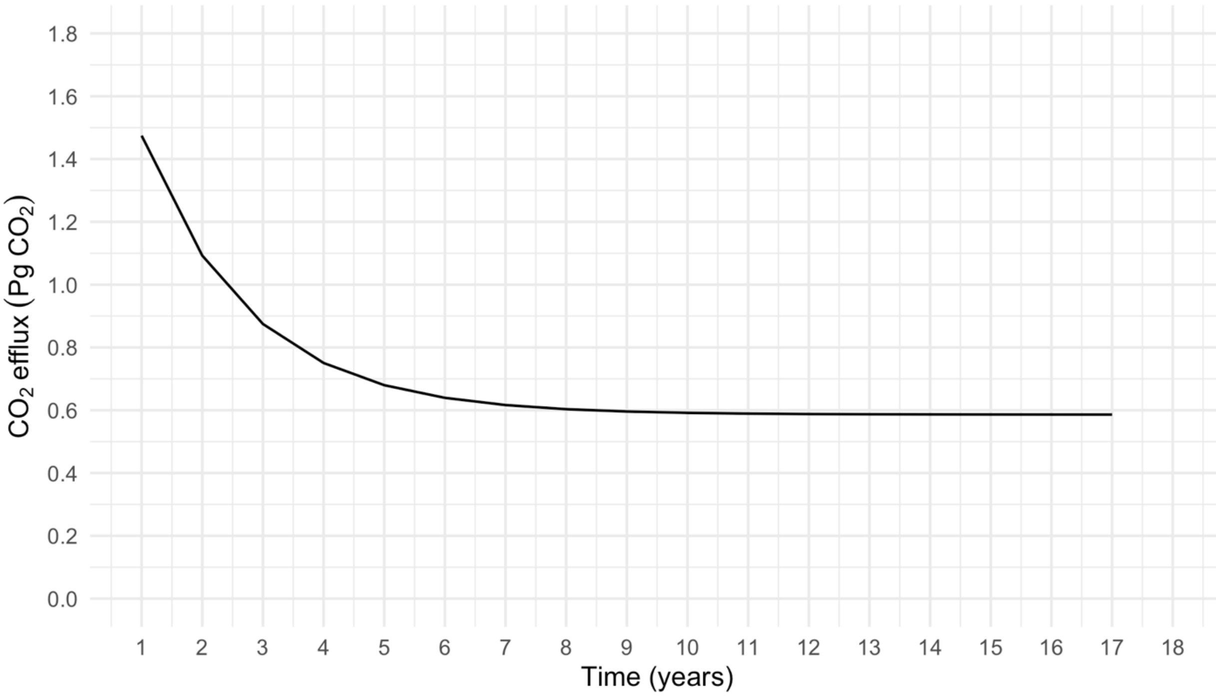
Supplementary Figure 33. Sensitivity of the biodiversity conservation priorities ranking to the z parameter.

Map shows the difference in ranking between using a z value of 0.4 and 0.1. The Kendall tau correlation coefficient for the top 30% of the solution suggests priorities are robust to z (τ =0.95).



Supplementary Figure 34. Dynamics of the two fishing effort redistribution models.

The figures illustrate a set of model parameters (mobility=0.9, K=100, r=1). "Full transfer" assumes that effort redistributes across the range of a stock proportionally to the distribution of effort before protection. "Constant effort" in unprotected areas assumes that effort in areas to be protected vanishes after protection. $E/E_{msy} > 1$ are overfished fisheries.



Supplementary Figure 35. Changes in CO2 remineralization rates over successive years of trawling.

Supplementary Table 1. Number of species included in the analysis by IUCN extinction risk[9].

IUCN Category	**# of species**
Least Concern	2200
Data deficient	615
NA	541
Vulnerable	381
Near threatened	349
Endangered	106
Critically endangered	50

Supplementary Table 2. Carbon model validation results

Region	Measured CO_2 efflux (mol CO_2 km^{-2} $\times 10^9$)	Predicted CO_2 efflux (mol CO_2 km^{-2} $\times 10^9$)	% error
Aarhus Bay	0.01260	0.00481	61.7
Sweden	0.00439	0.00404	7.9
Thermaic Gulf	0.00874	0.00734	15.9
Westerchlede	0.03550	0.03075	13.3

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Supplementary Information – Reference List

1 Halpern, B. S. *et al.* Recent pace of change in human impact on the world's ocean. *Scientific reports* **9**, 1-8 (2019).
2 Oregon State University, IUCN World Commission on Protected Areas, Marine Conservation Institute, Society, N. G. & Centre, U. W. C. M. An Introduction to The MPA Guide. Https://https://www.protectedplanet.net/c/mpa-guide (2019).
3 Kaschner, K. *et al.* AquaMaps: Predicted range maps for aquatic species. World wide web electronic publication, www.aquamaps.org, version 08/2016c. (2016).
4 Cheung, W. W. *et al.* Projecting global marine biodiversity impacts under climate change scenarios. *Fish Fisheries* **10**, 235-251 (2009).
5 Spalding, M. D., Agostini, V. N., Rice, J., Grant, S. M. J. O. & Management, C. Pelagic provinces of the world: a biogeographic classification of the world's surface pelagic waters. **60**, 19-30 (2012).
6 Spalding, M. D. *et al.* Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. *BioScience* **57**, 573-583 (2007).
7 Watling, L., Guinotte, J., Clark, M. R. & Smith, C. R. A proposed biogeography of the deep ocean floor. *Progress in Oceanography* **111**, 91-112 (2013).
8 Atwood, T. B., Witt, A., Mayorga, J., Hammill, E. & Sala, E. Global patterns in marine sediment carbon stocks. *Frontiers in Marine Science* **7**, 165 (2020).
9 IUCN. 2018 IUCN Red List of Threatened Species. http://www.iucnredlist.org/. (2018).

Data sources used in this study

Objective	Dataset ID	Data input	Reference	URL
BIODIVERSITY	1	Species distributions of marine species (current and 2050)	Kaschner, K. et al. AquaMaps: Predicted range maps for aquatic species, version 08/2016c.	https://www.aquamaps.org/
	2	Species distributions sea birds	BirdLife International (2019)	Data available by contacting BirdLife at http://datazone.birdlife.org/species/requestdis
	3	Species conservation status and main threats	IUCN. 2018 IUCN Red List of Threatened Species. (2018).	https://www.iucnredlist.org/
	4	Seamounts	Clark, M. R., Watling, L., Rowden, A. A., Guinotte, J. M. & Smith, C. R. A global seamount classification to aid the scientific design of marine protected area networks. Ocean Coastal Management 54, 19-36 (2011).	http://seamounts.sdsc.edu/
	5	Biogeography (coastal and pelagic provinces)	The Nature Conservancy (2012). Marine Ecoregions and Pelagic Provinces of the World. GIS layers developed by The Nature Conservancy with multiple partners, combined from Spalding et al. (2007) and Spalding et al. (2012). Cambridge (UK): The Nature Conservancy. DOIs: 10.1641/B570707; 10.1016/j.ocecoaman.2011.12.016. Data URL: http://data.unep- wcmc.org/datasets/38	https://data.unep-wcmc.org/datasets/38
	6	Biogeography (bathyal provinces)	Watling, L., Guinotte, J., Clark, M. R. & Smith, C. R. A proposed biogeography of the deep ocean floor. Progress in Oceanography 111, 91–112 (2013).	Data available by contacting the author
	7	Functional and Evolutionary distinctiveness	Rabosky, D. L. et al. An inverse latitudinal gradient in speciation rate for marine fishes. Nature 559, 392 (2018). Stein, R. W. et al. Global priorities for conserving the evolutionary history of sharks, rays and chimaeras. Nature Ecology Evolution 2, 288 (2018).	Data available by contacting the author

			Fritz, S. A., Bininda-Emonds, O. R. & Purvis, A. Geographical variation in predictors of mammalian extinction risk: big is bad, but only in the tropics. Ecology letters 12, 538-549 (2009). Jetz, W., Thomas, G., Joy, J., Hartmann, K. & Mooers, A. The global diversity of birds in space and time. Nature 491, 444 (2012).	
CARBON	8	Sediment carbon stocks	Atwood, T. B., Witt, A., Mayorga, J., Hammill, E. & Sala, E. Global patterns in marine sediment carbon stocks. Frontiers in Marine Science 7, 165 (2020).	https://figshare.com/articles/dataset/marine_soil_carbon/9941816
FOOD	9	Food provision potential	Cabral et al. (2020) A global network of marine protected areas for food. PNAS.	https://doi.org/10.25349/D9C32R
	10	Fishery status and exploitation	RAM Legacy Stock Assessment Database, version 4.491	https://www.ramlegacy.org/
	11	Fishery status	Costello, C. et al. Global fishery prospects under contrasting management regimes. Proceedings of the National Academy of Sciences 113, 5125-5129 (2016).	Data available by contacting the author
	12	Stock ranges	Kaschner, K. et al. AquaMaps: Predicted range maps for aquatic species, version 08/2016c.	https://www.aquamaps.org/
	13	Life history information (fish)	Froese, R. & Pauly, D. FishBase, version 12/2019.	https://www.fishbase.org
	14	Life history information (invertebrates)	M. L. D. Palomares, D. Pauly, SeaLifeBase, version 07/2020.	https://www.sealifebase.org
	15	Species movement	Cabral et al. (2020) A global network of marine protected areas for food. PNAS.	https://doi.org/10.25349/D9C32R
	16	Management boundaries of RAM stocks	Free, C.M., Thorson, J.T., Pinsky, M.L., Oken, K.L., Wiedenmann, J. and Jensen, O.P., 2019. Impacts of historical warming on marine fisheries production. Science, 363(6430), pp.979-983.	https://marine.rutgers.edu/~cfree/ram-legacy-stock-boundary-database/
THREATS	17	Abatable and unabatable threats to biodiversity	Halpern, B. S. et al. Spatial and temporal changes in cumulative human impacts on the	https://knb.ecoinformatics.org/view/doi:10.5063/F1S180FS

			world's ocean. Nature communications 6, 7615 (2015)	
	18	Bottom Trawling Fishing Intensity	Global Fishing Watch. 2016-2019. Accessed on August 11th, 2020.	access to raw data is available by contacting the GFW research team.
OTHER	19	Current MPAs	Marine Conservation Institute (2020). Atlas of Marine Protection.	https://mpatlas.org
	20	Ocean	Halpern BS, Longo C, Hardy D, McLeod KL, Samhouri JF, Katona SK, et al. (2012) An index to assess the health and benefits of the global ocean. Nature. 2012;488: 615–620. doi:10.1038/nature11397	https://mazu.nceas.ucsb.edu/data/
	21	EEZs	Flanders Marine Institute (2019). Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM), version 11. Available online at http://www.marineregions.org/.https://doi.org/10.14284/386	http://www.marineregions.org/.
	22	Land mask	Andy South (2017). rnaturalearth: World Map Data from Natural Earth. R package version 0.1.0. https://CRAN.R-project.org/package=rnaturalearth	https://CRAN.R-project.org/package=rnaturalearth