Title: Global patterns of the functional diversity of marine megafauna

# Abstract

*What we know about marine megafauna and functional diversity*

* Marine megafauna (i.e. all large-bodied marine animals with a body mass of >45 kg) perform a vast array of key ecological functions in the world’s ecosystems, yet ongoing anthropogenic pressures are undermining the integrity of their functional diversity.
* Maintaining the breadth of ecological functions performed by a species community (i.e., functional richness) is important for ensuring the functioning and stability of ecosystems. Ecological contributions will be most vulnerable under species loss where functions are maintained by a single or few species (i.e., where functional redundancy is low).
* Identifying where the diversity of such contributions is most at risk is therefore crucial for preserving healthy ecosystems.

More specifically: we expect some links between species richness and functional richness, and perhaps low richness areas and low redundancy, but does richness cover it all? No. We see some large deviations.

*The knowledge gap*

* Spatial prioritization in conservation planning have long focused on identifying areas with high species richness, thus maximizing the number of species safeguarded. However, these areas may not effectively capture areas with the most functionally diverse and vulnerable species and therefore may fail to protect the full range of species’ roles in ecosystems.
* While the functional diversity of marine megafauna and its vulnerability to species extinction have been previously assessed, the biogeography of these patterns remain unknown.

More specifically: we know global contributions, but local contributions and importance may vary, and we may see different species’ contributing most strongly in different regions.

Are functional richness areas covered by species richness?

Is there any overlap between areas of high functional richness and low redundancy?

*Objectives*

* Here, we combined functional trait data with species’ global distributions in order to assess the spatial patterns of functional diversity of marine megafauna and pinpoint where their ecological contributions are most diverse and most vulnerable to species loss . Specifically, we identified and compared hotspots of species and functional richness and those lacking functional redundancy to identify areas of conservation interest. Within these hotspots, we further applied the FUSE (Functionally Unique, Specialized and Endangered) index to identify species of high conservation concern inordinately supporting functional diversity.

*Results*

* Functional richness concentrated along the continental shelves, peaking at the tropics. Functional redundancy peaked in the Caspian Sea, while plummeting at polar latitudes.
* Hotspots of functional and species richness overlap at tropical latitudes. However, coastal hotspots in the Mediterranean Sea, Northern European Sea, and Islands of the Tropic and Temperate Pacific remained exclusive functional richness hotspots. WE NEED TO EMPHASISE THIS MORE.
* Areas lacking functional redundancy were limited to high temperate and polar latitudes, thus not encompassing any other diversity hotspots.(WE NEED TO LOOK AT WHETHER THIS IS ALL DOWN TO LOW SPECIES RICHNESS)
* Provinces of hotspots of functional richness harbored species featuring in the top 20% of the global FUSE species, predominantly sharks and sea turtles, while cetaceans and fish dominated provinces lacking functional redundancy, spanning a much larger portion of the FUSE rank (90%).
* YES BUT WE ALSO SAW THAT SPECIES COULD BE LOCALLY IMPORTANT WHILE GLOBALLY LOWER RANKED. WHAT SPECIES SHOWED THE GREATEST DEVIATION IN RANKING FROM GLOBAL TO LOCAL? THE TURNOVER IN IMPORTANT SPECIES IS ALSO INTERESTING: ALTHOUGH MANY OF THESE SPECIES HAVE WIDE RANGES, THEY MOVE IN AND OUT OF THE PRIORITIES DEPENDING ON THE REGION.
* THEREFORE, THIS WORK IDENTIFIES SPATIAL AREAS AND SPECIES OF FUNCTIONAL CONSERVATION INTEREST.
* VULNERABLITY OF AREAS WITH LOW SPECIES RICHNESS – SPECIES ARE MORE UNIQUE.
* SPECIES RICHNESS EXPLAINS A LOT OF THE PATTERN IN FUNCTIONAL METRICS, BUT NOT ALL; I THINK WE NEED TO VERIFY/CHECK THIS FOR FUNCTIONAL REDUNCANY AS WELL.

REDUNDANCY AND RICHNESS ARE DECOUPLED IN FISH: HIGHER RICHNESS AND LOWER REDUNDANCY ALONG COASTS, WITH LOWER RICHNESS AND HIGHER REDUNDANCY IN THE PELAGIC ZONE, ESPECIALLY IN THE TROPICS.

WE CAN SEE SURPRISINGLY LOW REDUNDANCY OVERALL ALONG THE COASTLINES;

*The contribution of this study to scientific knowledge*

* Our results highlight the high functional diversity of global coasts and vulnerability of polar latitudes. Furthermore, the observed spatial complementarity among diversity metrics proves the importance of assessing biodiversity patterns from multiple diversity perspectives in providing a comprehensive, informative framework for future conservation plans.

Few thoughts from John on overall framing:

We expect functional redundancy to be low where species richness is low, but there may be areas of high functional diversity and low redundancy (in theory).

A major contribution is the identification of what species are contributing locally (as opposed to globally) to functional diversity. We approach this by first identifying FR and F-red hotspots/coldspots and then identifying the key species. We show: 1) the same species are not critical in all areas (though some contribute very strongly to many areas); and 2) previously overlooked (lower ranked FUSE species) are important for low redundancy areas.

In a way this provides a warming that global estimates of species’ contributions to functional diversity may overlook key contributions to hotspots and thus more regional/local functional diversity.

Figures S3 and S4 should be combined into one figure and put into the main text.

Our main message is not clear: is it that functional diversity hotspots are supported by many different taxa? In fact, how many species rank in top 10 across all the hotspots? That would be a useful thing to know.

Is it that functional redundancy and functional richness areas are different? I guess we would expect this, but I guess the more relevant thing is identifying the important species within these low redundancy areas that would be overlooked globally?

Is it linear, story, of a message: where and what are the hotspots and who sustains them?

# Results and Discussion

*Global distributions of SR, FRic, FRed*

* Species richness concentrated along continental shelves and peaked in the subtropics and tropical belt (**Figure 1A**).
* Despite the expected correlation with species richness and functional richness (R = xx, p = ; **Supplementary figure S2B**), functional richness (volume of trait space) showed divergences from that of species richness. Specifically, high latitudes, the coast of Chile and the Central Indo-Pacific display a functional richness up to 16% higher than expected based on species numbers (**Supplementary figure S2A**). Furthermore,
* there were stronger localised peaks in California (USA and Mexico), the Galapagos Islands (Ecuador), and most significantly, the Central Indo-Pacific (**Figure 1B**).
* Functional redundancy (remind the reader here how this was calculated as I did for FRic) peaked in the Caspian Sea, reflecting the cluster of functionally similar sturgeons occupying this region, while it remained consistently low across polar latitudes, where marine megafaunal richness was the lowest (**Figure 1C**).
* Clade-specific analyses revealed that while SR and FRic of bony fish (**Figure S1D** and **S1E**) and sharks (**Figure S1G** and **S1H**) followed the global patterns previously observed, diversity of marine mammals had a different distribution: SR extended further into pelagic waters (**Figure S1A**), and peaks of FRic mirrored peaks of deviation between global SR and FRic (e.g., (**Figure S1B**). Marine mammals also drove patterns of low redundancy at polar latitudes (**Figure S1C**), while boy fish were responsible for high redundancy in the Caspian Sea (**Figure S1F**).
* [INSERT DISCUSSION FOR THIS SECTION]

*Hotspots/coldspots*

* When we compared hotspots of species and functional richness with coldspots of functional redundancy, we observed a 51% spatial congruence between SR and FRic but, as expected, no overlap with FRed (**Figure 1D**).
* SR and FRic overlapped? in 27 marine provinces along the coasts of USA, Mexico, Ecuador, Venezuela, from Senegal to Angola, South Africa and Mozambique, China, Taiwan, Japan, Burundi, Thailand, Cambodia, Vietnam, Malaysia, Indonesia, East Timor, Philippines, Australia, New Caledonia, and Papua New Guinea.
* Hotspots specific to SR extended to the continental shelves of further 9 marine provinces along the Gulf of Mexico,the Caribbean Sea and Eastern North Atlantic?, ~~Guyana, Suriname, French Guiana~~, from Brazil to Uruguay, from France to Portugal, from Morocco to Mauritania, from South Africa to Somalia and Madagascar, Pakistan, India, Sri Lanka, Southeast and Southwest Australia and New Zealand.
* The Mediterranean and European Seas, as well as islands in the Warm Temperate Southeastern Pacific and Tropical Northwestern Pacific were exclusive to hotspots of FRic.
* Coldspots of FRed were restricted to 13 continental and pelagic provinces of the Arctic circle along USA (Alaska), Canada, Greenland, Norway (Svalbard), Russia, and Antarctica.
* [INSERT DISCUSSION FOR THIS SECTION]

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**Figure 1**. Global spatial patterns of Species richness (A), Functional richness (B), Functional redundancy (C), and the distribution of species and functional richness and coldspots of functional redundancy (D).

*FUSE index per province of FRic hotspots*

* The species communities underpinning FRic-rich provinces (i.e., the marine provinces where FRic hotspots aggregated) consisted of a variety of clades, each occupying distinct portions of the global functional space and contributing to the magnitude of functional diversity that characterised the FRic hotspots (**Figure 2**).
* The top 10 FUSE species identified per FRic hotspot province consisted prevalently of sharks, rays and reptiles, all either endangered or critically endangered (**Table S1**).
* These sets of species were highly similar across provinces (the Hawksbill sea turtle *Eretmochelys imbricata* featuring in the top 10 FUSE species of every province; see **Figure S4A**), with the Mediterranean Sea, Lusitania, and Northern European Sea presenting the most unique set of FUSE species (**Figure S3A**).
* It is noteworthy that the top 10 FUSE species of each province features in the top 20% of global FUSE species rank, some of which upholding the extremes of either the province’s or global functional space (e.g., *Rhincodon typus, Balaenoptera musculus, and Balaenoptera borealis*; see **Figure 2** and **Table S1**).
* [INSERT DISCUSSION FOR THIS SECTION]

*FUSE index per province of FRed coldspots*

* The species upholding the functional diversity of FRed coldspots were predominantly marine mammals (Figure X Table X?). Although low in numbers, these species occupied an extensive portion of the global functional space (FRic = xxx%) and in certain instances supported its extremes (e.g., *Balaenoptera physalus, Lobodon carcinophaga*; see **Figure 3**)
* The top 10 FUSE species per province were mostly cetaceans and fish (**Table S2**), and highly dissimilar across provinces (**Figure S3B**), as a consequence of biogeographical species turnover. Only spatially adjacent provinces (such as Continental High Antarctic, Scotia Sea, and Subantarctic Islands) showed the least dissimilarity. Given its global distribution, the blue whale *Balaenoptera musculus* featured as the top FUSE species in every province but in the Cold Temperate Northwest Pacific (**Table S2** and **Figure S4B**).
* Each province of Fred coldspots included species spanning almost the entire global FUSE rank (top 90%; **Table S2**).
* [INSERT DISCUSSION FOR THIS SECTION]

Map

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**Figure 2.** Distribution of FRic hotspots across marine provinces. Below the map is the projection of the species assemblages of three marine provinces in the multidimensionaA picture containing text

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Diagram

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**Figure 3.** Distribution of FRed coldspots across marine provinces. Below the map is the projection of the species assemblages of two marine provinces in the multidimensional functional space. The coloured polygons indicate the volume of the functional space occupied by the province-specific species pool, while the dashed lines trace the volume of the functional space occupied by the global species pool. Dots with black outline indicate the top 10 FUSE species of each marine province.

# Conclusions

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# Materials and Methods

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