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Mapping global shipless areas and conflict zones between shipping and large marine vertebrates

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ABSTRACT

The growth of global maritime traffic poses increasing threats to marine biodiversity, including vessel collisions, behavioural disturbances, and pollution. Protecting areas with minimal shipping activity and identifying high-risk conflict zones between biodiversity and vessel traffic is crucial for conservation and mitigation efforts. However, a comprehensive assessment of these threats has yet to be conducted. We present a global analysis of shipless areas and examine the overlap between shipping density and the distribution of marine taxa known to be impacted by vessel activity—namely, cetaceans, sea turtles, pinnipeds, and seabirds. We identify regions where high biodiversity coincides with either low or intense vessel activity, designating them as Priority Preservation Areas and Priority Mitigation Areas, corresponding to low- and high-conflict zones. We also assess the extent to which Marine Protected Areas, Exclusive Economic Zones, and High Seas encompass these zones. Our results show that MPAs currently cover 12.1 % of shipless areas, 15.2 % of PPAs, and 16.2 % of PMAs, while no-take MPAs cover 6.8 % of shipless areas, 9.5 % of PPAs, and 5.6 % of PMAs. Our findings reveal that shipless areas are mainly restricted to polar and remote oceanic regions. PPAs are mostly located at high southern latitudes, while PMAs are concentrated along coasts, particularly in the mid-Pacific, southern Indian Ocean, and South Atlantic. We underscore the need to preserve low-conflict zones and implement targeted mitigation strategies—such as traffic rerouting and speed reductions—in high-conflict areas. Our framework supports global marine conservation goals, including the 30 × 30 biodiversity target.

1. Introduction

Ocean shipping is the cornerstone of the global supply chain, facilitating approximately 80–90 % of worldwide trade by volume. (Del Rosal, 2024; Lun et al., 2023). Beyond its economic significance, shipping is vital for global food security, energy distribution, and access to essential goods, profoundly shaping human livelihoods and well-being. However, its impacts on marine biodiversity are extensive and severe, particularly on large animals, including cetaceans, pinnipeds, sea turtles, and seabirds (Jones et al., 2017; Ritter and Panigada, 2019; Schwemmer et al., 2011; Welsh and Witherington, 2023). These may include vessel collisions (Nisi et al., 2024), pollution (Schaap et al., 2023), and behavioural disturbances (Fliessbach et al., 2019). With global marine traffic steadily increasing since 1990 and projections indicating exponential growth in the coming years (Naghash et al., 2024; Sardain et al., 2019), urgent global action is needed to map and quantify shipping-biodiversity conflict range areas in order to inform conservation and management strategies.

Vessel strikes constitute a major threat to cetaceans, with the International Whaling Commission indicating that fin whales (*Balaenoptera physalus*, endangered), humpback whales (*Megaptera novaeangliae*, least concern), and sperm whales (*Physeter macrocephalus*, vulnerable) account for roughly half of all documented incidents (Winkler et al., 2020). In addition to collisions, cetaceans are significantly affected by acoustic disturbance, which has been shown to impair foraging activities (Blair et al., 2016) and disrupt communication (Jensen et al., 2009). For sea

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turtles, estimates suggest hundreds to thousands of strikes annually in U. S. waters (NOAA, 2024). In Florida alone, the mean estimated annual mortality from vessel strikes is estimated at 712–2292 for loggerheads (*Caretta caretta*), 505–1624 for green turtles (*Chelonia mydas*), 79–316 for Kemp's ridleys (*Lepidochelys kempii*), 19–65 for leatherbacks (*Dermochelys coriacea*), and 11–37 for hawksbills (*Eretmochelys imbricata*). Similarly, on Australia's Queensland East Coast, vessel collisions caused at least 65 turtle fatalities annually between 1999 and 2002, primarily affecting green turtles and loggerheads (Hazel and Gyuris, 2006). Shipping impacts on pinnipeds can also be relevant, particularly due to noise pollution and physical disturbances (Kovacs et al., 2012). Underwater noise can interfere with their communication (Tripovich et al., 2012), trigger hauling-out behaviour (Erbe et al., 2019), and threaten critical pupping areas (Wilson et al., 2020, 2017). Vessel traffic also poses substantial risks to seabirds (Schwemmer et al., 2011), through chronic oil exposure, which compromises feather waterproofing and leads to inhalation of toxic fumes, skin contact, and oil ingestion (Alonso-Alvarez et al., 2007; Stienen et al., 2017), as well as through forcing evasive responses (Fliessbach et al., 2019). Noise and artificial light pollution further intensify these threats by interfering with seabird communication and orientation, thereby increasing the likelihood of predation and collisions (Lyons and Menezes-Oliveira, 2020; Merkel and Johansen, 2011).

Given the extensive impact of shipping on these large predators and consequently on biodiversity, food chains, and ecosystems (e.g. Heithaus et al., 2008), there is an urgent need to identify shipless areas, defined as regions with low maritime traffic (Votsi, 2023). These areas can be safeguarded as refuges free from shipping impacts, both now and in the future, similar to roadless (Ibisch et al., 2016) and wilderness areas in terrestrial conservation (Sanderson et al., 2002; Venter et al., 2016). Equally crucial is determining the risk of conflict across the oceans, highlighting areas of high biodiversity that overlap with shipless areas, and designating them as Priority Preservation Areas (e.g., through the designation of new Marine Protected Areas). Conversely, areas of high biodiversity that overlap with intense shipping activity should be prioritised for traffic-related mitigation measures and designated as Priority Mitigation Areas (e.g., through management of traffic routes and vessel speed). A key component of such assessment is evaluating the current coverage of these areas within the existing network of Marine Protected Areas and analysing their distribution across Exclusive Economic Zones and international waters beyond national jurisdictions (i. e., the High Seas). Mapping and quantifying these zones can provide essential insights to guide more effective conservation and management strategies that balance maritime traffic with biodiversity protection.

Our study provides a comprehensive global assessment of the overlap between shipping and marine biodiversity, focusing on four key taxa, cetaceans, pinnipeds, sea turtles, and seabirds. We identify shipless areas and perform a risk assessment to distinguish priority areas for preservation efforts and priority areas for mitigation measures. We further analyse the extent to which these areas intersect with existing Marine Protected Areas (MPAs), Exclusive Economic Zones (EEZs), and the High Seas. Our research can inform important policy programs, namely on marine shipping traffic, such as the Convention on the High Seas, as well as directly supporting the 30 × 30 initiative, contributing to the global target of protecting 30 % of the ocean by 2030, as outlined in Target 3 of the Kunming-Montreal Global Biodiversity Framework and the High Seas Treaty.

2. Methods

2.1. Biodiversity and shipping datasets

We focused on four key marine groups, cetaceans, pinnipeds, sea turtles, and seabirds, chosen for their documented vulnerability to shipping impacts and relatively well-known distributions. Information on sea turtles (7 species), cetaceans (85 species), and pinnipeds (32 species) was sourced from AquaMaps (https://www.aquamaps.org/), a dataset that combines environmental niche modelling with expert knowledge on the known geographic distribution of species, improving the ecological accuracy and reliability of the maps (Kaschner et al., 2019). Given their dependence on the marine environment for feeding (Schreiber and Burger, 2001), we further included seabirds (370 species), having retrieved the data on species richness from Carneiro et al. (2024), who derived this information from BirdLife range maps (see Supplementary information table S1 for the list of all species considered). The combination of all species layers resulted in a single composite representing overall species richness. This composite was interpreted as an indicator of biodiversity value.

The vessel density data used were obtained from the Global Maritime Traffic Density Service (https://globalmaritimetraffic.org), which processes and aggregates Automatic Identification System (AIS) messages from ocean-going vessels. Ships are mapped by integrating their AIS positions across time into vessel tracks, which are then rasterised to quantify the time spent by vessels in each grid cell. This system is mandatory for vessels over 300 gross tonnage on international shipping routes, vessels over 500 gross tonnage on domestic routes, and all passenger routes, overall ensuring comprehensive coverage of commercial maritime traffic (IMO, 2025). The AIS data are made available into monthly traffic density raster layers at a 1 km^2 spatial resolution, free of potential redundancies and errors - a combination of manual review and automated algorithms are used to detect and eliminate anomalous or erroneous data (GMT, 2024). These raster layers represent the total number of vessel/h recorded in each cell per month, allowing for consistent estimation of spatial and temporal patterns of ship traffic - even for vessels that traverse large distances within a few weeks (GMT, 2024; GMTDS, 2021).

2.2. Shipless areas and risk assessment

Shipless areas were defined as regions characterised by minimal or negligible vessel activity, identified here as those where total vessel density falls within the lowest tercile of vessel density distribution (calculated from the sum of all monthly data to account for the overall vessel density through the period studied). We also examined the temporal trends of shipless areas by analysing the yearly spatial distribution patterns of low ship-density regions globally from 2012 to 2023.

Regarding the risk assessment, we propose that the risk of ship-related impacts on biodiversity is a function of the interplay between shipping density and species richness as a measure of biodiversity importance (Ascensão et al., 2022, 2024; D'Amico et al., 2019). We classified both richness and vessel density into terciles (low, medium, and high levels). The overlap of these two layers in a bivariate map enables the identification of regions where species richness exceeds the third tercile and coincides with the first tercile of ship density (shipless areas). These regions, which offer valuable opportunities for safeguarding rich biodiversity, are here classified as Priority Preservation Areas (PPA). On the other hand, areas characterised by both high species richness and high shipping traffic density (and thus susceptible to direct impacts such as collisions or pollution) are deemed to be at elevated risk (Nisi et al., 2024) and therefore are here identified as Priority Mitigation Areas (PMA).

We conducted a detailed country-level analysis quantifying the coverage of shipless areas, PMA, and PPA within Exclusive Economic Zones (EEZ; Flanders Marine Institute, 2023). This approach allowed us to identify countries whose EEZs encompass significant areas of high biodiversity value (as indicated by shipless areas, PMA, and PPA) with relatively low shipping density, highlighting opportunities for preservation. Conversely, the analysis also pointed to countries where high shipping traffic intersects high-richness areas within their EEZs, underscoring the need for dedicated mitigation strategies. Moving to areas beyond national jurisdiction, we quantified the extent of PMA and PPA within the High Seas (Flanders Marine Institute, 2024). This analysis focused on five major open sea regions: the North Pacific, South Pacific, North Atlantic, South Atlantic, and Indian Oceans. Finally, we assessed the coverage of shipless areas, PMA, and PPA by the existing network of Marine Protected Areas (Protected Planet: The World Database on Protected Areas WDPA Online, 2025). We also determined the proportion of these areas that fall within MPAs designated as no-take zones. While no-take zones exclude extractive activities, such as fishing, they do not universally prohibit or limit vessel passage, particularly in offshore and high-seas areas. Therefore, overlap with low-traffic or shipless areas cannot be safely assumed in these regions.

All computations were conducted in R version 4.4.1 (2024-06-14). All the code is available on a permanent GitHub repository and the output raster layers are available on Figshare.

3. Results

Shipless areas are mostly found at higher latitudes, spanning across most of the polar regions (with more extensive distribution in the Southern Hemisphere, from approximately 45°S southward, compared to areas north of 70°N in the Northern Hemisphere) (Fig. 1). This pattern appears to have emerged in recent years (Supplementary information, Fig. S1), although the available data on tracked vessels makes it difficult to determine whether this trend is due to an increase in ship activity, or simply more vessels being tracked. Some large shipless areas are also found near Pacific archipelagos, including Polynesia, Hawaii, and the Marshall Islands, in the Indian Ocean west of the Australian coast, south to Indonesian islands, and near the Maldives and Mauritius. Very few large areas remain shipless in the Atlantic Ocean, including those near Saint Helena, Trindade, and Ascension Islands.

High species richness of the four faunal groups (third tercile) are found across the Polynesia region, most continental coastal areas (e.g., the western coast of North America, the North Sea, the Atlantic coast of Europe, the Yellow Sea, and the Sea of Japan), the northern Atlantic near the Azores Archipelago, and the southern regions of the Pacific, Atlantic, and Indian Oceans (Fig. 2A).

Overlaying species richness with the vessel density data (Fig. 2B) produced a bivariate map that can be interpreted as an indicator of the potential risk of shipping impacts on the focal faunal groups (Fig. 2C). This bivariate map allows distinguishing two types of areas: those where a higher risk of shipping-related impacts is likely to occur for more species (PMAs, highlighted in Fig. 2D by the redder colours); and those where higher overall richness overlaps with areas of lower vessel density (PPAs, represented by yellowish colours in Fig. 2D). PMAs are distributed along the coast, in the Pacific Ocean (mid-Pacific southeast of Hawaii, east of Australia), south Indian Ocean and South Atlantic (to the west of the coast of Africa). PPAs, on the other hand, are mostly in the southern hemisphere, in high-latitude areas.

Currently, only about 12 % of shipless areas are covered by the existing MPA network, indicating a significant gap in protection (Supplementary Material S3). This highlights a substantial opportunity to expand protection for these regions, which are characterised by minimal shipping impacts, through targeted conservation designations.

In terms of MPA coverage of priority regions, several MPAs effectively protect a substantial portion of PPA (15.1 % total MPA coverage) – those located in the upper range of the y-axis in Fig. 3A, such as the French Austral Lands and Seas (“a” in Fig. 3A) in the southern Indian Ocean. However, other MPAs contain large proportions of PMA (16.2 % MPA coverage), positioned along the upper range of the x-axis in Fig. 3A, such as the Mid-Atlantic Ridge North of the Azores (“i” in Fig. 3A). This suggests that many MPAs hosting high species richness also experience high shipping density, highlighting the need for targeted mitigation measures within these protected areas.

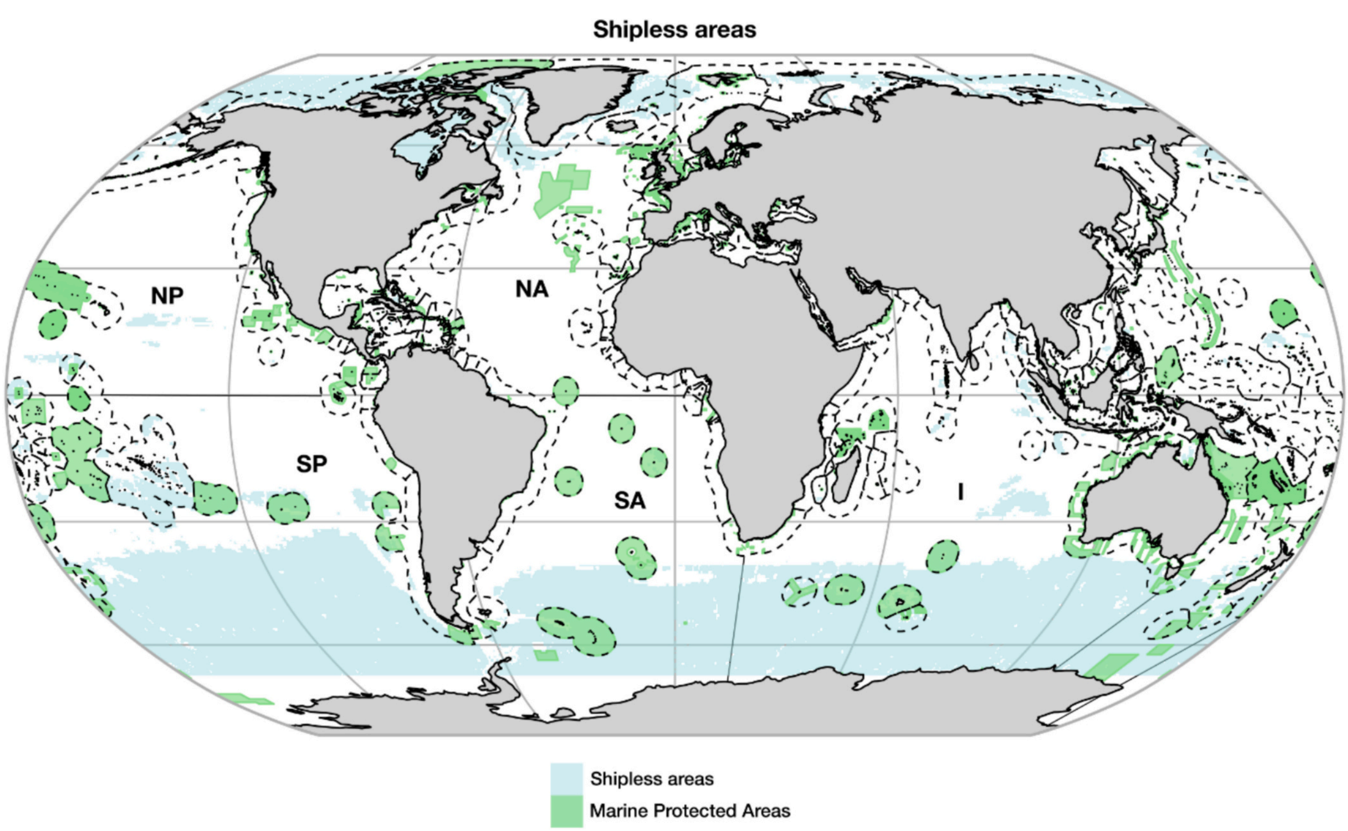

Fig. 1. Distribution of shipless areas (blue), representing regions with minimal or negligible vessel activity, defined as marine areas falling below the first tercile of the combined vessel density distribution (all vessel types). Marine Protected Areas (>100,000 ha) are overlaid in green, while Exclusive Economic Zone boundaries are marked with dotted lines. Open sea areas are labelled as North Pacific (NP), South Pacific (SP), North Atlantic (NA), South Atlantic (SA), and Indian Ocean (I). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

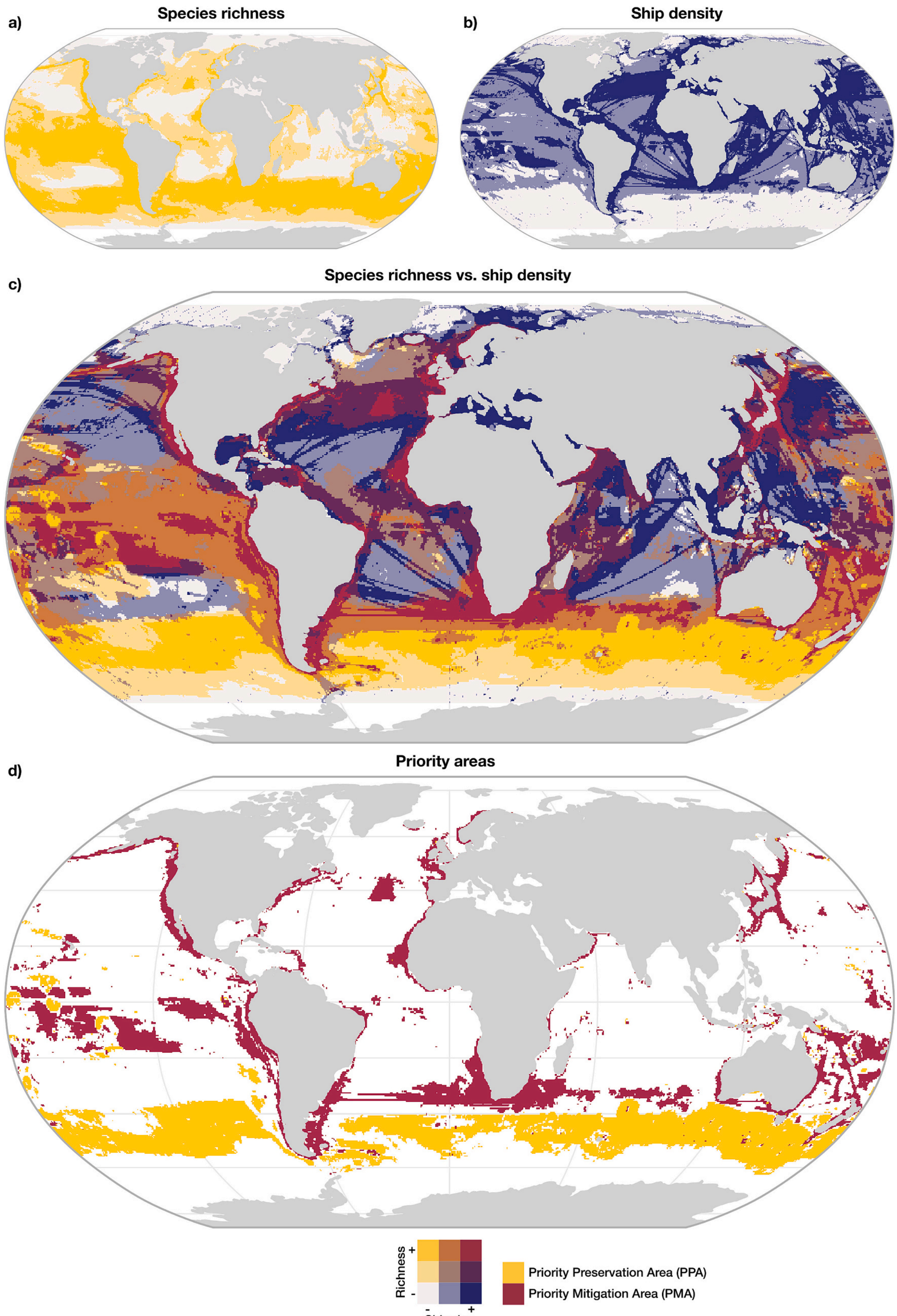

Fig. 2. (a) Overall species richness and (b) ship density, both classified into terciles, with lighter shades representing the bottom tercile and darker shades the upper tercile. (c) A bivariate map combining species richness and ship density. (d) Priority areas for shipping-related mitigation (PMA, in red) and priority preservation areas (PPA, in yellow). The colour legend applies to panels (c) and (d). See text for further details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

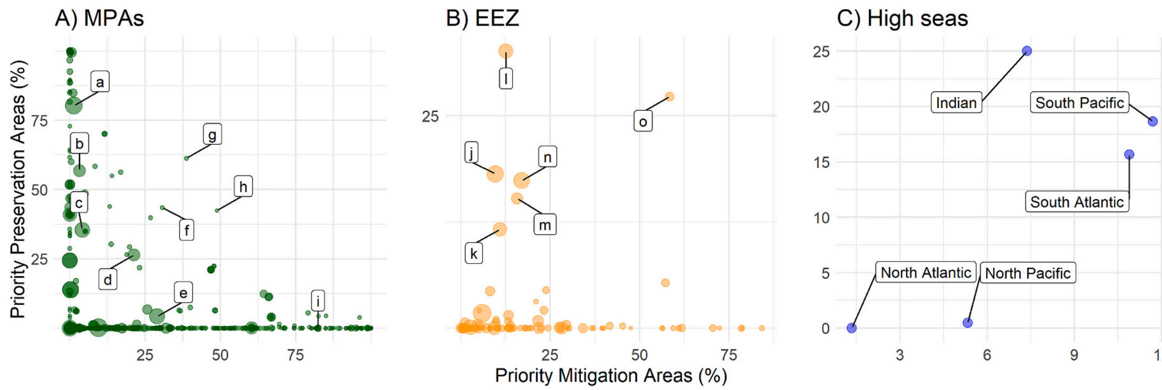

Fig. 3. Coverage of Large Marine Protected Areas (> 100.000 ha, MPA, in panel A), Exclusive Economic Zones (EEZ, in panel B), and high seas (in panel C) for priority mitigation areas (where both species richness and shipping density exceeded the third tercile) and priority preservation areas (where species richness exceeded the third tercile and shipping density fell within the first tercile). Dot size is proportional to area. Letters in the panels indicate: (a) Terres Australes Françaises, (b) French Austral Lands and Seas, (c) South Georgia and South Sandwich Islands, (d) Tristan da Cunha, (e) Natural Park of the Coral Sea, (f) Macquarie Island, (g) Auckland Islands - Motu Maha, (h) West Coast of the Outer Hebrides, (i) Mid-Atlantic Ridge North of the Azores (MPAs), (j) France, (k) United Kingdom, (l) New Zealand, (m) Chile, (n) Australia, (o) South Africa (EEZ). Note the difference in scale between panels. Detailed site-specific information is provided in the supplementary material.

MPA with no-take zones cover 9.5 % of PPA and 5.5 % of PMA. Additionally, species with higher IUCN threat levels (e.g., endangered and critically endangered) tend to have a greater proportion of their range overlapping with both Priority Mitigation Areas (up to 27.5 %) and Priority Preservation Areas (up to 13.8 %), underscoring the conservation relevance of these zones (see Supplementary information table S4).

The country-level analyses showed that some EEZs host a high proportion of PPA (Fig. 3B), such as the New Zealand Exclusive Economic Zone ("l" in Fig. 3B). Other countries, however, have a significant proportion of PMA, such as the South African Exclusive Economic Zone ("o" in Fig. 3B), suggesting a high overlap between richness and shipping density within their territorial waters. Finally, when analysing the high seas, beyond the jurisdiction of any country, we observe that the southern regions (Indian Ocean, South Pacific, and South Atlantic) are where high species richness overlaps with both low and high shipping activity. This suggests the presence of areas that should be prioritised for expanding conservation efforts, as well as regions where enhanced shipping mitigation management is crucial (Fig. 3C).

4. Discussion

We present the first global assessment of shipping potential impacts across several taxonomical groups, identifying shipless areas and defining priority areas for mitigation and preservation. Current shipless areas are predominantly located in higher latitudes. As a result, most priority preservation areas are concentrated in the Southern Hemisphere, near Antarctica, although significant shipless areas still exist in regions such as Polynesia. On the other hand, areas that should be prioritised for implementing shipping impact mitigation are mostly found across coastal regions. Identifying these areas is crucial for strengthening conservation efforts to reduce conflicts between shipping and the large marine vertebrates considered in this study, thereby supporting broader biodiversity protection.

Currently, large MPAs (>100,000 ha) cover just under 12 % of shipless areas. Shipless areas – and particularly the priority preservation areas identified in this study – offer valuable opportunities for expanding this conservation network to meet the global goal of protecting 30 % of marine areas. This could involve designating new MPAs within these priority regions, recognising their role as ecological corridors connecting key biodiversity hotspots, or safeguarding areas expected to become ecologically significant in the near future (Bruno et al., 2018). Conversely, some MPAs experience high shipping densities, necessitating targeted management strategies to mitigate the diverse impacts on marine biodiversity. For example, the Natural Park of the Coral Sea is intersected by major shipping routes connecting Southeast Asia, Australia, and the Indian Ocean (see Figs. 1 and 2D). While some activities such as fishing are prohibited in that MPA (Menini et al., 2023), the heavy vessel traffic across this region disperses shipping-related impacts throughout the protected area, posing significant challenges for conservation.

At the country level, we found that a considerable number of EEZs host large areas of priority preservation areas, such as New Zealand. Countries with significant biodiversity-rich areas, particularly those with low shipping activity, should be supported to maintain these areas vessel-free. In many of these EEZs, Priority Preservation Areas may already accommodate economic activities compatible with conservation objectives. Nonetheless, the primary aim of delineating shipless areas is to identify ecological refuges—regions of high biodiversity value that are insulated from both current and future shipping impacts. While certain areas, particularly in temperate or tropical regions, may allow for carefully regulated low impact uses, such as ecotourism, this may not be appropriate in more remote polar environments. Countries such as South Africa host extensive priority mitigation areas within their EEZs, requiring tailored strategies to mitigate shipping impacts on biodiversity. These nations should also receive support to implement management guidelines and practices that minimise ecological harm.

A key point to consider is that the spatial distribution of priority preservation and mitigation areas is dynamic, shifting with changes in underlying data. For instance, geopolitical instability can alter shipping routes, as seen in 2023–2024 when Houthi attacks in the Strait of Bab al-Mandab forced hundreds of commercial vessels to reroute around South Africa instead of using the Suez Canal. (Peng et al., 2024). Likewise, climate change threatens to dramatically redistribute biodiversity (Pinsky et al., 2020) and shipping traffic (Ng et al., 2018). Emerging Arctic trade routes are set to reshape global shipping. The Northern Sea Route along Russia's coast could be ice-free by 2030, cutting the East Asia–Europe journey by 9000 km and two weeks. Similarly, the Northwest Passage along Canada's Arctic coast offers a faster route from North America to the Bering Strait. While reduced fuel use and emissions present environmental benefits, increased shipping in the fragile Arctic ecosystem poses significant ecological risks.

We note some limitations of our study that should be considered in future developments of this framework. Firstly, we assumed that higher shipping density has a higher detrimental effect on all species, being all (equally) impacted by vessel density. This may not be the case for more synanthropic species. Gulls often thrive in coastal areas, urban environments, and other human-dominated landscapes, where they can find abundant food sources and shelter (Goumas et al., 2024). Their ability to adapt to human presence and their more flexible foraging habits mean they are less reliant on pristine, remote marine habitats, making them more resilient to disturbances like shipping traffic. In contrast, petrels, albatrosses, and shearwaters are more specialised in their habitat requirements, often relying on remote, less disturbed marine environments for breeding and foraging (Phillips et al., 2016; Rodríguez et al., 2019). These species are more vulnerable to threats like vessel strikes, noise and light pollution, as their behaviour and navigation are more directly impacted by such disturbances. Similarly, certain marine mammals such as grey and harbour seals and bottlenose dolphins are known to frequent human-altered coastal environments and areas with intense fishing activity, where they may benefit from foraging opportunities associated with human presence (Glemarec et al., 2024; Marçalo et al., 2024). Their behavioural plasticity and tolerance to anthropogenic disturbance can render them somewhat less sensitive to moderate levels of vessel traffic. However, there is currently little information on species-specific vulnerability to shipping impacts, precluding the differentiation of the impacts across species. This is also why we choose to use species richness, and not some metric of susceptibility that would allow better discrimination of impacts, already achieved when dealing with a small number of well-known species (Nisi et al., 2024).

Secondly, our maps are designed to illustrate large-scale patterns of conservation priorities, with their strength relying upon providing an overview for strategic planning, not using these maps to guide local conservation actions. This broader perspective is essential for effectively mitigating shipping-related threats to biodiversity, particularly for the faunal groups we're focusing on. This approach allows us to identify key areas and inform policies that can have the greatest impact on protecting these vulnerable species.

Thirdly, despite our effort to integrate information from diverse groups, the effects of shipping on other taxonomic groups should be considered in future developments. Shipping effects, such as those that physically disturb the seafloor or generate underwater noise, have been associated with declines in biodiversity, alterations in animal behaviour, and changes in physiological responses across a range of marine species. Similarly, other marine activities, such as seabed mining, oil drilling, and military exercises, also pose significant threats to marine biodiversity. Future research could expand this framework, incorporating the cumulative human impacts.

It should also be noted that our use of species richness rather than density metrics reflects data availability constraints at global scales. While richness effectively captures biodiversity value for cross-regional comparisons, density-based analyses would better characterise local population-level risks where abundance data exist.

4.1. Policy and management recommendations

Our study lays the groundwork for policy guidance to mitigate the ecological challenges posed by shipping. We recommend the official designation of areas with minimal-to-no shipping activity and high biodiversity value, prioritising their integration into the MPA network in alignment with established wilderness protection guidelines (Sanderson et al., 2002; Venter et al., 2016). Recognising that high-biodiversity areas are often subject to intense shipping activity, creating substantial conflict, we further propose targeted shipping management strategies in these zones to mitigate impacts and balance conservation with maritime use. Strengthening international cooperation to establish consistent and effective regulations will be pivotal in mitigating shipping's impact on marine biodiversity and ecosystems.

Key recommendations include implementing speed reductions, which can lower underwater noise, and the risk of vessel strikes, and optimising shipping routes to avoid more sensitive biodiversity hotspots (Findlay et al., 2023; Wiley et al., 2011). Additionally, adopting taxa-specific measures, such as noise reductions to benefit cetaceans and pinnipeds, or maintaining a minimum distance from haul-out sites, can further enhance conservation efforts (Brynolf et al., 2016; Lindgren et al., 2016). For instance, research in Alaska has led to recommendations for maintaining a distance of at least 500 m between cruise vessels and harbour seals (*Phoca vitulina*) to reduce disturbance (Jansen et al., 2010). By adopting these strategies, countries can work toward balancing marine biodiversity conservation with sustainable shipping practices. Equally important is evaluating and enhancing mitigation strategies. This includes optimising shipping routes to minimise impacts on sensitive areas and employing real-time monitoring and adaptive management tools. Our results can help define where such actions will be tested and implemented.

5. Conclusion

Our findings underscore the urgent need to preserve low-conflict polar and remote oceanic regions, as well as to implement targeted mitigation in shipping-intensive areas, to reduce ecological impacts. Our assessment provides a comprehensive framework for evaluating the impacts of shipping on marine biodiversity, encompassing a diverse range of taxa and highlighting critical conflict zones. As maritime trade continues to expand at an accelerating pace, our insights can inform more strategic, large-scale planning efforts aimed at mitigating biodiversity loss. By balancing the demands of economic development with the urgent need to protect vulnerable species and habitats, it provides a pathway toward sustainable and responsible management of shipping activities.

CRediT authorship contribution statement

F. Mestre: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. D'Amico:** Writing – review & editing, Writing – original draft. **V.A.G. Bastazini:** Writing – review & editing, Writing – original draft. **J. Assis:** Writing – review & editing. **D. Jacinto:** Writing – review & editing. **A. Marçalo:** Writing – review & editing. **F. Ascensão:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization.

Declaration of competing interest

I have nothing to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2025.111431.

Data availability

The link to the data and code was shared in the methods section.

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