RESEARCH ARTICLE

MARINE CONSERVATION

Ship collision risk threatens whales across the world's oceans

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After the near-complete cessation of commercial whaling, ship collisions have emerged as a primary threat to large whales, but knowledge of collision risk is lacking across most of the world's oceans. We compiled a dataset of 435,000 whale locations to generate global distribution models for four globally ranging species. We then combined >35 billion positions from 176,000 ships to produce a global estimate of whale-ship collision risk. Shipping occurs across 92% of whale ranges, and <7% of risk hotspots contain management strategies to reduce collisions. Full coverage of hotspots could be achieved by expanding management over only 2.6% of the ocean's surface. These inferences support the continued recovery of large whales against the backdrop of a rapidly growing shipping industry.

Marine shipping is a massive and growing industry that presents a variety of threats to the ocean environment. With an estimated 90% of all traded goods traveling by sea in an increasingly globalized economy (*1*), shipping traffic has increased more than fourfold since 1992 and is expected to grow even further in the coming decades because maritime trade volume is projected to triple by 2050 (*2*, *3*). Some of the negative impacts that marine shipping has on ocean ecosystems include accelerating climate change [i.e., maritime shipping produces 2.89% of the world's anthropogenic greenhouse gas emissions, on par with the global airline industry (*4*)], causing chemical and noise pollution (*5*), spreading invasive species (*6*), and causing behavioral disturbance for marine life (*7*). One of shipping's most pernicious impacts is direct collisions with wildlife (*8*).

Collisions with ships (i.e., ship strikes) are a major source of mortality for whales across the planet (*8*, *9*). Large whales play critical roles in marine ecosystems, including top-down and bottom-up forcing of marine food webs, cycling and transferring of nutrients, and provisioning of detrital energy to deep sea species (*10*, *11*). They are also culturally, spiritually, and economically important for people around the world (*12–14*). These species are highly vulnerable, with most populations of large whales at a fraction of their historical abundances after the industrial whaling era (*15*). Ship strikes are now a serious threat to whales, causing higher rates of mortality than are legally permissible from anthropogenic sources for some populations (*16*), contributing to the decline of critically endangered species (*17*), and occurring in all oceans (*9*, *18*). However, whale-ship collisions largely go unobserved and unreported, even in areas of high potential risk (*18*, *19*). Interventions to reduce whale-ship collisions, including reducing vessel speeds and changing vessel routings (*20*), depend on an accurate understanding of patterns in ship-strike risk. Despite a growing number of regional studies (*16*, *21–24*), the spatial distribution of ship-strike risk remains undescribed across the majority of the world's oceans, which is a critical impediment to scaling up effective solutions. Understanding the spatial dynamics of this problem at the global scale—at which both the shipping industry operates and whales migrate and inhabit the oceans—is essential because transboundary and multinational efforts will be needed to mitigate this threat.

Robust global characterization of ship-strike risk to whales is now possible owing to two recent technological advances. First, the increasing volume and accessibility of automatic identification system (AIS) data have made it possible to generate high-resolution maps of the global spatial footprint of marine shipping (*25*) and quantify exposure to vessels at locations where species are observed (*26*, *27*). Second, advances in species distribution modeling allow for the integration of diverse data types and sources, supporting predictive species distribution modeling across larger geographic scales (*28*). This makes it possible to characterize whale distributions globally, which, until now, has proven difficult because of challenges in collecting and integrating data across remote and dynamic pelagic habitats but is essential for understanding collision risk.

In this work, we present a global assessment of ship-strike risk to large whales, drawing from 435,370 records of whale locations from hundreds of datasets (figs. S1 to S5) and AIS vessel location data for 175,960 large vessels. We first developed global integrated species distribution models for four globally ranging whale species that are among the most at risk from ship strikes yet for whom risk is unknown across large extents of their ranges (*9*): blue whales (*Balaenoptera musculus*), fin whales (*Balaenoptera physalus*), humpback whales (*Megaptera novaeangliae*), and sperm whales (*Physeter macrocephalus*) (Fig. 1A, figs. S6 to S13, movies S1 to S4, and table S1). We then combined whale distributions with shipping traffic AIS data (Fig. 1B) to calculate ship-strike risk (Fig. 2), identify risk hotspots for each species (Fig. 3), evaluate coverage of current ship-strike management efforts, and quantify how risk changes across jurisdictional and protection boundaries (i.e., exclusive economic zones and marine protected areas; Fig. 4). This work draws attention to the pervasive scale of ship-strike risk and exposure to other shipping-related impacts, such as noise pollution, and provides a forward-looking road map to support the continued recovery of the great whales.

Global patterns of ship-strike risk to whales

We find that whales are at risk of ship strikes across the world's oceans, with 91.5% of all grid cells within focal species' ranges containing large vessel activity (Fig. 1, B and C, and Fig. 2). Within each of the blue, humpback, and sperm whale ranges [defined by the International Union for the Conservation of Nature (IUCN)], large vessels traveled the equivalent of more than 4600 times the distance to the moon and back each year, and within the smaller range of fin whales, vessels traveled more than 2600 times that distance. We calculated the

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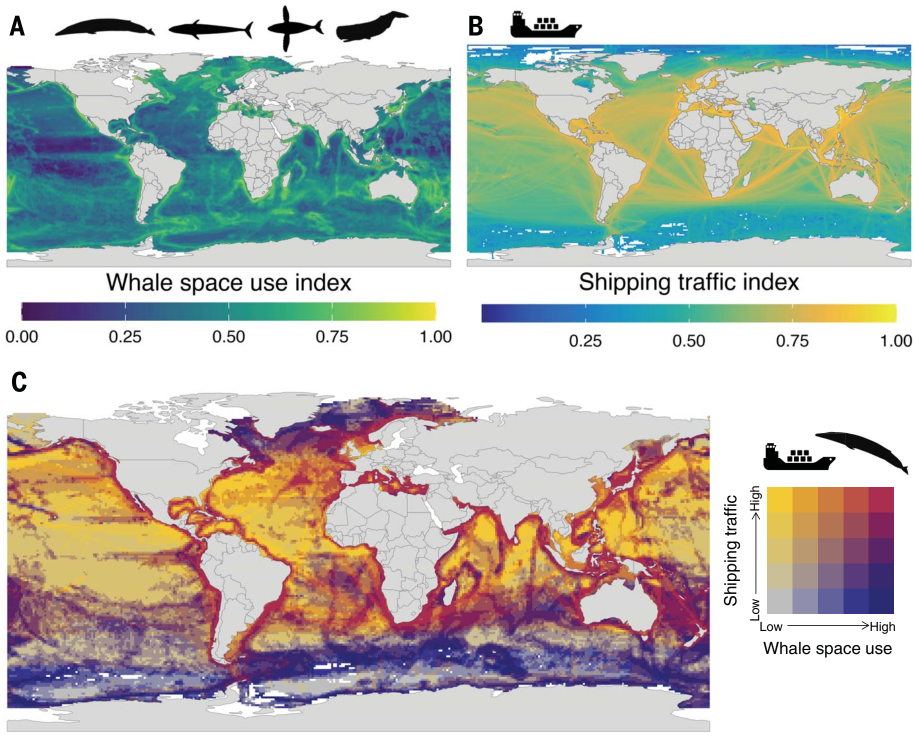

Fig. 1. Spatial overlap between whales and shipping traffic. (**A**) Average annual whale space use across blue, fin, humpback, and sperm whales. (**B**) Global marine shipping traffic for large (>300 gross tons) vessels, from AIS data from 2017 to 2022. The shipping traffic index weights shipping density by vessel speed on a log-scale, standardized between 0 and 1. (**C**) Bivariate map showing the intensity of both whale space use and shipping traffic in each 1° by 1° grid cell.

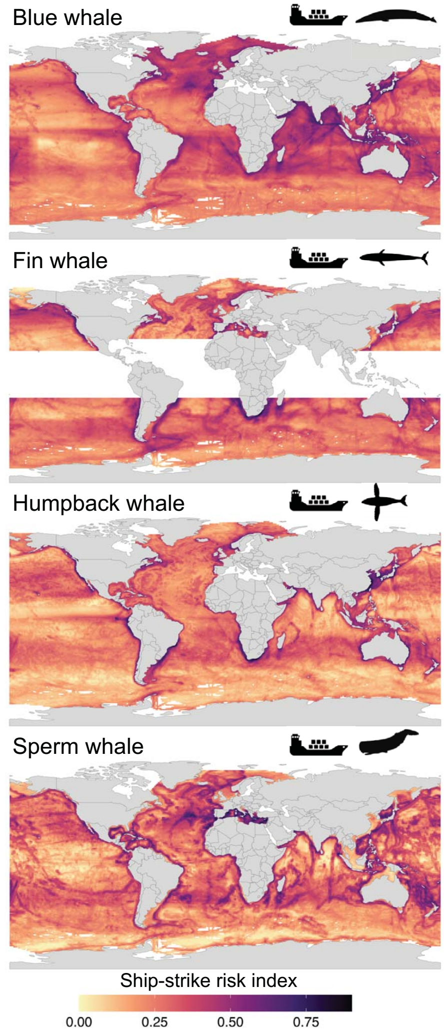

Fig. 2. Predicted global ship-strike risk at the species level for blue, fin, humpback, and sperm whales. Ship-strike risk is the product of the shipping traffic index and the modeled whale space-use index for each species. We predicted ship-strike risk across each species' range defined by the IUCN, with areas outside a species' range shown in white.

extent of the ocean that has risk levels equivalent to or higher than our estimate of risk in the California Current Ecosystem, an exceptionally well-studied region where ship-strike mortality rates for three of our focal species are estimated to greatly exceed the legal removal limits (*16*, *29*). More than 15% of the area of the world's oceans has risk levels equivalent to this region (Fig. 1C and fig. S14), which demonstrates that ship-strike risk is a major threat capable of producing high rates of whale mortality across all oceans.

All ocean regions contained substantial ship-strike risk to each species (Fig. 2 and fig. S15). Hotspots, defined as grid cells with the top 1% of ship-strike risk, occurred in all regions besides the Southern Ocean (Fig. 3 and figs. S16 to S18). Hotspots were mostly concentrated around continental coastlines (Fig. 3 and fig. S16), but high levels of risk were also found in some open ocean areas (e.g., the Azores) for blue, fin, and sperm whales (Fig. 1C, Fig. 2, and fig. S16). This highlights that although coastal regions have received the most study, ship-strike risk is high anywhere that shipping routes intersect with key habitat or migratory corridors (*30*) and is not limited to coastlines. The Indian Ocean, western North Pacific Ocean, and Mediterranean contained the highest percentages of risk hotspots across all species (21.6%, 14.5%, and 13.3%, respectively), with high levels of risk also found in regions in the eastern North Pacific Ocean, North and South Atlantic Oceans, South Pacific Ocean, and the South China and Eastern Archipelagic Seas (Fig. 2 and fig. S18). The Arctic Ocean contained a very small percentage of hotspots (0.56%), and the Southern Ocean was the only region that did not contain any ship-strike hotspots owing to low levels of shipping despite high whale space use (Fig. 1C, Fig. 2, and fig. S17).

Some hotspots were shared across multiple species, with 19.8% of hotspots affecting two species, 4.69% affecting three, and 0.09% affecting all four (Fig. 3A). Multispecies hotspots were distributed along coastlines of all continents except Antarctica, with most occurring in the North Pacific Ocean. A substantial number of multispecies hotspots also occurred in the Indian, western South Pacific, eastern North Atlantic, and South Atlantic Oceans (Fig. 3). This highlights the value in considering a multispecies approach to ship-strike risk mitigation because multispecies risk hotspots represent areas where mitigation measures based on reduced speed could be most effective and measures based on changing ship routings may need to take the distributions of multiple species into account.

The International Whaling Commission (IWC), the intergovernmental organization charged with whale conservation and management, has compiled a list of high–ship-strike risk areas based on previous local- and regional-scale analyses (fig. S19) (*9*). These areas are evident in our global ship-strike risk estimates, including Sri Lanka and the eastern North Pacific for blue whales, Panama and the Arabian Sea for humpback whales, the Canary Islands for sperm whales, and Mediterranean areas for fin and sperm whales (Fig. 2, Fig. 3, and fig. S16). Our analysis also identifies regions of high ship-strike risk that have received less recognition and study, including the Azores, multiple regions

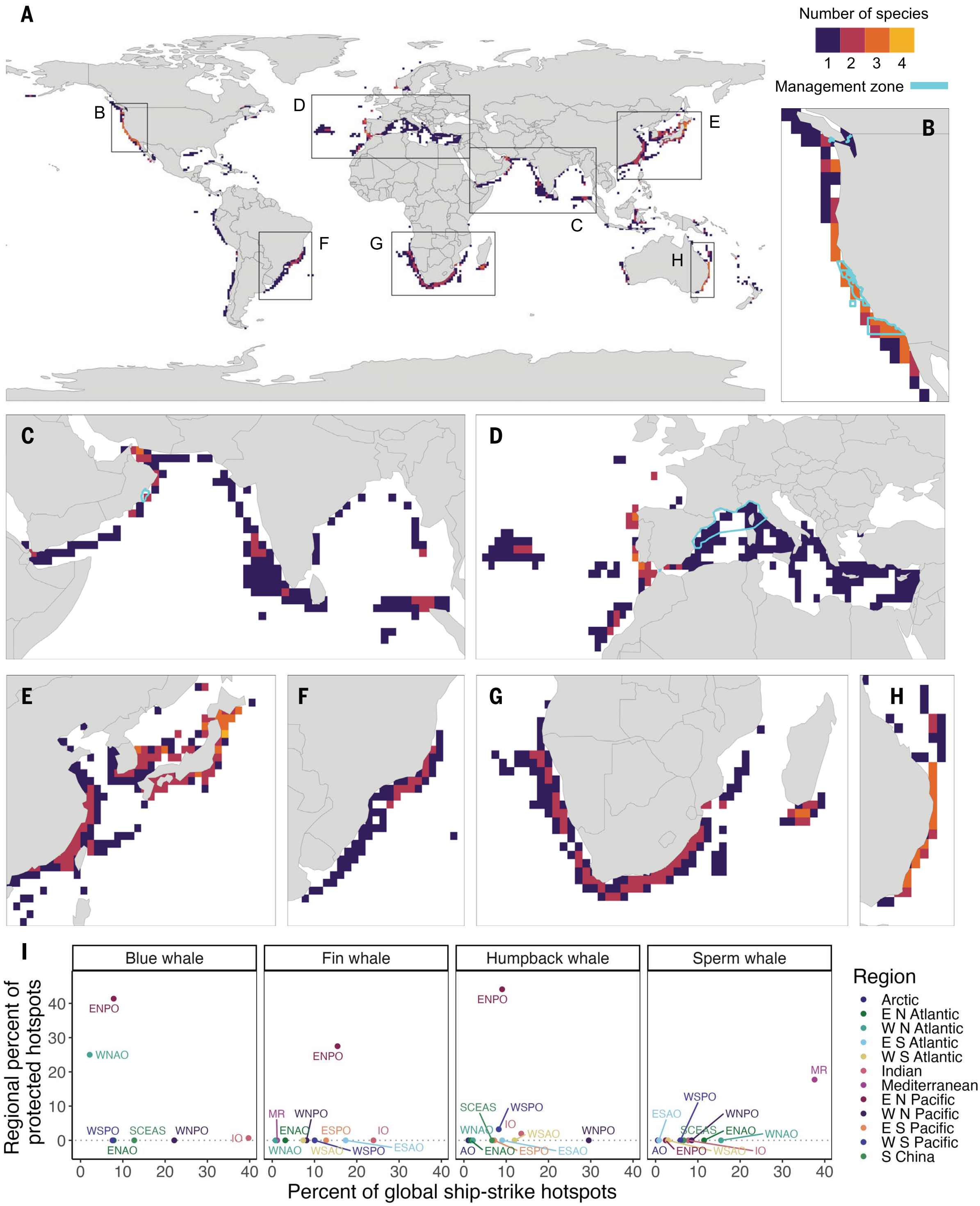

Fig. 3. Ship-strike risk hotspots for large whales. (**A**) The spatial overlap of ship-strike hotspots across blue, fin, humpback, and sperm whales. Hotspots were defined as the top 1% of ship-strike risk for each species. Boxes show the locations of zoomed-in panels (B) to (H). (**B** to **H**) Hotspots and management zones for the west coast of North America (B), the Northern Indian Ocean (C), the Mediterranean region (D), the coast of East Asia (E), the east coast of South America (F), the coast of Southern Africa (G), and the east coast of Australia (H). (**I**) Regional percentages of hotspot protection (i.e., the number of hotspots that contained any management measure, either voluntary or mandatory, divided by the number of hotspots in that region) versus the percentage of total global hotspots in each region. There were no hotspots in the Southern Ocean for any species.

along the South American coastline (e.g., the coasts of Brazil, Chile, Peru, and Ecuador), and the coast of southern Africa (e.g., the coasts of Namibia, South Africa, Mozambique, and Madagascar; Fig. 2 and fig. S16). These knowledge gaps reflect the need for additional regional studies examining whale ship strikes, particularly in the Global South. Downscaled regional whale models populated more strongly

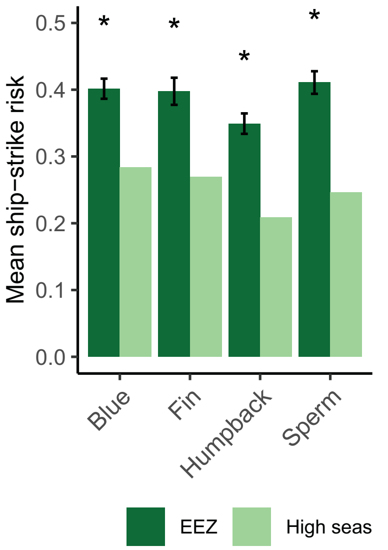

Fig. 4. Mean predicted ship-strike risk by species within exclusive economic zones (EEZs) compared with the high seas. Error bars are 95% confidence intervals, and asterisks indicate significant differences (P < 0.001).

by locally collected data will be essential for interrogating patterns of risk at higher resolutions and informing localized mitigation efforts in these understudied regions (*31*).

Our analysis underscores the importance of preserving areas with high whale space use but low shipping traffic, which were identified at high latitudes in the Arctic and Southern Oceans (Fig. 1C and fig. S20). High-whale, low-shipping areas can be considered relative spatial refugia for whales from collision risk, noise pollution, and other detrimental impacts of the shipping industry (*5*). However, it is important to note that whales are not completely free from the impacts of shipping even in these waters, as ship strikes have been reported in both regions (*18*). Climate change will also alter these dynamics at northern latitudes because of changes in whale distributions and shipping traffic. Declining sea ice in the Arctic is expected to open new trade routes and increase vessel traffic, which, combined with projected northward shifts in whale distributions driven by the same reductions in sea ice extent alongside whales tracking preferred sea surface temperatures, will likely result in higher rates of whale-ship collisions (*32*, *33*). Polar waters will also experience climate change–driven ecosystem changes that will likely be detrimental to many whale species and may compound the threats posed by shipping and ship strikes (*34*, *35*).

Our analysis additionally predicts high ship-strike risk off the coasts of China, Japan, and the Republic of Korea. Our dataset included limited whale sightings and research effort from these regions (figs. S1 to S5), with contemporary space-use patterns of our focal species in those areas remaining unclear [though see (*36*, *37*) for fin and humpback whales]. However, whaling records indicate that these regions were used historically by these species, which suggests that they may be suitable habitat that is currently unused by some species owing to the legacy of intense whaling pressure (*38*, *39*). If whale populations continue to recover, populations may increase in areas of historical whale importance—thus, regions with high levels of shipping traffic and high predicted ship-strike risk, yet limited contemporary whale sightings, remain important areas to monitor pending continued recovery.

Most ship-strike risk hotspots do not have mitigation measures in place

The majority of predicted ship-strike hotspots, even defined conservatively as the top 1% of ship-strike risk (table S2), lack any current management efforts aimed at reducing collisions. Reducing vessel speeds, which has been shown to reduce the probability that whale-ship collisions will occur as well as the lethality of vessel strikes (*40*), and routing vessels to avoid important whale habitats are the primary proposed ship-strike mitigation methods (*20*, *41*). The World Shipping Council collated existing ship-strike management measures across the globe (*42*). We digitized vessel speed reduction zones (including voluntary or mandatory zones that were spatially static and had a specific speed limit) and routing measures (including voluntary or mandatory area closures aimed at preventing ship strikes) to evaluate whether hotspots intersected a ship-strike management measure (fig. S21). We found that virtually no ship-strike risk hotspots were protected by mandatory measures (Fig. 3 and fig. S22; 0.54% of hotspots for blue whales, 0.27% for humpback whales, and 0% for fin and sperm whales). When voluntary measures were also considered, fewer than 7% of hotspots contained any management intervention for each species: 4.05% of hotspots for blue whales, 4.25% for fin whales, 4.52% for humpback whales, and 6.67% for sperm whales. Calculating the area of hotspots that currently lack any management efforts (either mandatory or voluntary) reveals that implementing vessel speed reduction zones over an additional 2.60% of the ocean's surface would be sufficient to reduce risk in all ship-strike risk hotspots, and expanding only over 0.58% would reduce risk in all multispecies hotspots (fig. S21, B and C). Although mandatory management measures are uncommon, they are likely more effective at reducing whale mortalities than voluntary programs (*43*), so expanding mandatory measures may be particularly impactful and should be considered an important piece of management portfolios.

Regional levels of hotspot protection varied substantially, and there were often mismatches between predicted risk hotspots and areas with management measures (Fig. 3I). The highest rates of regional protection were in the eastern North Pacific Ocean, with 44.1%, 41.4%, and 27.5% of humpback, blue, and fin whale hotspots protected, respectively, and the Mediterranean region exhibited the highest regional protection rate for sperm whales (17.7%). With the exception of a high regional protection rate for the very few blue whale hotspots in the western North Atlantic, all other regions exhibited very low regional protection rates (Fig. 3I). For example, the Indian Ocean contained the majority of ship-strike hotspots for blue whales, but <1% overlapped with a management measure. Similarly, several regions contained relatively high proportions of species' hotspots but none that intersected with any management measures, including the Indian Ocean, eastern South Atlantic, and South Pacific for fin whales; the western North Pacific for humpback whales; and the North Atlantic for sperm whales. These results reflect the fact that there are entire regions that lack any ship strike–related management efforts for the species considered in this work, such as the South American coastlines and the coast of southern Africa (Fig. 3, A, F, and G). This highlights the widespread opportunities for expanding ship-strike mitigation programs, which can confer important cobenefits beyond whales. For example, slow-speed measures result in reduced air pollution [which negatively affects human health and is often high around ports (*44*)], greenhouse gas emissions (*45*), and underwater noise pollution (*46*). Implementing vessel speed reduction programs can thus be a win-win-win for marine species, the climate, and public health (*41*).

The international nature of the shipping industry as well as the cosmopolitan nature of whale migrations and space use pose challenges for implementing mitigation efforts. However, risk was higher within exclusive economic zones compared with the high seas (Fig. 4A), and exclusive economic zones contained nearly all risk hotspots (98.1% of blue whale hotspots, 95.8% for fin whales, 100% for humpback whales, and 97.6% for sperm whales). Within exclusive economic zones, countries have exclusive jurisdiction over marine resources and can propose changes in vessel operations, including speed reductions and routing changes, to the International Maritime Organization (*20*). Thus, this result indicates that ship-strike risk could largely be addressed with national proposals and resulting regulation rather than through international mandates necessary for high seas conservation. In addition, most marine protected areas do not currently include any ship-strike management measures (*42*), and risk was higher within compared with outside marine protected areas for most regions (fig. S23); this indicates that including speed restrictions could be a pathway for marine protected areas that contain risk hotspots to more fully meet mandates to protect biodiversity and marine resources. Because all large whales are transboundary species, international coordination across neighboring countries that share adjacent ship-strike hotspots is essential to effectively protect whale populations across their migratory routes and to ensure that management in one area does not lead to unintended spillover of shipping traffic to other sensitive areas (*47*, *48*).

Conclusions

Whales experience high ship-strike risk across large extents of the world's oceans, and the majority of high-risk areas lack management efforts aimed at mitigating this issue. Ship-strike management measures, such as vessel speed reductions and changes in vessel routings, must be urgently expanded to conserve and recover the great whales. This is especially important in the many regions that have received less research attention and lack ship-strike management efforts—including regions along the South American coastlines and the coast of southern Africa—and for whale populations that are struggling to recover, such as Arabian Sea humpback whales. Our study highlights that expanding management efforts over only an additional 2.6% of the ocean would protect the highest-risk areas and could largely be accomplished through changing regulations within preexisting management boundaries. Moving forward, there is also an urgent need to expand and support country-led long-term monitoring of shipping lanes to improve ship-strike reporting (*18*, *19*), implement effective enforcement of management measures, and ensure that management efforts are adaptive to future changes in whale and shipping distributions.

Our study opens several doors for understanding threats to highly mobile species on our changing planet. First, the shipping industry is the largest source of anthropogenic ocean noise, which negatively affects whales through behavioral disruption, alteration of communication, and increased stress (*5*, *49*). Although underwater noise propagation is a complex process that depends on bathymetry and other factors, in quantifying whale-ship overlap, our analysis also sheds light on areas where whales are likely to be exposed to higher levels of noise pollution. Because vessels typically emit less noise when traveling at slower speeds, vessel speed reductions can often reduce both ship-strike risk and noise pollution (*41*, *46*). Additionally, our species distribution models can be used to quantify large whale exposure to other important anthropogenic threats, including entanglement with fishing gear (*50*), and to predict how cetacean distributions, and in turn ship-strike risk, will shift with climate change. Global leaders have committed to protecting 30% of the ocean by 2030; broadscale information on the distribution of whales and their threats is particularly timely to ensure that these newly protected areas are effectively placed to conserve whales. Finally, beyond the great whales, our predictive framework for integrating disparate data types to support large-scale modeling provides a road map for additional applications to evaluate other marine species that are threatened by the impacts of marine shipping, such as smaller cetaceans, sharks, sea turtles, and other marine mammals (*5*, *8*, *49*), thus paving the way for identifying multispecies and multitaxa hotspots. The increasing availability of biologging data makes it possible to synthesize species' space-use patterns across larger geographic scales, which can shed light on species' exposure to threats and inform mitigation efforts across wider extents of our planet.

Mitigating the negative environmental impacts of marine shipping is essential for the coming decades (*3*). Changes in ocean ecosystems caused by the loss of historic whale populations have been hard to reverse. Ship-strike risk is a ubiquitous yet solvable conservation challenge for large whales, and our results can provide a foundation for expanded management measures to protect these ocean giants.

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SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.adp1950
Materials and Methods
Figs. S1 to S23
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MDAR Reproducibility Checklist
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