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Review

Current global risks to marine mammals: Taking stock of the threats

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ABSTRACT

Marine mammals are impacted by many anthropogenic activities and mitigating these impacts requires knowledge about the geographic occurrence of threats. Here, we systematically reviewed, categorized and georeferenced information from > 1780 publications about threats affecting 121 marine mammal species worldwide between 1991 and 2016. We created risk maps by assigning threat to countries where they had been reported, further refining spatial allocation to specific ocean basins and Longhurst biogeographical provinces and subsequent intersection with mapped species' distributions. We superimposed risk maps for different taxa and threats to visualize geographic patterns of risks and quantify risk severity with respect to number of species affected. Almost all marine mammal species have been reported to face at least one threat. Incidental catch affected the most species (112 species), followed by pollution (99 species), direct harvesting (89 species) and traffic-related impacts (86 species). Direct human activities, mainly fisheries, urban development, whaling/hunting and tourism were the major source of threats affecting most species (> 60 species). Risk areas were identified for 51% of marine mammal core habitat. Besides, the majority of local marine mammal communities are at high-risk in 47% of world coastal-waters. Hotspots were located mainly in temperate and polar coastal waters and in enclosed seas such as the Mediterranean or Baltic Sea. However, risk areas differed by threat types and taxa. Our maps show that human activities in coastal waters worldwide impose previously unrecognized levels of cumulative risk for most of marine mammal species, and provide a spatially explicit frame of reference for the assessment of mammals' species conservation status.

1. Introduction

For decades, it has been well known that many marine species are threatened directly or indirectly by human caused deterioration of their environment (International Union for Conservation of Nature and Natural Resources – IUCN, 2016). Marine mammals, a variable group encompassing 121 recognized mammal species, including cetaceans, pinnipeds, sea otters and sirenians (Committee on Taxonomy, 2016), are distributed throughout all the world's oceans (Berta and Sumich, 1999). Regardless of their size and status as “charismatic megafauna”, our current knowledge about species distributions and conservation status is still patchy, with 45 species (37% of species) being classified as “data deficient” by the International Union for the Conservation of Nature (International Union for Conservation of Nature and Natural Resources – IUCN, 2016). Moreover, because of their diversity and cosmopolitan presence in marine ecosystems, many marine mammal species are known to be impacted by various anthropogenic activities, including fisheries, hunting, transportation, oil and gas extraction (Whitehead et al., 2000; Gales et al., 2003; Reeves et al., 2003; Helm et al., 2014). As a result, almost 33 species (i.e. half of all marine mammal species not classified as data deficient) are currently classified as globally endangered or threatened (International Union for Conservation of Nature and Natural Resources – IUCN, 2016).

Threat is a stressor, action or event that causes harmful effects, while risk is the possibility of experiencing harmful effects due to exposure to a threat factor (EPA, 1998). Threats impact the conservation status of taxa, putting species or populations at some level of risk of potential long-term or short-term extinction (Salafsky et al., 2008; International Union for Conservation of Nature and Natural Resources – IUCN, 2016). Threats can act at the level of individuals, or at population level. At either level, threats over marine mammals can have direct (mortalities and injuries) or indirect effects (physiological or behavioural changes resulting in reduced fitness or productivity). Generally, population-level effects – as well as synergistic effects of multiple stressors – are more difficult to quantify and measure (McHuron et al., 2017), however, even the magnitude of threats at the level of individuals can be difficult to assess for marine mammals. Threats acting at the level of individuals include, for instance, direct harvest (Clapham

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and Baker, 2009; Robards and Reeves, 2011), incidental entanglement in fishing gear (Read et al., 2006) and in marine debris (Baulch and Perry, 2014), as well as vessel collisions (Van Waerebeek et al., 2007) and infections (Van Bressem et al., 2015). Whale watching is another important type of threat acting at both levels which has been shown to cause disturbance resulting in changes in behaviour, potentially linked to temporary, or permanent habitat exclusion (Avila et al., 2015). Acoustic pollution of the marine environment can affect marine mammals by masking echolocation signals and social vocalizations, or by causing damage of the hearing system (Weilgart, 2007; Gómez et al., 2016). Especially in coastal areas, species are also threatened by habitat loss – including the depletion of foraging grounds due industrial development and destructive fishing techniques (Marsh et al., 2002; Reeves et al., 2003). Pollutants, through bioaccumulation, can disrupt normal endocrine physiology in animals and contribute to the increase of infectious disease outbreaks (Desforges et al., 2016) and oceanographic changes in marine environments related to climate change may either directly or indirectly impact many species through effects on prey or habitat availability (Simmonds and Isaac, 2007; Kaschner et al., 2011).

To mitigate negative impacts on species, identification of areas for marine mammal conservation is needed (Corrigan et al., 2014). Visualizations of geographic patterns of known or potential impacts on ecosystems and species in the form of maps, so-called “risk maps”, allow the identification of risk hotspots and are often used for prioritization of conservation measures or actions (e.g. Halpern et al., 2008, 2015; Schipper et al., 2008; Trebilco et al., 2011; Coll et al., 2012). To date, some efforts have been made to assess threats for all or some marine mammals at global scales. These efforts have either assessed worldwide anthropogenic impacts focusing on specific taxa, such as pinnipeds and mysticetes (Kovacs et al., 2012; Thomas et al., 2015) or only migratory species (Lascelles et al., 2014) and do not provide spatial detail. Similarly, Schipper et al. (2008), Pompa et al. (2011), Davidson et al. (2012), González-Suárez et al. (2013) and Albouy et al. (2017) have included all marine mammals in their analyses, but in a generic way and therefore do not allow the analysis of threats specific to species, to location or to time of year. Although some studies have attempted to summarize and visualize threat levels of a specific type of threat in geographic space (e.g. by-catch: Lewison et al., 2014), an overview of our current knowledge about the presence and location of different threats that different marine mammal species are exposed to worldwide is currently lacking. Hence, to establish appropriate conservation actions and mitigate any impacts for marine mammals, one first needs to know where threats have been documented and which species are known to be affected.

Here, we constructed a geo-spatial database of published information of threats affecting 121 marine mammal species, from which we subsequently produced a series of risk maps visualizing global patterns. Risk maps as GIS files and the database used for their construction are made freely available for non-commercial use to support global and local research and conservation actions. Our threat classification expands upon the existing IUCN Threats Classification (Salafsky et al., 2008; International Union for Conservation of Nature and Natural Resources – IUCN, 2016) by including new terms that are specific to marine mammals. Threat allocation in space was based on intersections of several geo-spatial layers including political, oceanographic and species-specific information. Superimposing the resulting risk maps for specific threat types across species groups and vice versa provides a quantitative visualization of our current knowledge about different threats affecting marine mammals, and offers a frame-of-reference for the assessment of conservation status of marine mammal species and a starting point for the quantification of the cumulative effects of human activities on marine mammal populations and habitats.

2. Methods

2.1. Database of marine mammal threats

We defined a threat to a marine mammal as an event that induces, to the individual, disturbance, behavioural and distribution changes, disease, health problems, physical restraint, injury or death; or, at the population level, decrease breeding success, gene flow or population size. To document which threats affect which marine mammal species where and when, we compiled a database from the scientific literature. This involved three steps: 1) the definition of threat types, 2) the compilation of information about species-specific threats documented in the scientific literature, and 3) the standardized spatial allocation of threats using available geo-political, oceanographic and ecological map layers.

2.2. Threat classification scheme

To define threat types, we modified and expanded the existing Threats Classification Scheme of the International Union for the Conservation of Nature (International Union for Conservation of Nature and Natural Resources – IUCN, 2016), including new terms that are relevant for marine mammals. Our approach classifies different types of threat by identifying the threat category (proximate origin, which is the agent inflicting the actual harm itself) and the threat source (defined as the ultimate origin of the threat). An attribute was added to allow for further distinction within the fairly generic threat categories used originally by the IUCN (e.g. within “traffic”: boat noise vs collision with boats). Within this classification scheme the same threat category can therefore be linked to different ultimate threat sources (e.g. noise pollution due to military activities or from energy production). Similarly, threat attributes can be associated with more than one threat category (e.g. incidental catch in ghost nets, which is both incidental catch and pollution; some liquid waste, such as ballast water, is part of pollution and traffic; noise produced from boat engines is part of pollution and traffic).

We identified seven threat categories, 28 threat attributes and 13 threat sources affecting currently the marine mammals (Fig. 1). The seven threat categories were based on the agent inflicting the actual harm and were: incidental catch, direct harvesting, pollution, traffic, pathogens, resource depletion and ocean-physics alteration. Each of the threat categories was subdivided into a threat attribute with additional information such as type of pollution or reason for harvesting and others. We distinguished two general types of threat sources, those related to direct human activities and those that are not. Threat sources, following the IUCN threat classification scheme were: aquaculture and agriculture; fisheries, hunting and whaling; energy production from oil, gas and mining; energy production from nuclear power; energy production from renewable resources; residential and industrial development; tourism and recreation; scientific research; military activities; climate change and geological events; and unknown or unreported (see Appendix A for definitions). Only climate change and geological events were defined as threat sources not directly related to human activities. Finally, the detailed combinations of threat category, threat attribute and threat source create 110 threat sorts (e.g. pollution-liquid wastes-URBA or pollution-liquid wastes-MILI; see threat database in Appendix B for details). This newly developed classification scheme allows for a maximum in flexibility and accuracy when encoding information from the literature, while at the same time ensuring that encoded data can be mapped back easily to the IUCN Threat Classification Scheme.

2.3. Literature sources, search criteria and data encoded

To compile documented threats to marine mammals we used sources provided in the IUCN Red List (International Union for Conservation of Nature and Natural Resources – IUCN, 2016) and the

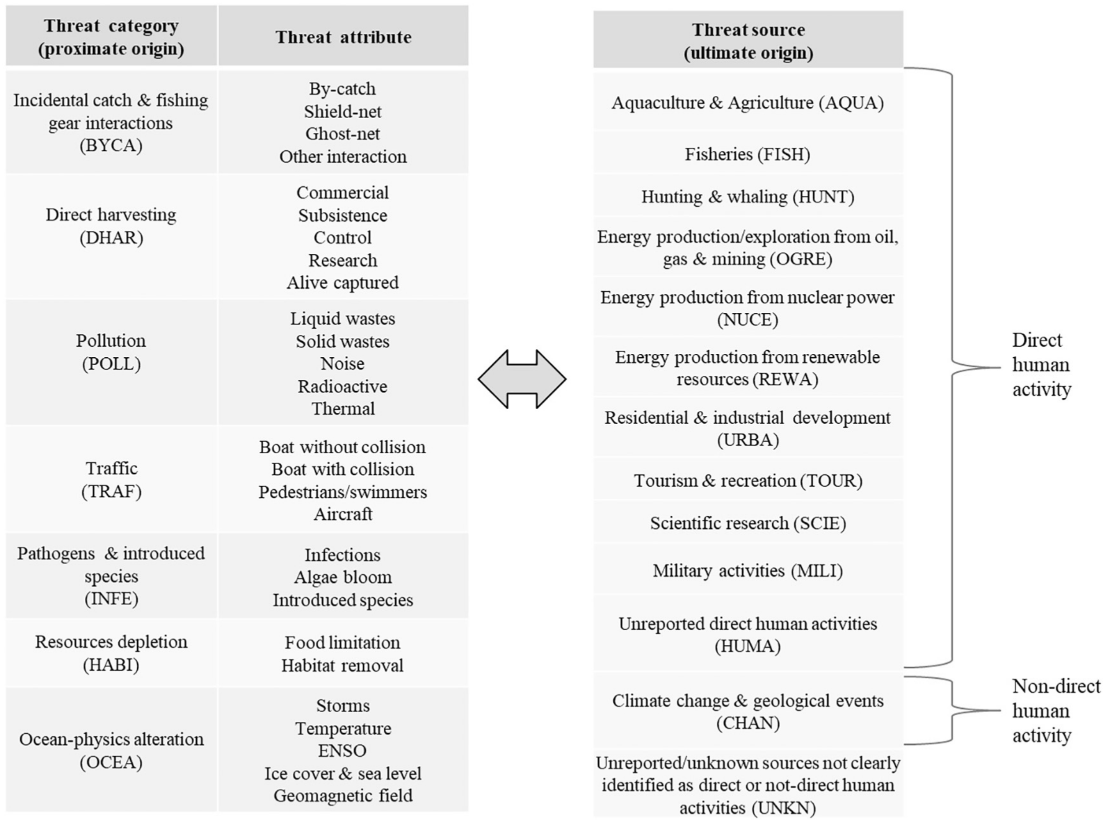

Fig. 1. Structure of the classification of threats for marine mammals used in our threat database. Threat sources (right) classified in this study as direct human activity or not, follow the general IUCN threat classification scheme (version 3.2), while category and attribute (left) provide a more natural scheme for marine mammals. Abbreviations are denoted in parenthesis (see definitions in Appendix A). The combination of threat category, attribute and source yield a fine-grained threat sort (see threat database in Appendix B for details).

Encyclopedia of Marine Mammals (Perrin et al., 2009) as starting points. These were supplemented by reviews focusing on threats specific to cetaceans (Culik, 2010; Thomas et al., 2015), pinnipeds (Kovacs et al., 2012) and sirenians (Marsh et al., 2011). We used a "snowball approach", reviewing references identified in one source recursively. Additionally, we conducted a literature search using the online search engines Google Scholar (https://scholar.google.de) and Web of Science (http://apps.webofknowledge.com). We included records of scientific journals, published books and available "grey" literature (e.g. International Whaling Commission papers). The web searches were performed using several key words, including the scientific and common name of the species, the genus of the species, and the name of the threats (e.g. by-catch, collision, hunting, pollution, contaminants, disease, habitat loss, whale-watching).

To be included in the database, the study had to meet the following criteria:

- Data were presented in a scientific publication (journals or reports) or had been collected using a published methodology;
- Studies were published between January 1, 1991 and December 31, 2016;
- Studies were conducted on wild animals and if reporting threats, these had to have occurred between 1991 and 2016;
- Threats were non-experimental (i.e. data collected during experimental and controlled studies such as playbacks were not included);
- Reports of threat had to be identified to the species level, as recognized by the Committee on Taxonomy (2016);
- We included 121 marine mammal species, which comprise those restricted to the marine environment, or those occurring in freshwater and marine, but using only the information occurring in the marine environment. We excluded freshwater species and those only found in inland body waters (include inland body saltwater). Specifically, we included 71 Odontoceti and 14 Mysticeti (Cetacea), 31 Pinnipedia and 2 Fissipedia (marine; Carnivora) and 3 sirenians (Sirenia). We excluded the polar bear (*Ursus maritimus*), because it spends several months on land, especially in the summer open water season (Wiig et al., 2015).

We subsequently encoded information about threats affecting specific marine mammal species in a relational database. From the documentation we collected, we obtained the following:

- Identities of the taxa threatened resolved to the species level;
- Threat the species is exposed to, identifying category, attribute and source of the threat;
- Year(s) during which the threats were reported; when available, we established the year when the threat started and the year when the threat ended;
- Geographic location where the threat was observed, based on a standardized allocation scheme using a set of geo-spatial filters (see below);
- Other information relevant to threats and affected species, such as more details on specific harm caused (e.g. death, injury, disturbance);
- Data source, including primary and secondary source (if there is another reference that complemented or reported the same case).

In our database, we encoded threat observations at the resolution of documented presence of each threat per species per location per year per data reference.

We initially assessed the actual extent of documented global threats, without considering their spatial distribution, by summarizing the total number of threats reported to affect different species/taxa of marine mammals. Based on the presence/absence of reported threats we obtained the number of species documented to be affected by different threat categories, attributes and sources. Based on the total number of species included in this study, we calculated the percentage of species of each taxon group (i.e. Odontoceti, Mysticeti, Pinnipedia, Fissipedia and Sirenia) documented to be affected by different threat categories and sources.

During our literature search, we screened about 3360 published and available papers and documents. Based on the criteria described above, we encoded information from a subset of 1786 references in the database (Appendix C). To ensure high literature coverage, after doing the first risk maps overview, we focused our search on the gaps, looking for species documented without threats (using as key words the scientific and common name of the species) and looking for places/countries without documented threats (using as key words the name of the place/country and marine mammals). Then, we performed a sensitivity analysis in R (R Core Team, 2016) to evaluate whether the total number of papers we screened was sufficient to assess the occurrence of the seven threat categories per taxonomic group. Within the pool of reviewed paper, we randomly drew N publications and counted the number of threat documented per taxon. We repeated the random draw 100 times, with N ranging from one to the maximum number of papers screened by taxon. The results show that our coverage far exceeded the required number of papers to identify all threats to any group of marine mammals (Appendix D).

2.4. Spatial allocation of threats

Information about geographic location of threats was reported with very variable precision, hence we developed a standardized approach using a set of biogeographic filters to allocate threat data to geographic regions at the highest possible resolution. We geo-referenced threats by assigning threat reports to national waters of countries in which the threat had been reported, further refining this by allocation to specific ocean basins and to Longhurst biogeographical provinces (Longhurst, 2006). We defined countries' national waters (EEZ) using the boundary definitions for 195 countries with territorial seas (VLIZ, 2014). Longhurst biogeographical provinces represent a classification scheme that partitions the world's oceans into 54 areas, based on their specific biogeochemical or oceanographic attributes. A higher level of aggregation of Longhurst regions are ocean basins: Mediterranean and Red Seas, Pacific, Atlantic, Indian, and Arctic oceans. Therefore, the highest spatial resolution for threat localization in the database was the intersection between these three different environmental and geo-political boundary layers, for which we created the threat maps (Fig. 2, layers 1–3). Maps were created using ArcGIS software (ESRI, 2015).

If a threat was reported at a coarser scale, for example in the Eastern Tropical Pacific, we inferred the country allocation based on the information provided by the reference (typically a map) or we assigned the threat to all the countries that are in this area. Furthermore, in the geo-referencing process, wherever possible we used the location information of the actual threat impact as provided. When it was not reported or not possible to be identified, we used the location of the report as the location of the threat (some threats were reported for the location where the threat occurred, e.g. site of ship collision, while others were reported according to the place where the animal or specimen was registered with a sign of a threat, e.g. a stranded animal with injuries or scars from a ship collision).

Finally, since the spatial co-occurrence of threats and species is a logical pre-requisite for any threat to have an impact, we imposed another layer of geographic restriction to further improve geo-spatial identification of risks by intersecting encoded species-specific threat localities with mapped species' distributions in a GIS framework. Here, we used predicted marine mammal species distributions produced by AquaMaps (Kaschner et al., 2016) (Fig. 2, layer 4). AquaMaps is an online atlas of marine species distributions (www.aquamaps.org). Species distributions are generated using an environmental niche modelling approach, which derives broad envelopes of species-specific habitat usage with respect to basic environmental parameters (depth, sea surface temperature, salinity, primary production and sea ice concentration and, in some cases, distance from land). The resulting maps represent the annual average predictions of the maximum range extent of species (defined as the maximum area between the known outermost limits of a species' regular or periodic occurrence) and gradients of relative environmental suitability, RES, ranging from 0.0 to 1.0, predicted for each 0.5 degree latitude by 0.5 degree longitude cells (Kaschner et al., 2006, 2011, 2016; Appendix E).

To take a more conservative approach with respect to assumptions about species occurrence, we produced risk maps based on binary (presence/absence) range maps using the *core habitat*, defined as species present in any cell with a species-specific predicted probability threshold of ≥ 0.60. AquaMaps maximum range extents for marine mammals show a very good correspondence with IUCN distribution both in terms of spatial alignment and overall size (O'Hara et al., 2017), but in some cases predicted maximum ranges correspond more closely to the potential or historical niche of a species. However, validation analyses showed the best fit between observed number of species and predicted species richness (indicating an increase of regular occurrence of species in areas of predicted suitability above the probability threshold of 0.60 (Kaschner et al., 2011). Therefore, species-specific risk maps based on predictions of core habitat correspond to locations where probability of exposure to the risk is likely highest.

We superimposed localized threat layers for different species or threat types to visualize geographic patterns of risk intensity with respect to the number of species affected by a given threat. These maps allow the assessment and comparison of current knowledge about different threats affecting all marine mammals. In addition, to visualize how much of the locally occurring marine mammal species community is known to be affected by threats, we also produced risk maps showing the calculated relative proportion of species predicted to occur in a given area for which threats have been documented. We identified risk intensity according to: 1) the number of species exposed to threats per cell, where high-risk areas or hotspots were defined as areas with a relative higher number of species exposed to threats; and 2) the percentage of species with documented threats of the total of species predicted to be present per cell, where high-risk areas or hotspots represent the top 25th percentile of locally predicted species richness, i.e. areas where > 75% of the marine mammal species occurring locally were exposed to threats. In addition, we calculated the "distribution area at risk" by identifying cells with documented threats per species, and calculating the mean areas-at-risk by summing the area of all cells within a species-specific predicted core area with a documented species-specific threat; then, we obtained the mean proportion of core area affected across all species by calculating the relative proportion of species core areas affected by any threat. Furthermore, to identify risks by coastal or oceanic waters, we defined coastal waters in our maps, based on the edge of the continental shelf, as those cells < 200 m in depth and oceanic $\geq$200 m (Mann, 2009).

Marine mammal species classification in AquaMaps follows the Taxonomy of Catalogue of Life (http://www.catalogueoflife.org/col/). There are some discrepancies between this classification and the taxonomy of the Committee on Taxonomy (2016). Some of the species recognized by the Committee are not yet considered as a separated species, including e.g. *Balaenoptera omurai*, *Mesoplodon hotaula*, *Neophocaena asiaeorientalis*, *Sousa sahulensis* and *S. plumbea*. Besides, some of the species recognized by AquaMaps are not considered as a separated species by the Committee on Taxonomy e.g. *Arctocephalus townsendi*, *Balaenoptera brydei* and *Delphinus capensis*. Here, we therefore lumped together information of geo-referenced threats of *B. omurai*, *B. brydei* and *B. edeni*, *A. townsendi* with *A. philippii*, *D. capensis* with *D. delphis*, *M. hotaula* with *M. ginkgodens*, *N. asiaeorientalis* with *N. phocaenoides*, and *S. sahulensis* and *S. plumbea* as part of *S.chinensis*. Furthermore, AquaMaps does not provide distribution information for

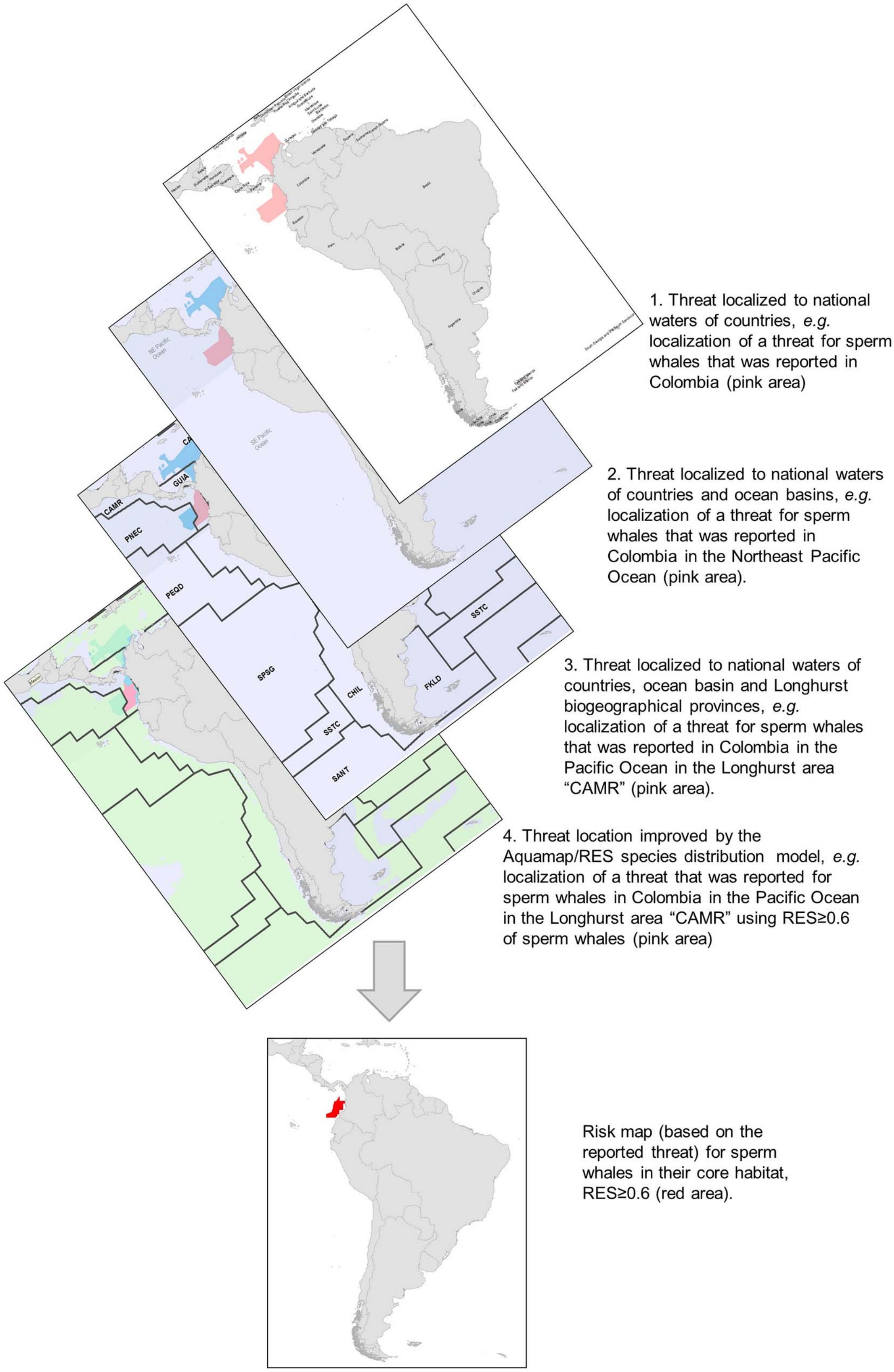

Fig. 2. Procedure for spatial allocation of documented threats per species. Layers 1–3 show localization of threat reports to national waters of countries, ocean basins and Longhurst biogeographical provinces, resulting in spatially-explicit threat maps. Risk maps were obtained by intersection of threat maps with predicted core habitat of the species reported to be affected by the threat (Layer 4) resulting in further refinement of threat localization.

marine otter *Lontra felina* and African manatee *Trichechus senegalensis*, therefore these marine mammal species were not considered in the risk maps. As a result of these taxonomic discrepancies we produced risk maps for 114 different species.

3. Results

3.1. Documented threats faced by marine mammals

It is important to note that the following results are based on only those threats that had been reported in the literature screened during the process of this study. Despite our efforts we may have missed some reports of threats and – probably more importantly – there are not necessarily published records of all threats affecting all species everywhere. As a consequence, our overview represents the minimum baseline of existing threats affecting marine mammal species. Our sensitivity analysis (Appendix D) indicated though that we screened a satisfactory number of papers able to detect the occurrence of all seven threat categories in all taxonomic groups and the results are therefore based on a representative sample of the literature. For some geographic areas, we found > 125 references documenting threats, namely coastal waters of the North Hemisphere in North America, Europe and eastern Asia (Appendix F).

Between 1991 and 2016 almost all studied marine mammal species, 98% (119 species), were documented to be affected by at least one threat. The only species for which no recent threats have been reported, are the spade-toothed beaked whale (*Mesoplodon traversii*) and Perrin's beaked whale (*M. perrini*). Both of these species are only known from a handful of stranding records and have never been seen alive (Pitman, 2009; Thompson et al., 2012). In contrast, the bottlenose dolphin (*Tursiops truncatus*), one of the most common and widespread marine mammal species (classified as least concern by the IUCN; Hammond et al., 2012) is documented to be affected by the largest range of threats (6 categories, 11 sources and 19 attributes, resulting in a total of 47 distinct threat sorts reported). Overall in terms of marine mammal families, Delphinidae was the family most threatened (70 distinct threat sorts) followed by Phocidae (50 threat sorts), while the less threatened were Neobalenidae (3 threat sorts) and Odobenidae (7 threat sorts; Appendix B).

We identify incidental catch as the most common threat category, affecting 112 species, followed by pollution (99 species), direct harvesting (89 species) and traffic (86 species) (Fig. 3A). In contrast, threats associated with ocean alterations were reported for comparatively few species. Across all threat categories, in absolute terms odontocetes and pinniped species are generally affected in highest numbers (69 species and 31 species respectively). However, threat categories seemed to affect a larger proportion of the overall taxonomic group for sirenians and fissipeds (Fig. 3A).

Our more detailed analysis of threat attributes showed an unequal distribution of specific threat types for most species groups with some threats having been documented much more frequently than others (Fig. 3B). For instance, reports of incidental catches were mostly related to by-catch (defined as the catch of marine mammals in active fishing gear), while incidental catches in ghost nets or shield nets were reported less frequently. Similarly, subsistence hunting represented the most common type of direct harvest and reports of threats related to solid wastes were more common than those related to noise pollution. Moreover, the relative impact of different threat types was variable across different taxa, except for by-catch, which was present in at least 90% of species in each taxon group. In addition to by-catch, commercial hunting and solid wastes were the main threats for odontocetes while boat collision and solid wastes were the largest threats for mysticetes. Ghost-net entanglements, solid and liquid wastes, and infections were the main threats for pinnipeds. Major threats for fissipeds were liquid wastes, boat traffic and infections. Harvesting (commercial, subsistence and live-capture), liquid wastes, boat collision and habitat removal were the main threats for sirenians (Fig. 3B).

There were a large number of different sources responsible for threats affecting marine mammals. Except for climate change and geological events (CHAN) and unidentified sources (UNKN), all threat sources were clearly due to direct human activities. Direct human activities affected all species documented with threats (119 species), while climate change and geological events affected 34% of threatened species (40 species). It should be noted that there was a high number of unidentified sources (UNKN) documented for 67 species (Fig. 3C). While some sources affected the majority, if not all species (e.g. fishery activities (FISH, 113 species) and residential and industrial development (URBA, 92 species)), other threat sources such as renewable energy production (REWA) were much restricted and have – so far – been only reported for a handful of species (8 species; Fig. 3C). Most threat sources were responsible for producing more than one type of threat category (Fig. 3D). For instance, fishing activities (FISH) was reported as the ultimate source for five out of all seven threat categories ranging from incidental catch to pollution and resource depletion. Other sources such as urban development (URBA) or energy production/exploration from oil (OGRE), in contrast, tended to be the ultimate cause of a lesser variety of threats, although this, of course, does not allow an assessment of the relative severity of threat category impacts of different types of sources (Fig. 3D).

3.2. Where are the risk based on documented threats?

3.2.1. Distribution area in risk

Threats for marine mammals have been documented on average in 51% of their core habitat (Table 1, Appendix G). For species with a higher IUCN conservation status (e.g. critically endangered, endangered) on average a higher proportion of core area was affected (Fig. 4). Although there was considerable variation between species, mean proportion of core area affected by threats was also quite high for species classified as "data deficient" as well as "least concern". In the latter case, almost 50% of core habitat was affected on average (Fig. 4).

3.2.2. Marine mammal diversity is at risk in coastal waters worldwide

We identified some high-risk areas where > 20 species were exposed to threats. Such hotspots of documented risks were located along both the Pacific and the Atlantic coasts of the United States as well as around Japan, while hotspots along southwest Australia and southeast South America and western Africa were much smaller (red areas Fig. 5A). In terms of the locally occurring marine mammal species community, we identified several high-risk areas, where > 75% of all marine mammal species occurring locally was exposed to threats. Such hotspots were mainly in coastal waters and existed around each continent, although hotspots were comparatively small along the coasts of Eastern Africa (red areas Fig. 5B). We identified 203.9 Mio km^2 in there is some documented risk for at least one species of marine mammals, which means that marine mammal species are at some level of risk in 56% of the total ocean worldwide. Similarly, we found that the majority of species was affected (> 75% of all locally occurring species) in 47% of coastal water (mean depth < 200 m; see Table 2).

3.2.3. Risks are globally distributed, with several hotspots that differ by threat category

The locations of reported threats affecting the largest number of species varied with different threat categories. We mapped global risk patterns of major threat categories, such as incidental catch and fishing gear interaction, direct harvesting, pollution and traffic (Fig. 6).

Again, we defined high-risk areas for different threat categories as areas in which > 75% of the locally occurring marine mammal species were exposed to different threats, respectively. As can be seen, incidental catch is the most widespread threat reported to occur – on average – in 39.1% of the core habitat of different species (Fig. 6A; Appendix G). High-risk areas for incidental catch were ubiquitous – at

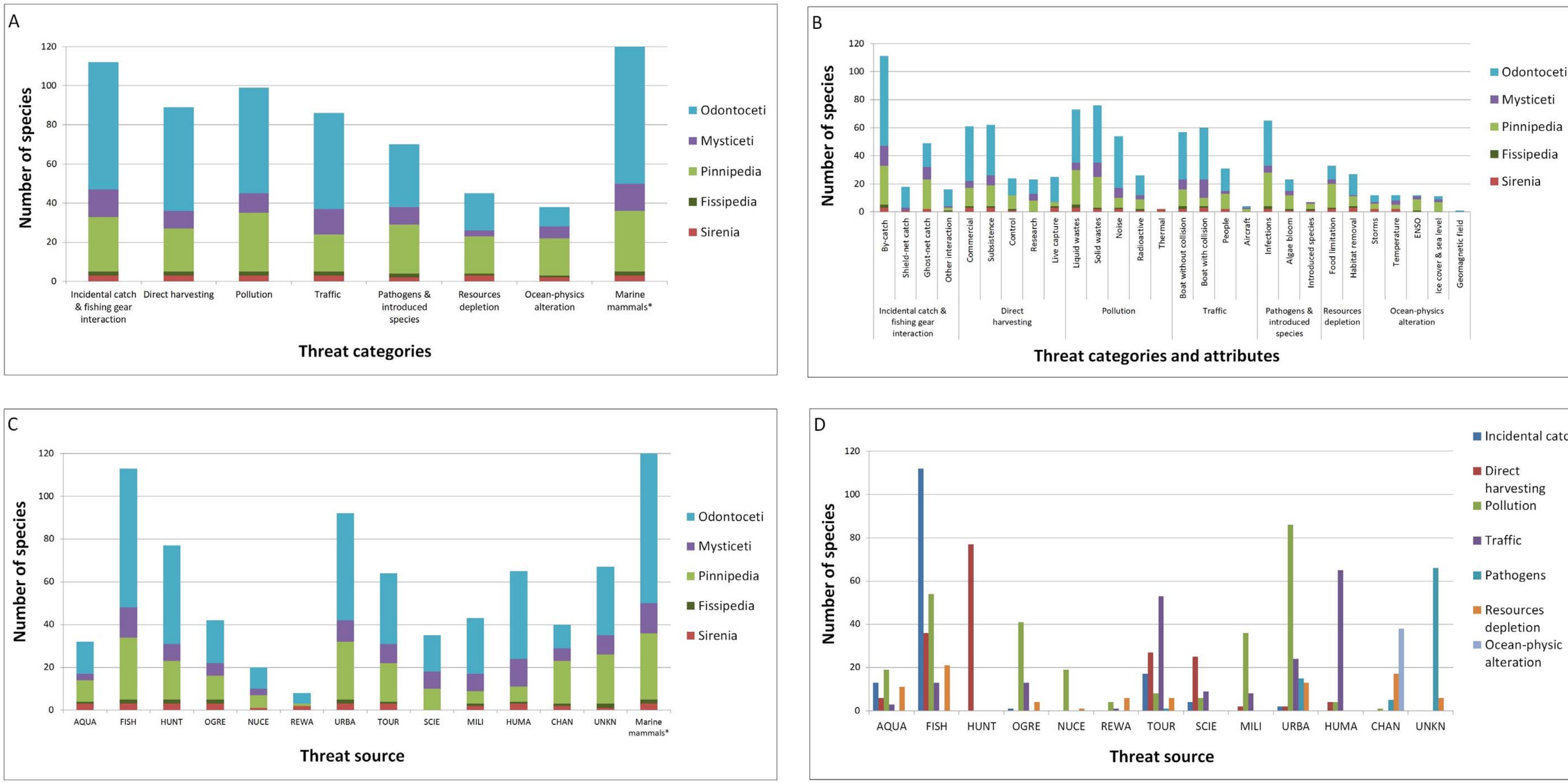

Fig. 3. Threats documented to affect (between 1991 and 2016) marine mammals. (A) Number of species of each taxon documented to be affected by different threat categories. (*) Last bar shows the number of species per taxon to allow an assessment of the proportion of affected species in each taxon. (B) Number of species per taxon group documented to be affected by different threat attributes in each category. (C) Number of species of each taxon documented to be affected by different threat sources. (*) Last bar shows the number of species per taxon. (D) Number of species in each threat category documented to be affected by different threat sources. See Fig. 1 for abbreviations.

Table 1
Showing average core areas at risk for different taxonomic groups including all marine mammals. Mean areas-at-risk were obtained by summing the area of all cells within a species-specific predicted core area with a documented species-specific threat. Mean proportion of core areas affected across all species was obtained by calculating the relative proportion of species core areas affected by any threat (see Appendix G for individual species). Large standard deviations indicate substantial differences between species within a group.

Taxonomic group	Mean size of core area (in Mio km^2) across species ± SD	Mean size of core area affected (Mio km^2) across species ± SD	Mean proportion of core area affected across species ± SD
Odontoceti	33.4 ± 44.2	7.1 ± 12.5	40.4 ± 34.8
Mysticeti	72.9 ± 74.3	16.7 ± 25.9	33.0 ± 31.7
Pinnipedia & Fissipedia	5.0 ± 10.8	2.2 ± 2.1	76.6 ± 28.1
Sirenia	1.9 ± 1.5	1.8 ± 1.5	94.5 ± 4.7
All marine mammals	29.4 ± 46.6	6.7 ± 13.5	50.7 ± 36.8

least in temperate waters – but were concentrated in coastal areas, enclosed seas and some oceanic areas of the Tropical Eastern Pacific and North Atlantic (red areas, Fig. 6A). A noted exception is Antarctic waters where comparatively less fishing activity takes place (Fig. 6A). Incidentally, patterns for incidental catch and direct harvesting were almost complementary, with incidental catch being concentrated in temperate waters and direct harvesting being comparatively more prevalent in polar waters of the Northern hemisphere (red areas, Fig. 6A,B). Given the time period covered by this study, which post-dated the IWC whaling moratorium, however, there were few hotspots of direct reported catches in waters of Antarctic and Arctic waters (Fig. 6B).

Reports of pollution and traffic, in comparison, were more restricted to coastal waters, especially at high latitudes and generally affected a smaller proportion of the core habitat of species (Fig. 6C,D). Not surprisingly, pollution hotspots were mostly located along the coasts of industrialized nations, but there were also a few noteworthy hotspots around northwest Africa and the Philippines (red areas, Fig. 6C). Documented traffic hotspots were more patchy and less widely distributed than other threat hotspots (red areas, Fig. 6D). Overall patterns of other threat categories, such as pathogens, resource depletion and ocean-physics alteration were similar to those shown, but tended to be more spatially restricted and were more concentrated in polar waters (Appendix H). Threat 'diversity', i.e. the number of different threat categories seemed to be highest in polar waters of the Antarctic and Arctic where there were numerous areas in which risks associated with different threat categories were high for a large proportion of species. However, overall, marine mammal communities in enclosed seas such as the Mediterranean and Baltic Sea or Hudson's Bay appear to be particularly at high-risk as these areas show up as hotspots for almost all threat categories. In contrast, documented risk areas were still comparatively rare for most threat categories in international waters (Fig. 6).

In relation to threat attributes, risk areas also differed (Appendix I). By-catch, solid wastes, subsistence hunting and boat collision were most important and affected most species (> 59 species, Fig. 3B). High-risk areas of by-catch were worldwide widespread (except in Antarctica), while hotspots of solid wastes were relatively smaller and concentrated in the Mediterranean Sea, the North Sea and around the Canary Islands. High-risk areas of subsistence hunting were large and focused in the Arctic, whereas hotspots of boat collision were coastal, small, disperse and mainly in the eastern coast of North America and North and Adriatic Seas (see maps in Appendix I).

Moreover, to assess the relative contribution of direct human activities to overall threat patterns, we also produced risk maps that distinguished between threat sources directly related to human activities from those that were either indirectly or not related to human activities i.e. climate change and geological events (Appendix J). Threat sources directly related to human activities seem to be the main driver of overall threat patterns. Specifically, in waters < 200 m, almost all the entire area that met our definition of threat hotspots for marine mammals (> 75% of species in risk) was affected primarily by direct human activities sources, while only half of the coastal hotspot area was affected by non-direct human activities (48% of the total coastal hotspot-areas; Table 2).

3.2.4. Risks differ according to taxonomic group and species

Due to differences in species-specific distributions and vulnerabilities to different threat types, hotspots obviously also differed by taxa and species. In terms of species composition, of the 114 mapped species, odontocetes represented the majority of species in the high-risk areas (59%), followed by mysticetes (> 18%). The overall size tent of areas with documented risks was similar for odontocetes and mysticetes (Table 1). Risk patterns for odontocetes and mysticetes were also similar and almost ubiquitous ranging from polar to tropical waters with highest concentrations in coastal waters, but also documented for more

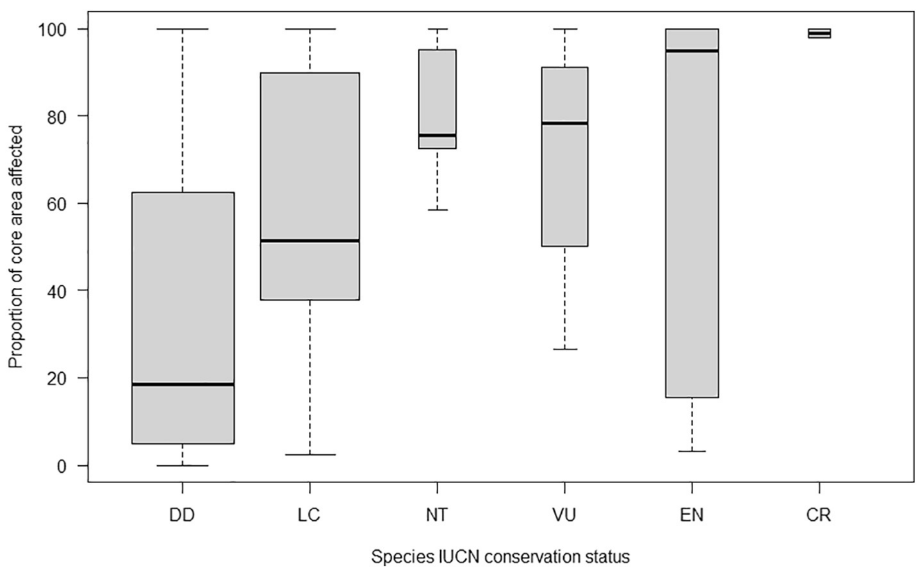

Fig. 4. Proportion of core habitat affected (Mean ± SD) by all threats documented (1991–2016) for all marine mammal species classified according to their IUCN conservation status (International Union for Conservation of Nature and Natural Resources – IUCN, 2016). DD (Data deficient) = 44 species, LC (least concern) = 41 species, NT (near threatened) = 6 species, VU (vulnerable) = 9 species, EN (endangered) = 12 species, CR (critical endangered) = 2 species (see Appendix G for individual species). Error bars are too small for CR to show. Width of boxes is proportional to number of data points.

oceanic areas (Fig. 7A,B). High-risk areas for both odontocetes and mysticetes were concentrated along the eastern coast of North America and the eastern coast of Asia, around Japan (Fig. 7A), but for mysticetes there were additional hotspots of risk along the western coast of South America and southern Australia (Fig. 7B).

By contrast, high-risk areas of pinnipeds and fissipeds were comparatively smaller and concentrated in coastal areas North Pacific (Sea of Okhotsk and Bering Sea) and there were slightly fewer species with documented risks in Antarctic waters (Fig. 7C). Proportionally, sirenians were the most affected group with risks documented for almost all of their range (Table 1). Sirenians' hotspots were located in the central east coast of America, east coast of Africa, India, north Australia and Southeast Asia (Fig. 7D).

With respect to individual species, humpback whales, *Megaptera novaeangliae*, and sperm whales, *Physter macrocephalus* were the two species most affected in terms of overall area of documented risk (see maps in Appendix K). In contrast, *Tursiops truncatus* was the species most affected in terms of threat variety (see maps in Appendix K). But based on the relative proportion of core area with documented threats, not surprisingly, the most affected species included those with comparatively smaller distributional ranges. These included *Cephalorhynchus eutropia*, *C. heavisidii*, *C. hectori*, *Phocoena sinus* and *Pontoporia blainville* (Odontoceti), *Eubalaena glacialis* and *Eschrichtius robustus* (Mysticeti) and *Arctocephalus galapagoensis*, *A. pusillus*, *Histriophoca fasciata*, *Monachus monachus*, *Neophoca cinerea*, *Phoca largha* and *Zalophus wollebaeki* (Pinnipedia; Appendix G).

4. Discussion and conclusions

The multitude of threats faced by marine mammal species is a well-documented fact, which has been known for decades (e.g. Reeves et al., 2003; Perrin et al., 2009; International Union for Conservation of Nature and Natural Resources – IUCN, 2016). The dire conservation status of many species can probably be directly attributed to these mostly human-induced impacts (e.g. Kovacs et al., 2012; Thomas et al., 2015). In general, our results show the high diversity of threats that marine mammals have been exposed to in recent decades (1991–2016) and highlight the urgent need for further conservation measurements. With respect to relative importance of threats, our findings support what has been stated in previous studies (e.g. Schipper et al., 2008; González-Suárez et al., 2013; Lewison et al., 2014), namely that a number of activities associated with fishing operations represent the most prominent threat types impacting marine mammals across the board. However, while Schipper et al. (2008) identified accidental mortality, particularly by-catch and vessel strike, as the greatest threat for marine mammals, we found specifically incidental catch (mainly by-catch), followed by pollution (wastes) and direct harvesting (commercial) to be problematic, while boat collisions was “only” seventh on the list as it affects mainly mysticetes.

However, in order to develop concrete management solutions for the often multi-faceted anthropogenic pressures impacting many marine mammal species, it is crucial to pinpoint threats and resulting risks to specific geographic areas for specific species as much as possible as attempted in this study. Previous analyses have either focused on the assessment of global threats for marine mammal species of high conservation concern and did not include species classified as data deficient and least concern in their threat maps (e.g. Schipper et al., 2008; Pompa et al., 2011). Most earlier studies did not incorporate specific threat's spatial dimensions (e.g. González-Suárez et al., 2013) or did not account for species-specific vulnerabilities to different types of threats (e.g. Pompa et al., 2011; Albouy et al., 2017). Moreover, the few existing studies that have attempted to localize potential risk hotspots have superimposed generic global human threat-layers over binary (presence-absence) IUCN range maps (e.g. Pompa et al., 2011; Albouy et al., 2017). Given the cosmopolitan or pan-global distributions of many marine mammal species (which will thus simply represent a uniform global background layer), the resulting patterns are therefore primarily driven by range-restricted species and paint a biased picture of global risk distribution. Similarly, the assumption that all species are impacted the same way by all threats or to the same extent wherever the threat is known to occur (Davidson et al., 2012) may mask existing patterns of species-specific risk hotspots and may represent an over-simplification of the real extent of risks. As a result, high risk areas for marine mammals identified in previous studies were predominantly driven by threat distributions (Schipper et al., 2008; Pompa et al., 2011; Davidson et al., 2012; Albouy et al., 2017) and may be of more limited use from a management perspective which often focuses more specific species in distinct locations.

To expand on previous efforts, in this study we have therefore focused on incorporating important additional details about species-specific vulnerabilities to threat types and on pinpointing known threat locations. Concentrating on published reports of species-specific threats, which we geo-referenced at the highest feasible resolution, our risk maps thus provide an overview which clearly distinguishes the *known* from the *potential* worldwide extent of threats. As our results depict documented actual threats reported for specific species at a specific location, we were able to greatly reduce potential errors of commission that will affect analyses that implicitly assume the same

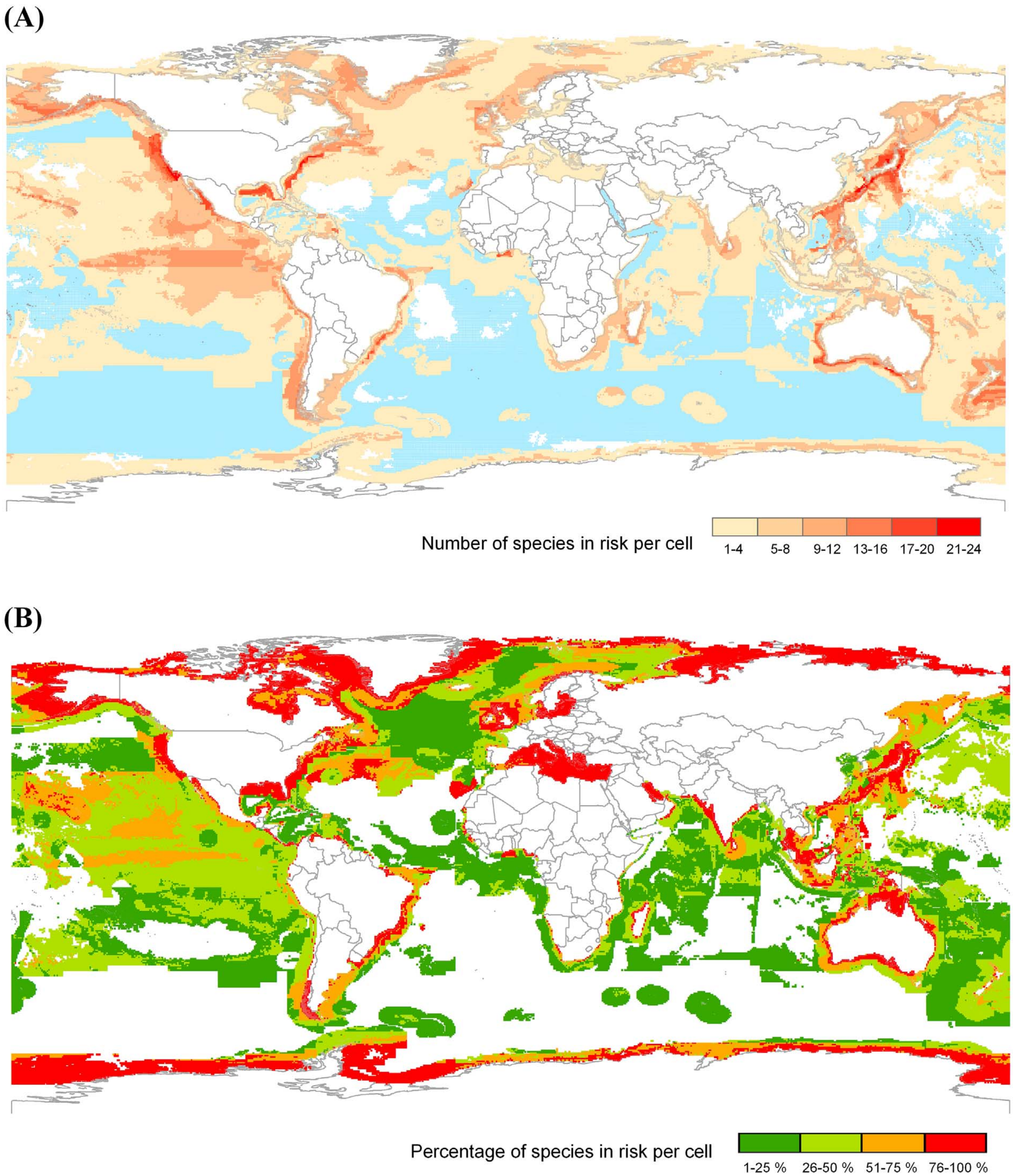

Fig. 5. Risk maps based on documented threats for all threat types and species combined. Cumulative risks maps for marine mammal species based on the intersection of published documented threat categories and predicted species core habitat (N species = 112; AquaMaps presence probability threshold ≥0.6; all threat categories). Red areas represent high-risk areas or hotspots. (A) Cumulative risk map showing the number of species affected by any threat category. Blue areas represent the core habitats for marine mammals without any documented threat. (B) Cumulative risk map showing the proportion of species of the total of species predicted to be present per cell with at least one documented threat. (GIS files of these maps are available in Avila et al., 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vulnerability of all species to all threats by superimposing species richness maps and global threat layers. Moreover, our risk maps are based on predicted core habitats, which generally correspond to locations where probability of exposure to the risk is likely highest for a given species. As a result, we further reduced commission errors and overestimation of risks hotspots such as those produced from range maps alone (Di Marco et al., 2017).

In this study, risk areas were identified for 51% of marine mammal core habitat. In addition to previous studies, which recognized risk areas for marine mammals mainly in coastal waters of the north Hemisphere (e.g. Schipper et al., 2008; Pompa et al., 2011; Davidson et al., 2012; Albouy et al., 2017) and in some coastal areas of the south Hemisphere (e.g. Davidson et al., 2012), we identified risk areas in coastal waters worldwide, in oceanic areas (e.g. in the Tropical Eastern Pacific and in the North Atlantic), enclosed seas such as the Mediterranean or Baltic Sea and in large areas around Antarctica. Furthermore, contrary to González-Suárez et al. (2013), who located the highest proportion of marine mammals affected by resource biological

Table 2
Area at risk in oceanic and coastal waters for marine mammal communities worldwide for different threat sources. Relative proportion category of marine mammal community refers to the percent of affected species of all species predicted to occur locally. Affected species are defined as those species for which a threat falling into a given threat source type has been reported. Total area of coastal water (cell mean depth < 200 m) = 25.4 Mio km^2, and total area of oceanic water (mean depth ≥ 200 m) = 338.3 Mio km^2.

Threat source type	Ocean water cells	Area (Mio km^2) of cells at risk for different relative proportion categories marine mammal communities			
		1–25%	26–50%	51–75%	76–100%
All sources combined	Coastal	0.9	2.9	5.4	11.8
	Oceanic	76.3	68.7	23.2	14.7
Direct human activities	Coastal	0.9	2.9	5.4	11.8
	Oceanic	76.2	68.6	23.2	14.7
Non-direct human activities	Coastal	0.2	0.7	2.6	5.7
	Oceanic	1.9	3.4	4.5	4.0
Undefined activities	Coastal	0.0	0.5	2.5	5.6
	Oceanic	0.6	7.0	6.2	7.7

use (harvesting and incidental take) in almost all of the ocean area of the world, we found acute hotspots for incidental catch in coastal areas ranging from Arctic waters to the Tropics, and for direct harvesting in Arctic and in some areas in the Antarctica waters. Also, hotspots varied according to taxonomic group. Similar to Kovacs et al. (2012) we identified hotspots for pinnipeds in the North Atlantic and North Pacific, but we also identified more specific risk areas in the Antarctica. On the other hand, high-risk areas for odontocetes and mysticetes were in the eastern coast of North America and the eastern coast of Asia. Our analysis illustrates how risk hotspots may vary with threat types and taxa (see Figs. 5–7).

Nevertheless, hotspots were located mainly in coastal waters. Direct human activities, such as fisheries, urban development, whaling/hunting and tourism were the major sources of threats on the marine mammals. Besides, risk areas caused by climate change and geological events (non-direct human activities) were smaller than those caused by direct human activities, but not less important, and contributed to high-risk areas for marine mammals in coastal Arctic waters. Although these threat-sources (which include ENSO, change in ice covered and storms, among others) are not clearly a direct human activity, they cause knock-on effects for direct human activity. For instance, several studies have been reported that the reduction in sea ice in the Arctic due to climate change has led to increase of several threats on marine mammals, e.g. shipping, development of oil and gas fields, reduction of habitat and preys (e.g. Tynan and DeMaster, 1997; Hovelsrud et al., 2008; Semyonova et al., 2015; Hamilton et al., 2016).

However, it is important to note that a mapped absence of risk on our maps does not necessarily mean lack of threats. Instead, it more likely reflects the well-known heterogeneity in global marine mammal sampling efforts (Schipper et al., 2008; Kaschner et al., 2012) and associated limited availability of information for some regions with respect to documenting threats. Although we scoped the review systematically, we acknowledge that we might have missed some published information. However, based on our sensitivity analysis, we would argue, that our literature search was systematic enough to produce results that reflect the status quo well in terms of existing and available threat reports. While searching for relevant threat reports, we found far more documents for coastal waters of the North Hemisphere in North America, Europe and eastern Asia than for the rest of the world while lack of sampling and reporting effort was most noticeable in international waters (Appendix F). Not surprisingly, patterns of reported threats mapped here matched e.g. the distribution of global marine mammal line-transect survey efforts (Kaschner et al., 2012) as the underlying drivers such as existing legal frameworks, socioeconomic and cultural settings that determine the extent of marine mammal monitoring in general are the same. In the future, a quantitative index describing the relative research/sampling effort intensity could be used to try and distinguish absence of reporting effort from real absence of threats – this, however, lies beyond the scope of this database and study.

In our study, a more substantial bias with respect to interpretation of overall impacts of global threat levels on marine mammals was introduced by a lack of consideration of threat severity when producing our risk maps. E.g. although we identified specific risk areas and threat types for different species, we did not encode information about the severity of threat with respect to impact, i.e. our maps do not distinguish between disturbance caused by whale watching and lethal impacts such as drowning of hundreds of animals in nets. Severity of threats is notoriously difficult to quantify and standardise, especially with respect to population level impacts. But even reported specific numbers of animals affected by a certain threat are difficult to encode without sufficient information about population size, area and time periods investigated which allow an assessment of the relative severity of impact. For instance, the incidental entanglement of ten individuals of a critically endangered species in a small area likely represents a far more severe impact for the survival of the species than by-catch of several hundreds of individuals of a different species in a much larger area. Impacts may differ with size of distribution (e.g. endemic versus cosmopolitan), sex or age of individuals or time of the year. Moreover, threat severity may vary due to synergistic effects of other impacts. Hence, the quantification of threat severity and assessment of cumulative impacts represent real challenges that were beyond the scope of this study. However, our database structure allows for easy incorporation of such information as it becomes available.

Another dimension of cumulative impacts may be more easily investigated is the assessment of threats to marine mammal biodiversity, i.e. areas where marine mammal communities as a whole are at risk. Hence, our study includes the quantitative visualization of the relative proportion of locally threatened marine mammal species. For example, using total number of species and in comparison to the rest of the world, the Mediterranean Sea does not seem to be a region of major concern, with only few species reported to be affected (Fig. 5A). However, these represent a very high proportion of Mediterranean marine mammal species, making this region a global threat hotspot (Fig. 5B). Overall, we show that marine mammal communities were reported to be at high risk in 47% of coastal waters of the world. This is not surprising, as almost all coastal areas worldwide are currently affected by human interventions, e.g. by coastal urbanization, pollution and over exploitation of natural resources (Newton et al., 2012), and the pressures are rising because the most rapid urbanization is taking place on the coast (Ramesh et al., 2015; Halpern et al., 2008, 2015). Our work thus complements previous results and clearly document that human activities in coastal waters worldwide impose previously unrecognized levels of cumulative risk for marine mammal species.

The reported risk maps are useful tools to assess the conservation planning for marine mammals. But risk maps based on core habitat could be misleadingly simplistic. Species core habitat maps fail to show the actual species distribution during crucial life stages and transient migration routes between summer and winter ranges. In addition, we did not take population size of different species into consideration but implicitly assumed a homogenous density of species throughout the core habitat. Incorporation of more detailed spatial and temporal variation in species occurrence as well as densities would further improve the specificity of conservation measurements. Furthermore, due to the spatial resolution of our analysis, some of the documented threats are not properly reflected in our risk maps. An example of this are dugongs (*Dugong dugon*), a species known to be threatened by direct harvesting, pollution and resources depletion in Palau, Southwest Pacific Ocean (Marsh et al., 2002), but on the global maps Palau is not visibly represented. This can be explained by to the resolution of the global grid of 0.5° grid cells used in AquaMaps (Kaschner et al., 2016). Because

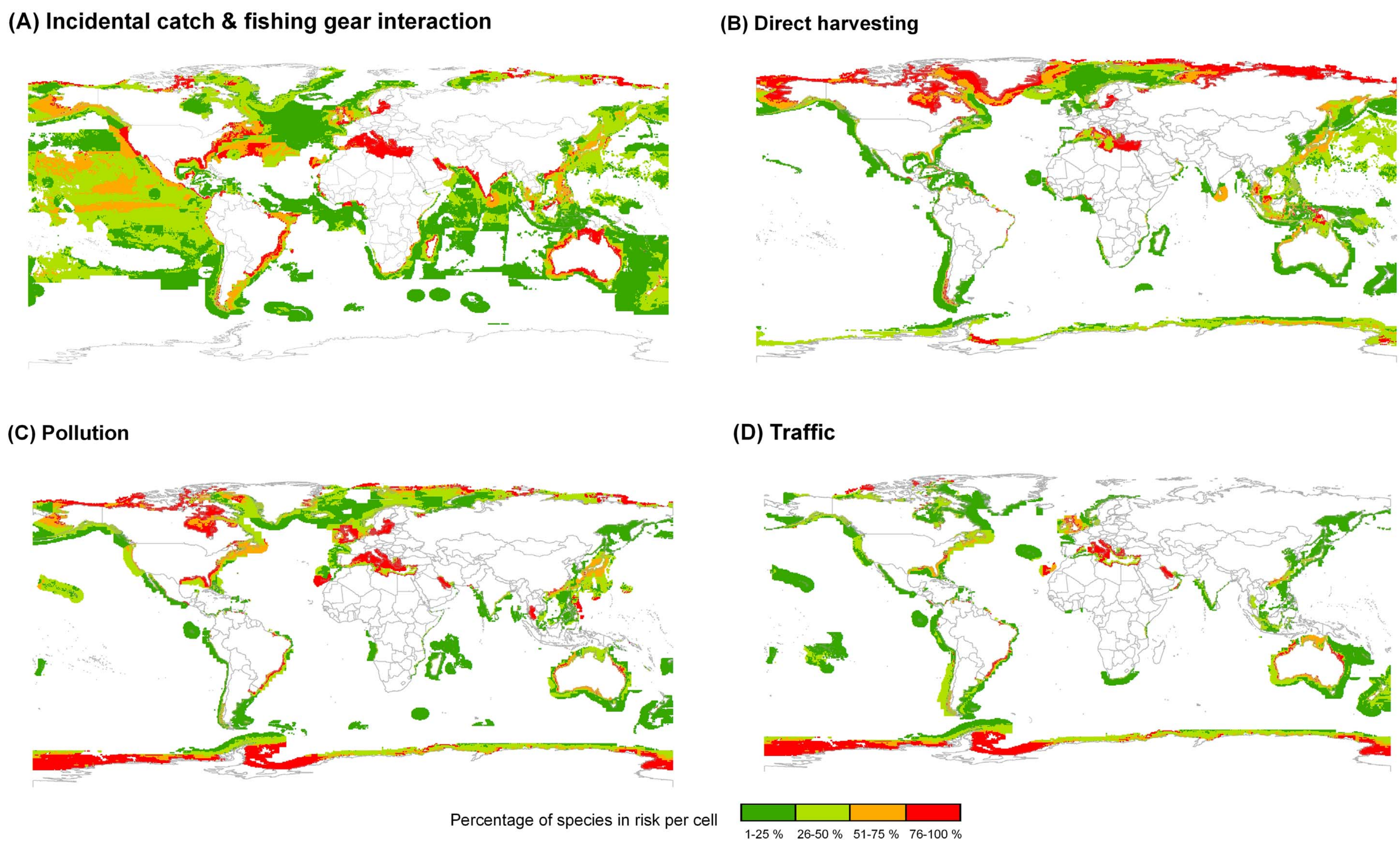

Fig. 6. Risk maps for specific threat categories (all species combined). Cumulative risk map showing the relative proportion of affected species vs total species present per cell for different threat categories (based on the intersection of published documented threat types and predicted species' core habitats; AquaMaps presence probability threshold ≥ 0.6). Red areas represent high-risk areas or hotspots. (A) Cumulative risk map of incidental catch (N species = 103). (B) Cumulative risk map of direct harvesting (N species = 81). (C) Cumulative risk map of pollution (N species = 92). (D) Cumulative risk map of traffic (N species = 77). (GIS files of these maps are available in Avila et al., 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

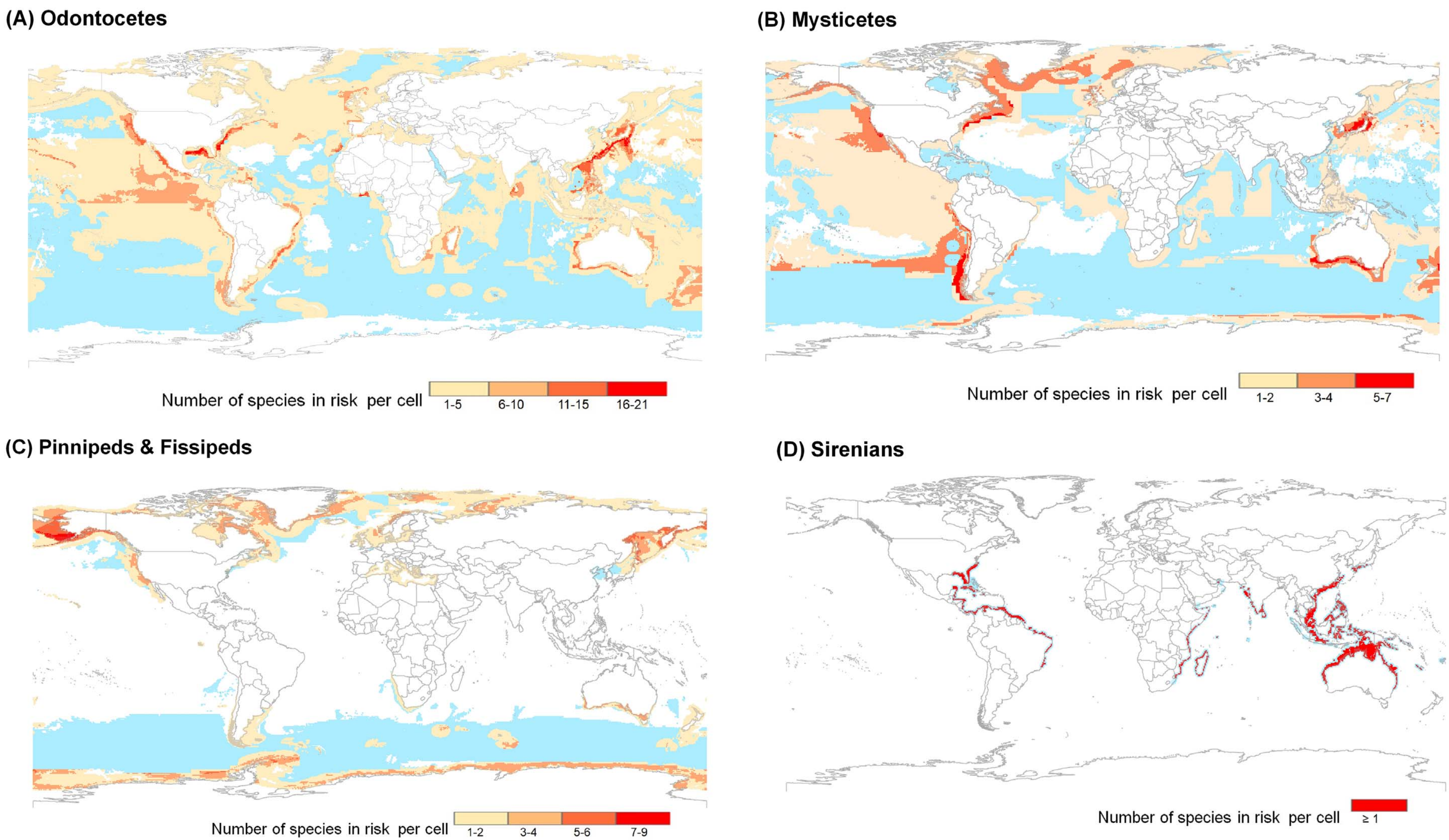

Fig. 7. Cumulative risks maps showing the number of species affected by any threat based on the intersection of published documented threat categories (all threat types) and predicted species core habitat (AquaMaps presence probability threshold ≥0.6). Blue areas represent the core habitats for each group without any documented threat. Red areas represent high-risk areas or hotspots. (A) Cumulative risk map for odontocetes (N species = 65). (B) Cumulative risk map for mysticetes (N species = 13). (C) Cumulative risk map for pinnipeds and fissipeds (N species = 32). (D) Cumulative risk map for sirenians (N species = 2). (GIS files of these maps are available in Avila et al., 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Palau is an offshore island, the average depth of the cells surrounding the island will probably be too deep for dugongs to be predicted there, and therefore is not reflected in our risk maps.

One of the primary targets set by the CBD for the next decade is the protection of > 10% of the marine environment by 2020 (CBD, 2010). Marine protected areas are recognized as one of the most important management tool to mitigate negative impacts on marine mammals and improve marine mammal conservation (Hoyt, 2011). However, currently only 5.1% of the ocean are protected (UNEP-WCMC, IUCN, 2016), and existing MPAs poorly capture marine biodiversity (Klein et al., 2015). To enable further establish priority sites for conservation of marine mammals the identification of threats, their sources, and resulting areas of high risk is an absolute pre-requisite. The risk maps presented in this study complement existing information by providing a spatially refined overview of known marine mammal risk patterns worldwide. These maps thus represent a more nuanced approach and could allow identifying priority sites for threat monitoring and for conservation efforts of marine mammal species.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2018.02.021.

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