Title: Global Tracking of Marine Megafauna Space Use Reveals How to Achieve Conservation Targets

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Abstract: The recent Kunming-Montreal Global Biodiversity Framework (GBF) sets ambitious goals, but no clear pathway for how zero loss of important biodiversity areas and halting human-induced extinction of threatened species will be achieved. We assembled a multi-taxa tracking dataset (11 million geopositions from 15,845 tracked individuals across 121 species) to provide a global assessment of space use of highly mobile marine megafauna, showing that 63% of the area they cover is used 80% of the time as important migratory corridors or residence areas. The GBF 30% threshold (Target 3) will be insufficient for marine megafauna's effective conservation leaving important areas exposed to major anthropogenic threats. Coupling area protection with mitigation strategies (e.g., fishing regulation, wildlife-traffic separation) will be essential to reach international goals and conserve biodiversity.

One-Sentence Summary: We provide a basis to design a global network of marine protected areas to conserve marine megafauna biodiversity.

Main Text:

Together with the recently finalised United Nations High Seas Treaty (*1, 2*), the Kunming-Montreal Global Biodiversity Framework (GBF) (*3, 4*) seeks to protect, conserve and manage at least 30% of oceans. This is a necessary step to support halting the loss of marine biodiversity (GBF Target 3), which has been particularly acute for large marine species (*5-7*). These include several iconic large marine vertebrates that have been driven to extinction by overexploitation (e.g., the Steller's sea cow – *Hydrodamalis gigas*, the great auk – *Pinguinus impennis*, and the Japanese sea lion – *Zalophus japonicus*), and many others currently showing precipitous declines in abundance (e.g., the hawksbill turtle – *Eretmochelys imbricata*, shortfin mako shark – *Isurus oxyrinchus* and North Atlantic right whale – *Eubalaena glacialis*). These mobile and highly migratory marine vertebrates, hereafter marine megafauna, can act as ecosystem and climate sentinels (*8; being good surrogates for other biodiversity*) and hold key functional roles that assist in structuring and maintaining ecosystems (*9-11*). However, close to a third of species across marine megafauna taxa are now threatened with extinction (*5, 12-18*).

Certain characteristics of marine megafauna, such as *K*-selected life history traits, place them at priority for systematic conservation planning (i.e., high vulnerability and high irreplaceability; *19*), and make the 'effective conservation' outlined in GBF Target 3 urgently needed. Many also migrate 1000s of km crossing multiple exclusive economic zones (EEZs) and areas beyond national jurisdictions (ABNJ) presenting a challenge for area-based conservation approaches (*20*). Importantly, such approaches are traditionally based on known geographical ranges reflecting historically known boundaries (*18*) or static maps of occurrence (*21*). However, devising a management plan that effectively conserves migratory species within Ecologically and Biologically Significant Areas (*22*) requires an understanding of how the species use space. Particularly, detecting important marine megafauna areas used for key life-history events, such as breeding or feeding and migratory behaviours, henceforth IMMegAs (to use a term similar to those recognised by IUCN, such as IMMA – Important Marine Mammal Areas or ISRA – Important Shark and Ray Areas) are only tractable using telemetry data (*20, 23-27*). Despite the challenges associated with collating such data at global scale (*28*), the detection of global IMMegAs is essential to understand marine megafauna conservation needs to inform global treaties, and should therefore be prioritised for creating the network of marine protected areas aimed by GBF (i.e., the planned increase to 30% of area protection).

Using telemetry data to understand global space-use by marine megafauna

We assembled a telemetry dataset unparalleled in size and scope (as the result of a global effort initiated by the MegaMove project; *29*) by accepting voluntary contributions of tracking data of highly mobile marine vertebrates - here referred to as marine megafauna, despite some (particularly flying birds) being under the 45 Kg threshold (*10*). Our dataset encompasses over three decades of tracked movements (1985 – 2018) from 15,845 individuals across 121 species, which after curation (*30*), resulted in 12,794 individual tracks from 111 species, covering 71.7 % of the area of the world's oceans (Fig. 1). Species include flying birds (hereafter birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles. See fig. S1 for latitudinal and longitudinal coverage of the dataset, and tables S1-S3, respectively, for lists of species tracked, tracking data details, and species-specific information. According to global assessments by the International Union for the Conservation of Nature (IUCN; *18*), of the 111 species considered, ~ 70% have decreasing (54 species) or unknown (23 species) population trends, and more than 50% (58 species) have a threatened conservation status of Critically Endangered (CR), Endangered (EN), or Vulnerable (VU) (table S4).

Five main regions exhibited the highest effective number of tracked species (as calculated based on the Shannon entropy; *31*): the central Indian Ocean, northeast Pacific, Atlantic northeast and northwest, and around Mozambique/South Africa. A few other locations empirically known as having high animal occurrence also showed high number of species (fig. S2). Areas where more tracking data could be made available include southeast Asia, north of Europe (e.g., Spitsbergen and Greenland), Australia, central Pacific Ocean, and western Africa (particularly the southwest Atlantic and Gulf of Guinea) (Fig. 1, fig. S2).

Using properties of the movement detected in the tracking dataset, including speed, direction and movement coherence (*30*) (fig. S12-S13), we identified IMMegAs based on key behaviours reflected in residency or migratory (including nomadic or dispersive) behaviour. We did this by using an approach (*30*) able to evaluate these behaviours collectively across multiple tracks without relying on interpolation across highly variable sampling intervals. This is not possible with the traditionally used state-space models that are typically designed to detect behavioural states on single tracks after interpolating position estimates (e.g., *32*).

We then assessed how much of the IMMegAs occurred within existing marine protected areas (MPA, including marine parks; *33*) or exclusive economic zones (EEZs; *34*) (shown in fig. S3). We used an optimization algorithm to estimate what configuration of the area covered by our tracking dataset would yield the best selection for setting protected areas for marine megafauna, giving priority to grid-cells that are used for both residency and migratory behaviours across multiple taxa (*30*). For comparison, we repeated this procedure after developing statistical models to predict areas likely to be used for residency or migration for each taxon within the areas covered by our tracking dataset (*30*). For data used as input for the models see Table 2. After this modelling procedure, we considered the priority grid-cells as those resulting in highest probabilities (i.e., >0.5 and closest to 1) of being an important area across taxa.

Finally, we assessed the extent to which the GBF's planned increase to 30% in area protection could assist with reducing impacts from marine megafauna's exposure to anthropogenic threats with a global footprint (*35*), such as fishing (*36-38*), shipping (*39-41*), warming (*42-45*), plastic (*46, 47*) and noise pollution (*48, 49*). We identified these as threats based on the IUCN Threats Classification Scheme (TCS) v3.3 (*50*) complemented with information from existing literature (*12, 51-53*) and expert knowledge (fig. S4, and see table S4 for details). We then obtained available global threat data for fishing intensity (*54*), shipping density (*55*), plastic density (*46, 56*), and warming (*57, 58*), and considered noise to be ubiquitous (based on *59*) as no noise dataset is currently available at the resolution needed for a global analyses (but see e.g., *60*).

Known biases (*61-63*) associated with uneven sampling and with tagging individuals in known aggregations or colonies were reduced in our analyses as far as possible by using multiple tagging sites for each species and, where applicable, by normalising data to allow for direct comparisons across species and taxa. From specific tests to assess the influence of (i) tagging location bias, (ii) temporal resolution of tracking data (i.e., including only one location per individual per day, in addition to all locations detected), and (iii) spatial resolution (i.e., repeating all procedures at 0.5°, 1° and 2° grid-cells), we found that these potential confounding factors had negligible effects on our main conclusions (fig. S5 – S8). Finally, randomisation of tracks confirmed animals are selectively using space for important behaviours (fig. S14).

Detected ecologically important areas for marine megafauna and extent of existing threats

We found that, on average, 66.1% of the total area covered by our tracking data was used as migratory corridors (50%) or residencies (44.8%) (Fig. 2A), with ~29% used for both behaviours (*30*); noting that for sirenians, data were insufficient to detect migratory behaviours (fig. S9). Animals spent on average 90% of their tracked time (estimated using one position per day) within areas where we detected these behaviours (Fig. 2B). Most of this time (~80%) was spent in areas used for residency (or both residency and migration) (fig. S10), with considerable overlap across both behaviours.

On average, only 7.5% of the entire area covered by our tracking dataset occurred inside MPAs (which currently cover ~8% of the global ocean), with ~5% corresponding to areas of detected residency or migratory behaviours (Fig. 2). Similarly, animals spent a greater amount of time outside, than inside, MPAs (on average >85%). The time spent inside MPAs corresponded, on average, to 13.6% of all time animals spent displaying residency or migratory behaviours (ranging between 0.3% for polar bears and 23.9% for penguins) (Fig. 2). The results indicate limited opportunity for significant conservation of marine megafauna within the current extent of global MPAs, which were mainly designed to protect specific habitats rather than threatened mobile marine megafauna. However, conservation efforts could be considerably improved in the future by specifically including IMMegAs in new MPA placement.

All space-use and identified residency and migratory behaviours occurred with a ~40-60% split respectively between EEZs and the high seas (which respectively cover 41.3% and 58.7% of the oceans) (Fig. 2). Similar split of space-use between EEZ and high seas was obtained across each taxa, with clear exceptions for sirenians and polar bears (for which most movements occurred inside EEZs). Despite this pattern of space-use slightly biased towards the high seas, most time (on average 74.1 %, of which 67.1% corresponded to detected migration or residency) was spent inside, rather than outside, EEZs, and ranged from 61.5 % for flying birds to 90.2% for cetaceans (Fig. 2). Although protection of high seas IMMegAs is urgently needed, the large proportion of time animals spend conducting important behaviours within EEZs suggests that an initial focus on enhancing protection within EEZs could provide the fastest benefits for marine megafauna conservation, particularly because implementation may be easier.

To identify what areas could be prioritised for protection, we used an optimisation algorithm (fig. S15 – S16) to select a total of 30% of the 71.7% area covered by our tracking dataset (i.e., 21.3% of the global ocean; Fig. 3). We did this because our tracking dataset does not cover the entire ocean, and also to allow for later additions of new protected areas if other IMMegAs are identified once new tracking data are available. The optimisation algorithm aims to highlight which areas could provide higher representativeness of IMMegAs, but also to indicate where the additional protected areas could be complementary to existing MPAs (sensu *19*), which currently fail to represent marine megafauna space-use (*25; Fig. 3*). Our results show that 30% area protection allows coverage of only less than half of the IMMegAs we discovered (41.6% and 38.8%, respectively, based on data and model predictions; fig. S17) , leaving ~60% unprotected (58.4%, and61.2% based on data and model predictions, respectively) (Fig. 3).

Our complemented IUCN Threats Classification Scheme(*50*) (table S4) showed that commercial fishing and climate change affect more than 80% of the species included in our dataset (fig. S4).

Shipping has impacts on species across all taxa, including all turtles, sirenians, polar bears, most species of cetaceans considered, plus five birds, four fishes, five seals, and one penguin. Plastic pollution is a threat for all turtles and seals (but not yet listed on IUCN for leopard seals – *Hydrurga leptonyx*), most cetaceans, and ~35% of birds. Some fishes are also listed as potentially being affected by this threat including two manta rays and five sharks. Noise is listed as affecting all cetaceans, some seals, both sirenians, and also the polar bear, but for the latter this is likely due to potential disturbance of maternal dens on land.

Overlaying the identified (and predicted) areas used by marine megafauna for migration or residency behaviours at a global scale with each of the major global anthropogenic threats considered here (fig. S11), we found that > 96% of IMMegAs are exposed to plastic pollution, shipping and warming, and ~75% to fishing. This exposure includes overlaps within the areas of highest pressure observed for most threats, for example, in the North Atlantic, where we detected important areas for birds, cetaceans, fishes and turtles (Fig. 2 and fig. S9).

Mitigation strategies will be needed in addition to the proposed increase in area protection to safeguard marine megafauna

Our results reveal that the 30% threshold is insufficient to encompass all IMMegAs globally (Fig. 3), leaving significant conservation risks for marine megafauna. Considering the ubiquity of existing threats, which are pervasive in the IMMegAs we detected (Fig. 3, fig. S11), and the limited scope of the 30% GBF target for area protection, attaining the goal of zero loss of important biodiversity areas and halting human-induced mortality of threatened species seems unlikely (noting some management measures already in place for some species, table S5). Shipping and fishing can in part be alleviated by increasing MPAs (particularly if the highest level of protection is afforded; *64*), which can also help reduce noise pollution. However, plastic pollution or climate change impacts will not be alleviated with the planned increase in area protection (even if MPAs can assist improving species resistance and resilience; *65*). Therefore, attaining the goal of zero loss of important biodiversity areas will need further action to mitigate anthropogenic pressures.

To reduce exposure of marine megafauna to existing threats and achieve the goals set out in the GBF, the introduction of additional forms of ocean management will be needed, including greater scrutiny of practices and additional direct management decisions with increased enforcement. For example, direct mortality can be reduced by applying fishing thresholds and enforcing standards in fishing operations (including modifications to gear) (*66-70*), and by developing wildlife-ship traffic separation schemes and slow-down areas (*71, 72*) (e.g., to 2.16 Knots; *73*). If applied in tandem with the increase in protected areas, such interventions will afford marine megafauna a much greater spatial protection from the major threats of industrialised fishing (*23*) and shipping (*41*) known to cause direct mortality (Table 1).

Our analyses show that animals spend the majority of their time within jurisdictions, which presents an opportunity for marine megafauna conservation because individual countries regulate and control most operations within their borders and are therefore able to implement mitigation measures to manage species that use their EEZs. Management of IMMegAs in the high seas, outside national jurisdictions, would benefit from better integration into the United Nations Convention for the Law of the Sea (UNCLOS), and should be considered in the ongoing process to better regulate biological resources in the high seas (*1, 2*). For shipping threats specifically, International Maritime Organisation regulations can reduce impacts and propel conservation success. For example, the double hull policy resulted in an average reduction of up to 62% in the size of oil spills (*74*). Engaging (and better regulating) the private sector is another timely way to advance conservation (e.g., *75*), as environmental damage is increasingly recognised as a threat to financial stability (*75, 76*). Past management decisions, either involving the private sector (e.g., end of the whaling industry following the moratorium by the International Convention for Regulation on Whaling; *77*) or by listing species on CITES (Convention on International Trade in Endangered Species; *78*) have demonstrated success by leading to populations' recovery. However, the drivers of contrasting trajectories of similar populations or species (e.g., right whales increase in the Southern Ocean *versus* decrease in the North Atlantic) are not well understood and likely relate to different exposure to anthropogenic threats.

Creating a larger network of marine protected areas will also greatly benefit from following a systematic conservation planning framework. Although our aim was to identify IMMegAs (rather than outlining what the final 30% of area protection should look like), we followed the initial necessary steps of that framework, including: (*i*) using marine megafauna biodiversity data (as surrogate for marine biodiversity), (*ii*) using the set targets from the GBF and UN High Seas Treaty as goal, (*iii*) focusing on complementing existing MPAs, and (*iv*) selecting IMMegAs for potential inclusion as MPAs. We then provide a scenario for up to 30% extension of MPAs to show that even if all areas selected specifically included IMMegAs, the 30% protection would still be insufficient to reach set targets, and other mitigation measures will be needed. To follow a systematic conservation planning approach, the final selection of protected areas should also take into consideration aspects not considered here, such as ecosystems of high ecological significance or habitat types that are not yet well represented, as well as considerations of equity and principles of environmental justice (*79*). It is, however, likely that the final selection of areas for protection will end up being designed to minimise impacts to stakeholders (including the fishing, shipping, energy production and tourism industries). Such possible result further reinforces our conclusion that relying on the 30% area protection will be insufficient to reach the goal of zero loss of important biodiversity areas and halt human-induced mortality of threatened species, and that additional mitigation measures are needed before it is too late.

The work we provide here shows the power of assembling tracking datasets to answer pressing conservation concerns. The continued expansion of MegaMove through voluntary contributions will foster greater collaborations allowing to fill data gaps and further reduce biases. Whereas our tracking data covers about 71% of ocean space, the tagging effort was neither random nor uniform in space and time, and 29% of the ocean space was not covered by our dataset (including the central and northwest Pacific ocean).We suggest that statistical models using existing tracking data as input could be used to develop refined global species distributions taking into account animal movements associated with short-term changes in environmental parameters to project the likelihood of encountering animals in areas underexplored by telemetry or bio-logging (*80-82*).

We also recognise that the available threat distribution data we used here are incomplete and do not include, for example, illegal or artisanal fishing fleets, nor discrimination across fishing gear (which affects species differently). This means that a more detailed spatio-temporal analysis of exposure to threats, as well as an assessment of the vulnerability of different species to specific threats, is required to quantify their potential impacts on species' life-history characteristics. Consideration of the phylogenetic diversity of marine megafauna by examining evolutionary drivers could also be relevant to improve spatial maps. Nevertheless, the IMMegAs we have identified are key to inform the expansion of existing MPAs to reach the 30% target both within EEZs and in the High Seas.

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Supplementary Materials

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Materials and Methods

Figs. S1 to S17

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Fig. 1. Tracked movements of marine megafauna at the global scale.

A) Map of the total number of 12,794 unique individual track locations in the global dataset at 1º resolution showing the global coverage of 71.7% of the global ocean. B) Maps per taxon showing the number of unique individual track locations within each 1° grid-cell. From top left to bottom right, maps per taxon show 6324 individual tracks for 39 species of flying birds, 749 for cetaceans including 11 whales and 3 delphinid species, 1760 for fishes including 23 shark species, 2 manta rays, and 1 ocean sunfish, 1324 for 6 species of penguins, 65 for polar bears, 1698 for 16 species of seals, 28 for sirenians including dugongs and West Indian manatees, and 846 for all 7 sea turtles. The latitudinal and longitudinal coverage of tracked data is displayed in fig. S1. For reference, the first position obtained for each tracked individual (i.e., representing tagging locations), as well as captured and expected global biodiversity are given in fig. S2. Maps showing the spatial extent of space use per species at 1° resolution can be seen in the data repository.

Fig. 2. Global space-use of marine megafauna and time spent in different behaviours. Fractions of area (A) and time (B) used by animals globally (left plots), within and outside exclusive economic zones (EEZs) (middle plots), and within and outside existing marine protected areas (MPAs) (right plots), showing how much of the movements corresponded to detected migratory corridors or residency. Results are shown across all species together (top bar) and for each taxon (as displayed in legend). For each taxon, the light grey portion in the bars indicates movement where no behaviours were detected. Species in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles. C) Map of detected migratory corridors, residence areas and both corridors and residencies across taxa. Grey indicates grid-cells where tracking data were available but no specific behaviour was identified for any taxon. Light blue areas depict regions where we did not have tracking data. Maps of detected behaviours per taxon can be seen in fig. S9.

Fig. 3. Increase in area protection to 30% will leave ~60% of IMMegAs exposed to major anthropogenic threats.

A) Maps depicting average threat intensities for major anthropogenic threats with a global footprint: (from top to bottom) fishing, shipping, plastic pollution and sea surface temperature (SST) warming. Displayed with an orange colour palette are the threat intensities occurring inside IMMegAs, while a grey colour palette is used to show the threat intensities outside IMMegAs. Note that we considered noise to be ubiquitous, as no noise dataset is currently available at the resolution needed for a global analyses. B) Maps showing how much the increase in marine protected areas (MPAs) from the current 8% (purple) to 30% (green) would cover from our prioritization of IMMegAs detected from movement data (top map) and from our model predictions (bottom results). Note that coverage by MPAs only translates into protection from the anthropogenic threats considered if they are designated with the highest level of protection (i.e., with no activities allowed), and even then MPAs could only be effective for protection from fishing and shipping, leaving plastic and warming threats to continue to affect species. In addition to the increase in the current extent of MPAs, the introduction of mitigation strategies will assist in reducing the impact of existing threats and therefore the likelihood of human-induced extinctions.

Table 1. Evidence of impacts from overlap of marine megafauna with anthropogenic threats. Examples of the range of impacts derived from the overlap of marine megafauna with anthropogenic threats such as climate warming, plastic pollution, shipping, noise pollution, and fishing. SST: sea surface temperature; UV: ultraviolet.

	BIRDS (FLYING)	CETACEANS	FISHES	PENGUINS	POLAR BEAR	SEALS	SIRENIANS	TURTLES
CLIMATE	**Decreased survival**	**UV damage**	**Habitat shift**	**Reduced prey**	**Habitat contraction**	**Habitat shift**	**Reduced food**	**Sex bias**
	Impacted survival & population growth rate of black-browed albatross juveniles with SST changes (*84*)	Increased skin lesions on whale related with increased UV irradiance (*85*)	Reduced counts of Scalloped hammerhead sharks *Sphyrna lewini* associated with rise in SST (*86*)	Decreased population size for penguin prey species with climate change (*87*)	Contraction of polar bear's habitat in the Arctic linked to long-term sea ice loss (*88*)	Decreased survival of southern elephant seal due to effects of sea ice dynamics on access to foraging (*89*)	Reduced dugong density by ~70% due to seagrass die-off triggered by an extreme heat wave (*90*)	Female-biased turtle populations linked to warming temperatures (*91*)
PLASTIC	**Ingestion**	**Ingestion**	**Ingestion**	**Ingestion**	-	**Entanglement**	**Ingestion**	**Ingestion**
	Death of shearwater and northern gannet due to plastic ingestion (*92*)	Stranded sperm whale stomachs with large amounts of plastic debris (*93*)	Threatened filter-feeding elasmobranchs by microplastic (*94*)	Plastic ingestion may have caused death (*95*)		Mortality of fur seals due to entanglement in marine debris (*96*)	Death of West Indian manatees from ingestion of plastic debris (*97*)	50% probability of mortality when turtles ingest pieces of plastic (*98*)
SHIPPING	**Habitat loss**	**Ship strike**	**Ship strike**	**Noise effects**	**Ship strike**	**Propeller strike**	**Ship strike**	**Ship strike**
	Habitat loss for Common Eider's avoiding shipping traffic (*99*)	Increased ship strikes with humpback whales in shipping lanes (*39*)	Mortality of whale sharks correlated with risk of collision with ships (*41*)	Population collapse concomitantly with increase in noise (*100*)	Increased vulnerability of polar bears to vessel strike (*101*)	Propeller strikes affect harbor seals (*102*)	Death of manatees due to boat collisions (*103*)	Decreased survival of green turtles due to boat strikes (*104*)
NOISE	-	**Behav. change**	-	-	**Disturbance**	**Physical damage**	**Behav. change**	-
		Change in humpback whales foraging activity due to ship noise (*105*)			Disturbance of maternal dens due to seismic surveys (*106*)	Temporary hearing loss of grey and harbor seals around the British Isles (*107*)	Reduced foraging habitat for manatees due to boat noise (*108*)	
FISHING	**By-catch**	**By-catch**	**Mortality**	**Reduced prey**	-	**Entanglement**	**Entanglement**	**By-catch**
	High bycatch of seabirds in longline fisheries (*38*)	Higher rates of dolphin bycatch in a trawl fishery (*109*)	Greater mortality of pelagic sharks where sharks have higher exposure to longline fisheries (*62*)	Decreased population size of prey species with increased fishing of Antarctic Krill (*87*)		Increased entanglement of Cape fur seals associated with fishing (*110*)	Manatee mortalities from entanglement in fishing gear (*111*)	High levels of turtle bycatch in fishing gear hotspots (*37*)

Table 2. Summary of the logistic modelling inputs and results per taxon

Results of the generalized linear models relating the probability of a grid-cell to be used as residence or for migratory behaviours with the set of environmental variables included in each model. Shown are the results for the highest ranked model according to the weight of the Akaike's Information Criteria (*wAIC*), as well as the number of parameters (k), the percentage of deviance explained (pcdev) and Kappa. Grey indicates the models not used to estimate the important marine megafauna areas (IMMegAs) derived from our modelling predictions (as presented in Fig. 3 and fig. S11). Species in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

Taxon	**Input**			**Results**									
	Number of grid-cells with:			**Residence Behaviour**					**Migratory Behaviour**				
	Presence	**Residency**	**Migration**	**Model**	***k***	***wAIC***	***pcdev***	***Kappa***	**Model**	***k***	***wAIC***	***pcdev***	***Kappa***
Birds	35,875	13,448	9,128	2	19	1.000	4.13	0.22	2	19	1.000	11.19	0.33
Cetaceans	4,397	1,501	1,758	2	19	1.000	16.52	0.44	2	19	0.980	12.62	0.29
Fishes	15,648	4,346	4,252	2	19	1.000	14.44	0.38	2	19	1.000	12.56	0.30
Penguins	1,385	446	452	1	17	1.000	13.62	0.4	2	19	1.000	40.16	0.56
Polar bear	1,124	451	803	2	14	0.995	24.78	0.33	2	14	1.000	27.78	0.48
Seals	11,358	5,510	7,175	2	19	1.000	3.12	0.22	2	19	1.000	14.91	0.30
Sirenians	114	27	0	-	-	-	-	-	-	-	-	-	-
Turtles	10,360	3,462	3,370	3	7	1.000	7.71	0.28	2	19	1.000	5.18	0.17

Supplementary Materials for

Global Tracking of Marine Megafauna Space Use Reveals How to Achieve Conservation Targets

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Materials and Methods

Fieldwork and deployment of tracking devices

Birds

Birds were all caught at nest sites either whilst incubating or attending chicks, except for some northern gannets (*Morus bassanus*, immature birds at the main colony), Trindade petrels (*Pterodroma arminjoniana*, non-breeding adult birds resting at the main colony), and great shearwaters (*Ardenna gravis*, attracted to a vessel at-sea using bait). Birds were captured using noose poles, crook poles, drop traps, net launchers, nets (landing, mist, purse or handheld), or removed by hand from their burrows. Tags were typically attached to the auxiliary leg band or taped to the mantle, scapular, dorsal contour, or tail feathers. Chest or leg-loop harnesses were used for herring gulls (*Larus argentatus*), ivory gulls (*Pagophila eburnea*), some Ross's gulls (*Rhodostethia rosea*), and some northern fulmars (*Fulmarus glacialis*). For great shearwaters, tags were attached dorsally using four subcutaneous Prolene sutures. In all cases, total instrument mass was <5% of body mass to minimise effects on flight efficiency and all birds were handled for less than 20 minutes.

Cetaceans

Smaller cetaceans (e.g., beluga - *Delphinapterus leucas*, bottlenose dolphins - *Tursiops truncatus*, narwhal - *Monodon monoceros*) were captured using seine or stationary nets. The animals were then brought to the surface, disentangled, and secured using hoop nets and loop ropes. In the case of bottlenose dolphins, animals were brought aboard the research vessel as part of capture-release health assessments. Tags were attached using nylon pins attached to the dorsal ridge or fin. Killer whales (*Orcinus orca*) were targeted from shore using crossbows and tags were attached to the dorsal fin using subdermal darts. Other cetaceans, such as blue - *Balaenoptera musculus*, bowhead - *Balaena mysticetus*, gray - *Eschrichtius robustus*, humpback - *Megaptera novaeangliae*, pilot - *Globicephala macrorhynchus* and *G. melas*, right - *Eubalaena glacialis* and *E. australis*, and sei whales - *Balaenoptera borealis*, were approached using a small research vessel. Tags were deployed using crossbows, air-powered applicator systems, or long fibreglass poles. Tags were attached to the dorsal fin (either anterior-to or at-the-base-of) using subdermal anchors or barbs and petals, which were sterilised and/or treated with antibiotic coatings prior to deployment.

Fishes

Fish, mostly sharks, were typically captured with baited hooks, bagan lift nets, or in purse-seine nets, then brought alongside the vessel and restrained in a sling or with straps, secured to a raisable platform, or taken aboard for tagging. If brought aboard, fish were on deck an average of approximately 3 minutes; the exceptions to this were white sharks - *Carcharodon carcharias* (average duration of restraint: 12 mins) and tiger sharks - *Galeocerdo cuvier* (some were placed in tanks with running seawater and moved to deeper isobaths as part of a shark attack mitigation strategy). Manta rays - *Mobula birostris* and *M. alfredi*, and some copper - *Carcharhinus brachyurus*, Galapagos - *Carcharhinus galapagensis*, scalloped hammerhead - *Sphyrna lewini*, whale - *Rhincodon typus*, and white sharks were tagged whilst free-swimming in the water column using pneumatic spear guns or rubber-propelled hand spears. The majority of sunfish (*Mola mola*) and some porbeagle sharks (*Lamna nasus*) were captured as bycatch in fisheries targeting tuna. Tags were typically attached using a tether affixed to a dart, which was implanted in the dorsal musculature or anchored to the first (or second in bluefin tuna - *Thunnus thynnus*; removed from analyses) dorsal fin. For some sunfish, tags were attached to the base of the caudal fin. For some of the blue - *Prionace glauca*, bull - *Carcharhinus leucas*, mako - *Isurus oxyrinchus* and *I. paucus*, sandbar - *Carcharhinus plumbeus*, scalloped hammerhead, silky - *Carcharhinus falciformis*, tiger, whale, and white sharks, tags were attached to the first dorsal fin using metal bolts, neoprene and high-carbon steel washers, and steel nuts. For some white sharks, tags were mounted on a custom-built spring clamp that was placed on the first dorsal fin.

Penguins

Penguins were captured and released on land at nesting sites. Tags were attached to the dorsal plumage using waterproof tape and/or epoxy glue, and in some cases secured under a bed of feathers using a small cable tie.

Polar bears

Adult female polar bears (*Ursus maritimus*) were located via helicopter and immobilised with a rapid-injection dart. Tags were attached using satellite collars.

Seals

Seals were approached whilst onshore or in shallow waters surrounding haul-out sites and captured using hoop nets, tangle nets, beach seine nets, and/or remote syringe darts. Once captured, seals were manually restrained, sedated, or anaesthetised. Tags were attached to the head or along the dorsal midline using quick-setting epoxy glue.

Sirenians

Manatees (*Trichechus manatus*) were located via an aerial observer and individuals were captured in a net deployed from a specialised capture boat. Dugongs (*Dugong dugon*) were captured using a ‘rodeo’ technique, where a personal watercraft is used to closely pursue an individual dugong until fatigued. The dugong is then caught around the peduncle region by a catcher leaping off the boat, and the animal is restrained at the water surface by several people. For all sirenians, tags were tethered to the animal using a peduncle belt.

Turtles

Turtles were primarily adult females captured at nesting beaches after a successful nesting event. In some cases, adult and juvenile turtles were captured at sea (both in the vicinity of nesting beaches or at foraging grounds) using tangle nets, dip nets, a “rodeo” technique, or by hand as they rested at the surface. Some turtles were found stranded or were incidentally captured by local fishers, then handed into conservation organisations for tagging and release. For hard-shelled turtles, tags were attached to the carapace or head with quick-setting epoxy glue, a fiberglass and polyester resin, or in the case of flatback turtles (*Natator depressus*), by using a specially-designed harness. Leatherback turtles (*Dermochelys coriacea*) were tagged via direct attachment surgical technique (tags were directly attached by drilling into the central-dorsal ridge and affixing with nylon or metal ties), tow technique (hole drilled in caudal peduncle and tag towed), or harness technique. Where post-hatchlings were used, they were collected from the nest, reared by head-starting programs, and then selected for tagging based on their size and swimming abilities. Post-hatchlings were tagged using an acrylic-silicone-neoprene attachment method, which for larger individuals sometimes also included drilling through the keratin part of the carapace crest and securing the tag with nylon ties.

Animal ethics information

Data providers obtained all licenses and ethical permissions required for data collection in their jurisdictions and ensured that each animal was handled and tagged by trained personnel. Details per taxon are presented below with name initials indicating the responsible co-author.

Birds (flying)

Tagging of black-browed albatrosses (*Thalassarche melanophris*) at Diego Ramirez Islands was conducted under a permit provided by the Chilean Antarctic Institute (**J.A.A.**).

Audouin's gull (*Ichthyaetus audouinii*) tagging was conducted with permission from the Catalan and Balearic Islands Governments, and Scopoli's shearwater (*Calonectris diomedea*) tagging was conducted with permission from the Balearic and Valencian Governments, as well as the Spanish Government (**J.M.A.**).

The sooty tern (*Onychoprion fuscatus*) tracking project in Seychelles was approved by the Seychelles Bureau of Standards and supported by the owners of Bird Island (**C.F.**).

Tagging procedures on little penguins (*Eudyptula minor*), crested terns (*Thalasseus bergii*), and short-tailed shearwaters (*Ardenna tenuirostris*) off South Australia were conducted under approval by the South Australian Department of Primary Industry and Regions (PIRSA) Animal Ethics Committee (32-12) and the South Australian Department for Environment and Water (DEW) (Scientific Permit A24684) (**S.D.G.**).

Broad-billed prion (*Pachyptila vittata*) fieldwork on Rangatira was conducted with the permission and cooperation of the New Zealand Department for Conservation and would not have been possible without the support of the Chatham Island Area Office. Northern gannets were ringed and loggers deployed with permits and approval from the British Trust for Ornithology (BTO) and Scottish Natural Heritage (**W.J.G.**).

All tracking of northern gannets, razorbills (*Alca torda*), Atlantic puffins (*Fratercula arctica*), and Manx shearwaters (*Puffinus puffinus*) in the Republic of Ireland were approved by the University College Cork (UCC) Animal Ethics Committee (2013/032 and 2019/001) and conducted under permits by the BTO (C/6143) and Irish National Parks and Wildlife Service (26/2010, 011/2013, 018/2014, 016/2015, 025/2016, 082/2017, C051/2011, C116/2012, C039/2013, C075/2014, C087/2015, C100/2016, C87/2017) (**M.J.**).

Barau's petrel (*Pterodroma baraui*) tracking work was authorized by Centre de Recherches sur la Biologie des Populations d'Oiseaux (CRBPO) permit number PP609, Ethic Committee of Réunion Island, Parc National de La Réunion, and direction de l'environnement, de l'aménagement et du logement de La Réunion (DEAL-Réunion). Red-tailed tropic bird (*Phaethon rubricauda*) tagging was authorized by Permit Le Corre PP616, Terres Australes et Antarctiques Françaises (TAAF), Mauritius National Park, and Madagascar National Parks. White-tailed tropicbird (*Phaethon lepturus*) tracking was conducted with research approval by CRBPO (PP616) and the Seychelles Bureau of Standard (SBS). Sooty tern tagging was authorized by PP616 M. Le Corre, Seychelles Bureau of Standard, and TAAF. Wedge-tailed shearwater (*Ardenna pacifica*) tagging was authorized by CRBPO permit PP616, Ethical committee of Réunion Island, Institutional Authorizations from DEAL-Réunion, Conservatoire du Littoral Réunion, Mauritius National Parks and Conservation Service, and Seychelles Bureau of Standard (**M.L.C.**).

Common eider (*Somateria mollissima*) tagging was conducted under Environment Canada (ECCC) Animal Care Permits, Canadian Wildlife Service (CWS) Scientific Permit NUN-SCI-04-02, and Nunavut Wildlife Research Permit WL1028. Herring gull tagging was conducted under Nunavut Wildlife Research Permit WL2008–1028; CWS Scientific Permit NUN-SCI-08-04, SC2761; and ECCC Animal Care permits EC-PN-08-026. Ivory gull tagging was conducted under CWS Banding Permit number 10694; CWS Scientific Permit NUN-SCI-09-02; and Nunavut Wildlife Research License WL2010-032. Northern fulmar collections were in accordance with Canadian Council on Animal Care guidelines, and were conducted under the following permits: research (NUN-SCI-03-02, WL000190, WL000714), animal care (2003PNR017, 2004PNR021, 2005PNR021), and land use (59A/7-2-2). Parasitic jaeger (*Stercorarius parasiticus*) tagging was conducted under CWS Banding Permit 10694; Animal Care EC-PNR-11-020, Scientific Permit NUN-SCI-09-01, and Territorial Permit WL 2010-042. Ross's gull tagging was conducted under CWS Banding Permit 10694; Animal Care Permit EC-PNR-11-020; Scientific Permit NUN-SCI-09-01; and Territorial Permit WL 2010-042. Sabine's gull (*Xema sabini*) tagging was conducted under permits CWS Animal Care EC-PN-11-020, CWS Scientific Permit NUN-SCI-09-01, Government of Nunavut Wildlife Research Licence WL 2010-042, Nunavut Water Board licence 3BC-TER0811, Indian and Northern Affairs Land Use Reserve 068H16001, and CWS Banding Permit 10694. Thick-billed murre (*Uria lomvia*) tagging was conducted under Canadian scientific and access permits (NUN-SCI-08-55, NUN-MBS-12-03, NUN-SCI-12-04, WRP2013040), banding permit (10694, 10322), and animal care (0800AG01) (**M.L. Mallory**).

Tagging work followed the ethical standards set out by the Mauritian Wildlife Foundation and its partner and consulting organisations, the North of England Zoological Society, the Durrell Wildlife Conservation Trust, and the International Zoo Vet Group (**M.A.C.N.**).

Permission to capture and tag Ascension frigatebirds (*Fregata aquila*) was granted by the Conservation Department of the Ascension Island Government. The attachment of devices met the ethical guidelines of the Special Methods Panel of the BTO. King eiders (*Somateria spectabilis*) were handled with approval by the University of Alaska Fairbanks Institutional Animal Care and Use Committee (IACUC) (protocol #05-29) and CWS Animal Care Committee (permit #PNR007). Masked booby (*Sula dactylatra*) tagging was carried out under permission and with collaboration of the St Helena Environmental Management Directorate. The capture and handling of birds and attachment of unconventional marks was carried out under licence from the BTO. Permission to capture and tag birds was granted by the Environmental Management Directorate on St Helena. The attachment of GPS devices met the ethical guidelines of the Special Methods Panel of the BTO. Tagging of Murphy's petrels (*Pterodroma ultima*) followed all applicable international, national, and/or institutional guidelines for the care and use of animals. Permission to access Henderson Island in order to conduct scientific research in 2015 was granted by the Government of the Pitcairn Islands (**S. Oppel**).

Tagging work was conducted under approval by the Portuguese Government Instituto de Conservação da Natureza e Florestas (ICNF) under licenses 188/2010/ CAPT, 152/2011/CAPT, 101/2012/CAPT, 99/2013/CAPT, 203/2014/CAPT, 169/2015/CAPT, and 89/2011/CAPT (**V.H.P.**).

Tagging work was authorized by the Government of South Georgia and the South Sandwich Islands (**R.A.P.**).

Tagging procedures were conducted under approval by the Portuguese Government ICNF (permit 89/2011/CAPT) and in compliance with Portuguese laws No. 140/99, No. 49/2005, No. 316/89, and No. 180/2008 (**J.A.R.**).

Buller's albatross (*Thalassarche bulleri*) tagging was approved by the Southland Conservancy, Department of Conservation, New Zealand (**P.M.S.**).

Sooty shearwater (*Ardenna grisea*) ethics was approved by the IACUC at the University of California Santa Cruz and approval for the research was provided by the Whenua Hou Management Committee, Rakiura Titi Islands Administering Body, and Southland Department of Conservation in New Zealand. Black-footed (*Phoebastria nigripes*) and Laysan albatross (*Phoebastria immutabilis*) tagging in the Hawaiian Islands was approved by the University of California Santa Cruz and San Jose State University IACUCs under Master Bird Banding permit 23411. Laysan albatross tagging on Guadalupe Island, Mexico was approved by University of California Santa Cruz IACUC under Master Banding Permit 20768.Western gull (*Larus occidentalis*) tagging was conducted under permission granted by Año Nuevo State Park, California State Parks, California Department of Fish and Wildlife, and the US Fish and Wildlife Farallon Islands National Wildlife Refuge (SUP# 81641). All research protocols were approved by the San Jose State University IACUC (protocol 979) (**S.A.S.**).

Common murre (*Uria aalge*) field work was conducted under Kukulget Inc. land crossing permits, University of Alaska Fairbanks IACUC protocol #471022, US Fish and Wildlife Service (USFWS) scientific collection permit #MB70337A, A. Kitaysky's Master Banding permit #23350, and Alaska Department of Fish and Game's permits #19-140, 18-131, 17-104, 16-089. Streaked shearwater (*Calonectris leucomelas*) tagging procedures were approved by the Animal Experimental Committee of the University of Tokyo and conducted in accordance with the Guidelines for the Care of Experimental Animals, with fieldwork conducted under permits from the Ministry of the Environment and the Agency for Cultural Affairs. Thick-billed murre tagging was conducted under Kukulget Inc. land crossing permits, UAF IACUC protocol #471022, USFWS scientific collection permit #MB70337A, A. Kitaysky's Master Banding permit #23350, and Alaska Department of Fish and Game's permits #19-140, 18-131, 17-104, 16-089. (**A. Takahashi**).

Capture and tagging of Northern fulmar in Scotland was carried out under licences from the BTO (Licence No: AO/4939) and UK Home Office (Licence No: PIL 60/698) following review by the University of Aberdeen ethics committee (**P.M.T.**).

Northern gannet capture and tagging on St Kilda was carried out with permission from the National Trust for Scotland and Scottish Natural Heritage and under licence from BTO (Licence No: A2332 with a specific unconventional methods endorsement) (**S. Wanless**).

Tagging procedures were conducted with approval from the US Department of the Interior #21963, Massachusetts Division of Fisheries and Wildlife #058.19SCB, Stellwagen Bank National Marine Sanctuary Permit # SBNMS-2019-001, and the Long Island University IACUC (**D.N.W.**).

Northern gannet capture and tagging was carried out under licences from the BTO and Natural England, with approval of the Royal Society of the Protection of Birds (**L.J.W.**).

Tagging work was conducted with permits from the Ministry of the Environment: No.060609001 for Sangan Island and No.18–340 for Mikura Island (**T.Y.**).

Cetaceans

Tagging was undertaken under US National Marine Fisheries Service (NMFS) Scientific Research Permits No. 17096, 731-1774, and 15330. Tagging was undertaken under protocols approved by the Cascadia Research Collective IACUC (**R.W.B.**).

Tagging was conducted under University of Auckland Animal Ethics AEC001587, New Zealand Department of Conservation Permit #44388-MAR, and approval from local Maori tribes (iwi) Ngāti Kuri and Te Aupōuri (**R.C.**).

Tagging was undertaken with the permission of the Environment Department of the province Sud of New Caledonia and of the Government of New Caledonia under permits 383-2010/ARR/DENV, 33313-2010/ARR/DENV, 3616-2011/ARR/DENV, 3157-2012/ARR/DENV, 1045-2014/ARR/DENV, 151-2015/ARR/DENV, 1105-2016/ARR/DENV, 899-2017/ARR/DENV, 2220-2018/ARR/DENV, 2016-1391/GNC, 2017-1107/GNC and 2018-923/GNC (**C. Garrigue**).

Tagging procedures were approved by Fisheries and Oceans Canada (DFO) Freshwater Institute Animal Care Committee (AUP # FWI-ACC-2002, 2003, 2004, 2005, 2006 and 2007) and under DFO License to Fish for Scientific Purposes #S-02/03 to 05/06-1019-NU and #S-12/13-1024-NU, S-13/14-1009-NU and S-16/17 1005-NU (**S.H.F.**).

Tagging was conducted under permits 11-101/VP/MPEEIA:SG and 12-100/VP/MPEEIA:SG issued by the Secretary-General of the Union of the Comoros, permits 105/DEAL//SEPR/2012 and 148/DEAL/SEPR/2012 issued by Direction de l'Environnement, de l'Aménagement et du Logement de Mayotte, and permit FR1397600001-E issued by Direction de l'environnement, de l'aménagement et du logement (DEAL) Mayotte (**S.F.**).

Tagging was conducted under NMFS permits (numbers 14907, 14809, and 14856) and ACA Permits (2009-013 and 2015-011). All animal work was approved and conducted under Duke University IACUC A049-122-02 and the Oregon State University Animal Care and Use Protocol (ACUP) 4513 (**A.S.F.**).

Beluga tagging was carried out with Animal Care Approval and Research Permits issued by the Canadian Government (**M.O.H.**).

Deployment of satellite tags on southern right whales at the Head of Bight, South Australia were conducted under approval by the South Australian Department of Primary Industries and Regions (PIRSA) Animal Ethics Committee (32-12), and under the following permits: PIRSA Fisheries Exemption (ME9902712), Department of Environment Water and Natural Resources (DEWNR) Permit and Licence to Undertake Scientific Research (A24684-12), Environment Protection and Biodiversity Conservation Act Cetacean Permit (20014-0004), Access to Biological Resources in a Commonwealth Area for Non-commercial Purposes (AU-COM2014-248), Approval for Activity in Commonwealth Marine Reserve (CMR-14-000196) and DEW Marine Parks Permit (MO00024-2) (**A.I.M.**, **S.D.G.**, and **R.H.**).

Beluga tagging was carried out under Animal Use Protocol permit number FWI-ACC-2015-018 and DFO license S-12/13-1022-NU. Narwhal tagging was carried out under Animal Use Protocol number FWI-ACC-2016-030 from the DFO Animal Care Committee (under the Canadian Council on Animal Care) and a DFO License to Fish for Scientific Purpose License S-16/17-1037-NU (**M. Marcoux**).

Sei whale fieldwork and tagging was approved by the Regional Directorate of the Environment/ Regional Government of the Azores under research permit 7/CN/2005, issued to the Department of Oceanography and Fisheries of the University of the Azores (**E.O.**).

Whale tagging was authorized by the NMFS under permit numbers 841 (for blue, bowhead, gray, and humpback whales), 369-1440 (for blue, fin - *Balaenoptera physalus*, gray, humpback and northern right whales), and 369-1757 (for blue, gray, and southern right whales). Tagging in Mexican waters was conducted under permits issued by the Secretaría de Medio Ambiente y Recursos Naturales, Mexico (permit number DOO 02.8319 and SGPA/DGVS 0576). Southern right whale tagging was also authorised under a permit issued by the South African Department of Environmental Affairs and Tourism in terms of Regulation 58 of the Marine Living Resources Act (no. 18 of 1998). Sperm whale (*Physeter macrocephalus*) tagging was conducted under permits # 08159 and SGPA/DGVS 01102 by the Secretaría de Medio Ambiente y Recursos Naturales of Mexico, and the NMFS under permit numbers 369-1757. For all eight species, research was approved by the Oregon State University IACUC (**D.M. Palacios** and **B.M.**).

Tagging was approved by the University of Pretoria's Ethics Committee (EC023-10; EC077-15) and permitted by the Prince Edward Islands Management Committee (PEIMC 17/12, 1/2013 and 1/2014) (**R.R.R.** and **P.J.N.B.**).

Blue, fin and sei whale fieldwork and tagging were approved by the Regional Directorate of the Environment/Regional Government of the Azores, under research permits: 20/2009/DRA (blue, fin and sei whales), 16/2010/DRA (blue and fin whales), 51/2011/DRA (blue and fin whales), 30/2015/DRA (blue whale), 37/2016/DRA (blue whale), 31/2012/DRA (fin whale), 20/2013/DRA (fin whale), 34/2014/DRA (fin whale), 76/2007/DRA (sei whale) (**M.A. Silva**).

Short-finned pilot whales were tagged under authorization from NMFS. Bottlenose dolphin tagging was conducted under NMFS Scientific Research Permit No. 15543 and approved by Mote Marine Laboratory's IACUC (**R.S.W.**).

Fishes

Tagging procedures were approved by the Committee on Ethics for the Use of Animals of the Universidade Federal Rural de Pernambuco (CEUA #23082.009679/2009 and #23082.025519/2014). Work permits granted by the Instituto Chico Mendes para a Conservação da Biodiversidade (ICMBio #43305–6 and #15083-8) (**A.S.A.**).

Tagging in the Philippines was performed in collaboration with the respective Regional Offices of the Department of Environment and Natural Resources, the Department of Agriculture-Bureau of Fisheries and Aquatic Resources and the Palawan Council for Sustainable Development (Wildlife Gratuitous Permit 2017-13). All research in Tubbataha Reefs Natural Park was done in collaboration with the Tubbataha Management Office (**G.A.**).

Tagging procedures in the Bay of Biscay followed established guidelines that met ethical reviews, with scientists limiting handling time and stress as much as possible during attachment (**I.A.**).

Tagging procedures were approved and conducted under Australian Fisheries Management Authority Scientific Permit #901193 and Great Barrier Reef Marine Park Authority G11/33231.1 (**A. Barnett**).

All procedures for whale shark tagging in the Red Sea were approved by the Institutional Biosafety and Bioethics Committee (IBEC) of the King Abdullah University of Science and Technology. KAUST IBEC serves as the registered (HAP-02-J-042) local committee for all National Committee of Bioethics (NCBE)-regulated activities including animal-related research. (**M.L. Berumen** and **J.E.M.C.**).

Tagging was conducted with the permission of Chico Mendes Institute for Biodiversity Conservation (number 50119-1), of the Brazilian Ministry of the Environment. Shark capture and tagging methods were approved by the Commission of Ethics on the Usage of Animals of Federal Rural University of Pernambuco (licence number 054/2013, protocol number 23082.022567/2012) (**N.P.A.B.**).

Tagging procedures were approved by Stanford University IACUC, the National Oceanic and Atmospheric Administration (NOAA), and the California Department of Fish and Wildlife (**B.A.B.**).

Tagging of blue, porbeagle and shortfin mako sharks in the northwest Atlantic was conducted in accordance with the animal care guidelines of DFO and the Canadian Council on Animal Care (**S.E.C.**).

Tagging was conducted with approval by the Province Sud of New Caledonia under permit 6024-4916/DENV/SMer and authorization issued by Affaires Maritimes for Chesterfield field trips (C110-3510-263/MM) (**E.E.G.C.**).

Tagging was conducted with approval by South African Institute for Aquatic Biodiversity Animal Ethics (Ref#25/4/1/7/5_2019-04) (**R.D.**).

Whale sharks in Madagascar were tagged by Centre National de Recherches Océano- graphiques (CNRO) in July 2016 under permit number No 16-12-CNRO-N (**S. Diamant**).

Tagging was conducted under permit from the St Helena Government (SHG 20-SRE-01) (**A.D.M.D.**).

Blue sharks (tagged in Irish waters) were tagged under license AE191130/I007 AE19130/P002 and issued by the Irish Health Products Regulatory Authority (HPRA) and complied with the EU Directive 2010/63/EU for scientific research on animals (**T.K.D.**).

Manta ray tagging procedures were approved by the Raja Ampat Marine Protected Area Management Authority and were in accordance with the protocols established by Conservation International Indonesia's and University of Auckland's Animal Ethics Committees (University of Auckland AEC approval #002228). Whale shark tagging was conducted under permits issued by the Cendrawasih Bay National Park Authority (SIMAKSI SI.18/BBTNTC-2/TEK/2015, SIMAKSI SI.46/BBTNTC-2/TEK/2015, and SIMAKSI SI.05/BBTNTC-2/TEK/2016). Tagging procedures were approved by the Cenderawasih Bay National Park Authority and are in accordance with the protocols established by Conservation International Indonesia's animal ethics review committee (**A. Sianipar**, **E.S.** and **M.V.E.**).

Great white sharks were tagged in New Zealand waters according to the protocols specified in Department of Conservation Animal Ethics Committee approvals AEC278, AEC216 and AEC260. Mako and porbeagle sharks were tagged according to the code of practice for ethical conduct of tagging carried out by the National Institute of Water and Atmospheric Research (NIWA Animal Ethics Committee 2009) (**M.P.F.**, **B.F.** and **C.A.D.**).

Tagging was approved by Griffith University ethics (ENV/16/08/AEC) and Ocean and Coast Research animal ethics approval (CA 2010/11/482), with fieldwork conducted under permits 6024-4916/DENV/SMer (New Caledonia), G10 33187.2 (Great Barrier Reef Marine Park Authority), 143005 (Queensland Fisheries), QS2010 GS065 (Great Sandy Marine Park) and LHIMP/R/2012/009 (Lord Howe Island) (**J.G.** and **J.M.W.**).

Tagging was conducted under permit MAF/LIA/22 to conduct scientific marine animal research supplied by the Department of Marine Resources, Bahamas to Bimini Biological Field Station Foundation (**T.L.G.**).

Tagging was conducted under permits from the NMFS Highly Migratory Species Division and under the University of Miami IACUC. Additionally, blacktip shark tagging was conducted under permits from Florida Fish and Wildlife, Everglades National Parks; bull shark tagging was conducted under permits from the Florida Keys National Marine Sanctuary, Florida Fish and Wildlife, and the Biscayne and Everglades National Parks; and great hammerhead shark and tiger shark tagging was conducted under permits from the Florida Keys National Marine Sanctuary, Florida Fish and Wildlife, Bahamas Department of Marine Resources, and the Biscayne and Everglades National Parks (**N.H.**).

Tagging procedures were conducted under Galapagos National Park Permits PC-13-01, PC-37-11. PC-01-14, PC-51-15, PC-69-16, PC-34-17, and MAE-PNG/CDS-2012-0020. Field methods were also approved under University of California, Davis IACUC #16022 (**A.R.H.**).

Tagging procedures were approved by the University of Windsor Animal Care Committee with a permit through Coastal Oceans Research and Development – Indian Ocean (CORDIO) (**N.E. Hussey**).

Tagging was conducted under Flinders University Animal Welfare Ethics Permits E349 and E360, and was authorised by the Victorian Department of Primary Industries under General Research Permit RP1048 and PIRSA Ministerial Exemptions Section 115: 9902064 and 9902094 (**C.H.**).

Tagging procedures for scalloped hammerhead and Galapagos sharks were approved by the Zoological Society of London's ethics committee under the project code BPE/0708. Research tagging activities around Mikomoto Island, Japan, were communicated to and approved by fisheries officers within the Japanese government (a formal research permit was not required) (**D.M.P.J.**).

For South African white sharks, all research methods were approved and conducted under the South African Department of Environmental Affairs: Oceans and Coasts permitting authority (Permit #RES2012/OCEARCH/umbrella-project) (**A.A.K.**).

Tagging was conducted with the full approval of the Instituto Chico Mendes de Conservação da Biodiversidade of the Brazilian Ministry of the Environment (permit no. 14124) (**B.C.L.M.**).

Tagging procedures were reviewed and approved by the Seychelles Bureau of Standards, the Seychelles Ministry of Environment, Energy and Climate Change, and The University of Western Australia (RA/3/100/1480) (**L.R.P.**).

Tagging was conducted under Direcção-Geral de Alimentação e Veterinária ethics approvals from Decreto-lei N° 129/92 (6 de julho); Portaria N° 1005/92 (23 de outubro) (**N.Q.**).

Tagging was carried out under the general auspices of Consejo Nacional de Ciencia y Tecnología (CONACYT), Dirección General de Vida Silvestre (DGVS), Secretaría del Medio Ambiente y Recursos Naturales (SEMARNAT), and Comisión Natural de Áreas Naturales Protegidas (CONANP). These are the relevant Mexican authorities governing all research actions on wildlife and protected animals and areas in Mexico. CONACYT registration: RENIECYT No. 030 (currently 1602199) and 13920. DGVS authorization numbers are: SGPA/DGVS/02677/08, SGPA/DGVS/02888/09, SGPA/DGVS/03848/10, SGPA/DGVS/03155/11, SGPA/DGVS/03362/12, SGPA/DGVS/05555/16 and SGPA/DGVS/05970/17 (**D.R.**).

All tagging was conducted under animal ethics approvals from Murdoch University's Animal Ethics Committee (permit numbers: W2058/7; W2402/11; R2926/17) and an animal ethics permit from The University of Queensland: SBS/085/18/WA/INTERNATIONAL. Permits to conduct research on wildlife in Western Australia were issued by the Western Australian Department of Environment and Conservation (DEC) (permit numbers: SF007471; SF007949; SF008572) and Department of Parks and Wildlife (DPaW) (permit numbers: SF009184; SF009897; SF010414; SF010781; 08-000533-2; 08-002082-2) (**S.D.R.**).

Tagging was conducted with permission by the Qatar Ministry of Environment (**D.P.R.**).

Tagging in Mozambique was compliant with ethics guidelines from the University of Queensland’s Animal Ethics Committee and was conducted under their approval certificate GPEM/186/10/MMF/WCS/SF. Madagascan fieldwork was conducted with the approval of and in partnership with the CNRO in Madagascar. Filipino fieldwork was performed in collaboration with the respective Regional Offices of the Department of Environment and Natural Resources, the Department of Agriculture-Bureau of Fisheries and Aquatic Resources and the Palawan Council for Sustainable Development (Wildlife Gratuitous Permit 2017-13) (**C.A.R.**).

Tagging methods for broadnose sevengill sharks (*Notorynchus cepedianus*) were approved by the University of Tasmania Animal Ethics Committee (Approval No A0011590) (**J.M.S.**).

Tagging procedures were approved by the Marine Biological Association of the UK (MBA) Animal Welfare Ethical Review Body (AWERB) and licensed by the UK Home Office through Personal and Project Licences under the Animals (Scientific Procedures) Act 1986 (**D.W.S.**).

Smooth hammerhead shark (*Sphyrna zygaena*) tagging was approved by the Massachusetts Division of Marine Fisheries. Porbeagle shark tagging was approved by the University of Massachusetts, Dartmouth IACUC (Protocol #05-07). White shark tagging was conducted under Exempted Fishing Permits (SHK-EFP-11-04, SHK-EFP-12-08, SHK-EFP-13-01, SHK-EFP-14-03) issued to the Massachusetts Division of Marine Fisheries by the NMFS Highly Migratory Species Management Division (**G. Skomal**).

Tagging procedures were approved by the University of California, San Diego IACUC (protocol S12116) (**J.D. Stewart**).

Whale shark tagging procedures were approved by the University of Western Australia (RA/3/100/1110; RA/3/100/1437), University of Adelaide (S-2009-109), or Charles Darwin University Animal Ethics Committees (**M.T.** and **M.G.M.**).

Tagging data according to protocols approved by the South African Department of Environmental Affairs: Oceans and Coasts (now the Department of Forestry, Fisheries and the Environment) and adhered to the legal requirements of South Africa. All research methods were approved and conducted under the South African Department of Environmental Affairs: Oceans and Coasts permitting authority (Permit #RES2012/OCEARCH/KOCK) (**A. Towner**).

Tagging procedures were approved by the Nova Southeastern University IACUC (#064-398-15-0203) (**B.M.W.**).

Tagging was conducted under permits given by the Subsecreataría de Pesca y Acuicultura de Chile. Resolución exenta (Undersecretary of Fishing and Aquaculture) (**P.M.Z.**).

Penguins

Tagging procedures for little penguins from Montague Island were approved by the Macquarie University Animal Ethics Committee (Animal Research Authority2014/057), and work was conducted under Office of Environment and Heritage NSW Scientific Licence SL100746 (**G.C.** and **R.H.**).

Tagging procedures were conducted under approval from Monash University Animal Ethics Committee (approval numbers BSCI/2006/12, BSCI/2010/22, BSCI/2011/33), Phillip Island Animal Experimentation Ethics Committee (approval numbers 3.2007, 2.2010, 3.2011, 2.2014, 7.2017), and research permit issued by the Department of Sustainability and Environment of Victoria, Australia (permit numbers 10003848, 10004360, 10005601, 10005605, 10006148, 10007320, 10008506) (**A. Chiaradia**).

Tagging procedures on little penguins off South Australia, were conducted under approval by the South Australian Department of Primary Industries and Regions (PIRSA) Animal Ethics Committee (32-12), and Department for Environment and Water (DEW) (Scientific Permit A24684) (**S.D.G.**).

Tagging procedures were approved by the Australian Animal Ethics Committee (Department for the Environment and Heritage) and the University of Tasmania Animal Ethics Committee Work was carried out under Macquarie Island special permits M1/3/95 and MI/13/96 (**M.A.H.**).

Tagging procedures were permitted under US Antarctic Conservation Act Permits (Permit #2017-012). Field protocols were approved by the University of California San Diego IACUC (S05480) (data used courtesy of Jefferson T. Hinke).

Adelie penguin (*Pygoscelis adeliae*) tagging procedures were approved by the TAAF ethic committee and the French regional ethic committee. King penguin (*Aptenodytes patagonicus*) handling procedures were approved by the Ethical Committee of the French Polar Institute (Institut Polaire Paul-Emile Victor). Authorizations to enter the king penguin breeding site (permits nos. 2005–191, 2006–67) and handle birds (permits nos. 99/346/AUT, 00/240/AUT, 01/315/AUT, 01/322/AUT, 2003–113, 2003–114, 2004–182, 2004–183, 2005–203 and 2006–73) were delivered by the French Ministère de l'Aménagement du Territoire et de l'Environnement (MATE) and TAAF (**Y.R.**).

Animal handling procedures were approved by the joint University of Cambridge / British Antarctic Survey Animal Ethics Committee (**P.N.T.**).

Tagging procedures were approved by the Animal Ethics Committee of the Australian Antarctic Division (ATEP-12-13-4086-4088-SUMMER) (**B.W.**).

Polar bears

Tagging procedures were conducted under USFWS research permit MA 690038 Animal Care and Use Committees of the US Geological Survey (assurance no. 2010–3) (**A.M.P.**).

Seals

Tagging was permitted by the Russian Federal Veterinary and Agricultural Control Service (Rosselkhoznadzor, Kamchatka and Koryakia regions, Permit No. 1194) and was approved by the Alaska Sea Life Center IACUC (**R.D.A.**).

Tagging procedures were approved by the Adelaide University Animal Ethics (permit S80-2004) and South Australia Department for Environment and Heritage (permit A24684-3) (**A.M.M.B.**).

Weddell seals (*Leptonychotes weddellii*) tagged in Dumont d'Urville, Adélie Land by LOCEAN laboratory were treated in accordance with the Institut Paul-Emile Victor (IPEV) ethical and Polar Environment Committees guidelines (**J. Charrassin**).

Animal use protocols for northern elephant seal tagging was reviewed and approved by the University of California at Santa Cruz IACUC and followed the guidelines established by the ethics committee of the Society of Marine Mammalogy. Research was carried out under NMFS permits: #786-1463 and #87-143. Southern elephant seal (*Mirounga leonina*) captures were conducted under NMFS permit No. 87-1851-00. All animal procedures were approved by the IACUC at University of California Santa Cruz. Weddell seal handling protocols were approved by the University of Alaska Anchorage and University of California Santa Cruz's IACUCs. Research and sample import to the United States were authorized under the Marine Mammal permit No. 87-1851-04 issued by the Office of Protected Resources, NMFS. Research activities on southern elephant seals and Weddell seals were also approved through Antarctic Conservation Act permits while at McMurdo Station (**D.P.C.** and **P.W.R.**).

Ringed seal (*Pusa hispida*) handling and tagging was approved by the University of Windsor Animal Care Committee (AUPP #12-12,13-10) and a DFO License to Fish for Scientific Purposes (S-12/13-1019-NU) (**S.H.F.** and **D.J.Y.**).

Australian sea lion (*Neophoca cinerea*) tagging procedures were approved by the PIRSA Animal Ethics Committee (32-12), South Australian DEW (Scientific Permit A24684), and Western Australian Department of Environment and Conservation (Licence to Take Fauna for Scientific Purposes SF009529). Long-nosed fur seal tagging procedures were approved by the PIRSA Animal Ethics Committee (32-12) South Australian DEW, Scientific (Permit A24684) (**S.D.G.**).

Tagging procedures for Australian fur seal (*Arctocephalus pusillus doriferus*) and New Zealand fur seal (*Arctocephalus forsteri*) were approved by the Macquarie University Animal Ethics Committee (Animal Research Authority2014/057), and work conducted under Office of Environment and Heritage NSW Scientific Licence SL100746. Weddell seal tagging procedures were approved by Macquarie University (#3223) ARA 2014_057 (**R.H.**) or approved by the New Zealand Department of Conservation, Ministry of Foreign Affairs and Trade, and NIWA Animal Ethics Panel (DOC-69331-MAR) (**M.P.**).

Animal Ethics were obtained from NIWA to manipulate New Zealand sea lions (*Phocarctos hookeri*) at Campbell Island, with the proviso that all work was undertaken with approval from the Department of Conservation and the NZ Department of Conservation permit issued under the

Marine Mammal Protection Act (1978). Southern elephant seal tagging procedures were approved by University of Tasmania Animal Ethics (permit A0014523) (**M.A.H.**).

All animal captures and procedures were authorised under NMFS permits (numbers 87-1593 and 87-1851-00) and approved by the University of California, Santa Cruz IACUC. Fieldwork in Antarctica was approved by the Antarctic Conservation Act (**L.A. Huckstadt**).

Tagging procedures were approved by the UCC Animal Ethics Committee, Irish National Parks & Wildlife Service, and HPRA (**M.J.**).

Southern elephant seals, Antarctic fur seals (*Arctocephalus gazella*), Weddell seals, crabeater seals (*Lobodon carcinophaga*) and leopard seals (*Hydrurga leptonyx*) were tagged under ethics and permits provided by the Brazilian Antarctic Programme "in lieu" of SCAR as their local representatives for all the field work conducted on pinnipeds at Elephant Island, South Shetlands (**M.M.C.M.**).

Tagging procedures were conducted under the permit #572/208 approved by the National Administration of Aquatic Resources, Ministry of Livestock, Agriculture and Fisheries (DINARA), Uruguay (**F.G.R.**).

Tagging procedures were approved by the Dirección Nacional del Antártico, Buenos Aires, Argentina, and were carried out according to the Scientific Committee on Antarctic Research Code of Conduct for Animal Experiments under University of New South Wales Animal Care and Ethics Committee (Protocols 08/103B and 11/112A), and the Animal Care and Ethics Committee of the Antarctic Science Advisory Committee (permit number 1144) (**T.L.R.**).

Northern fur seal (*Callorhinus ursinus*) tagging in the Pacific North East and Pacific East Central was conducted in accordance with and under the authority of the United States Marine Mammal Protection Act (NMFS Permits 782–1455 and 782–1708). At the time this work was conducted there was no additional requirement for review of these procedures by an institutional review board or ethics committee. In 2010, a NMFS IACUC was established for the Alaska Fisheries and Northwest Fisheries Science Centers and the capture and handling protocols were reviewed and approved by this committee (**J.T.S.** and **R.R.**).

Harbor seal (*Phoca vitulina*) studies in Scotland were carried out under UK Home Office licence under the Animal (Scientific Procedures) Act 1986 (PIL nos. 60/3303, 60/4009 and 70/7806), following approval by the University of St Andrews animal welfare and ethics committee. Licences to capture and release animals in the wild for research were also granted by Marine Scotland Licensing (**P.M.T.**).

Animal handling and instrumentation complied with animal care regulations and applicable national laws of Ecuador. This research was approved by the Chancellor’s Animal Research Committee at University of California, Santa Cruz. The appropriate animal use and care committee of Ecuador (Parque Nacional Galapagos) approved all research protocols. This work was performed under the permit No PC-11-08 and PC-043-09 and authorization No. 084⁄06 PNG of the National Park service, Galapagos (**S.V.**).

Grey (*Halichoerus grypus*) and harbor seals were caught under licenses Number 05/475/AUT, 05/485/AUT, 06/82/AUT, 07/481/AUT, 08/346/DEROG, 08/347/DEROG, 10/102/DEROG, 11/873/DEROG, 11/874/DEROG, and 13/422/DEROG delivered by the French ministry of the environment (**C.V.**).

California sea lion (*Zalophus californianus*) capture and procedures were approved by the University of California Santa Cruz Chancellor's Animal Research Committee (CARC) protocol (COST 01.10) and authorized under National Marine Fisheries Service permit number 87-1593-05 (**M.J. Weise**)

Sirenians

Dugong tagging was conducted under the conditions of ethics permit DEC AEC 2009/11 (**R.A.C.**).

Permits required to capture and satellite track dugongs were obtained from the James Cook University Animal Ethics Committee (Permits A1735 and A1936) and the North (60912155-2013/JJC) and South (3157- 2012/ARR/DENV) Provinces of New Caledonia (**C.C.**).

Tagging procedures were approved by the Charles Darwin University Animal Ethics Committee and wildlife research permits were obtained from the Parks and Wildlife Commission of the Northern Territory (**S.D.W.**).

Manatee tagging procedures were carried out in accordance with the USFWS Permits MA107933-1 and MA37808A-0, Alabama Department of Conservation and Natural Resources, and Alabama Division of Wildlife and Freshwater Fisheries annual permits. Approvals obtained by the University of South Alabama IACUC for protocols 581568 and 1038636 (**R.H.C.**).

Turtles

Tagging was conducted under permits from Dirección General del Medi Natural de la Generalitat Valenciana, Generalitat de Catalunya, Consejeria de Medio Ambiente y Ordenación del Territorio de la Junta de Andalucia, and Región de Murcia. A general permit for tagging adult females was obtained from Ministerio para la Transición Ecológica y el Reto Demográfico (GPM/BDM/AUTSPP/23/2020) (**S.A.** and **E.J. Belda**).

The Indonesian Institute of Sciences provided research permits for telemetry deployments at the nesting beaches. Telemetry deployments at California foraging grounds were conducted under Endangered Species Act permit nos. 1159, 1227, and 1596 (**S.R.B.**).

Queensland Scientific purposes permit and a University of Queensland Animal Ethics permit (**H.A.C.**).

Tagging procedures were conducted under permits granted by the Commonwealth of Dominica Ministry of Agriculture and Forestry to Domenicia's Sea Turtle Conservation Organisation Inc (**R.W.C.**).

Green turtle (*Chelonia mydas*) tagging procedures were carried out in compliance with Mexican regulations (permit SGPADGVS/SEMARNAT, Mexico, No.09583/15). Hawksbill turtle (*Eretmochelys imbricata*) tagging was carried out in compliance with Mexican regulations (permit SGPADGVS/SEMARNAT Mexico, No.09583/15) (**E. Cuevas-Flores**).

Loggerhead turtles (*Caretta caretta*) were handled under license "Nº 04/IFCN/2018- FAU MAO" and previous licenses issued by the Government of the Autonomous Region of Madeira (**T.D.**).

Leatherback turtle tagging procedures were conducted under NMFS Endangered Species Act Section 10 Permits #1557 and #15672, University of New Hampshire IACUC #060501 and

#090402, and University of Massachusetts IACUC #2010-0019. Turtle disentanglement was conducted under the authority of NOAA 50 CFR Part 222.310 (**K.L.D.**).

All sea turtle research was conducted under NMFS Permit 1260 and 16733 to take protected species for scientific purposes and USFWS permits TE-676379-4 and TE676379-5 issued to the NMFS Southeast Fisheries Science Centre (SEFSC) and according to IACUC-reviewed procedures outlined in the NMFS SEFSC Sea Turtle Research Techniques Manual (**L.L.D.**).

Loggerhead and green turtle tagging procedures were conducted under permit issued by the wildlife agencies of Buenos Aires and Río Negro provinces and the National Wildlife Agency of Argentina (**V.G.C.**).

Green turtle tagging procedures were conducted within the Statia National Marine Park programme and complied with all relevant national legislation. Hawksbill turtle tagging was conducted within the Statia National Marine Park and St Maarten Marine Park programmes and complied with all relevant national legislation (**N.E.**).

Leatherback turtle tagging procedures were reviewed by the University of New Hampshire IACUC (060501) (**B.J.G.**).

Leatherback turtle were tagged under permit number SGPA/DGVS/08562/17. Green and hawksbill turtle tagging procedures were authorized by the SEMARNAT (permit numbers 150496–213–03, 280597–213–03, 190698–213–03, 280499–213–03, SGPA/DGVS/002m SGPA/DGVS/05137/12, SGPA/GDVS/02259/14, and SGPA/DGVS/04478/15) (**C.E.H.**).

Tagging procedures were approved by Swansea University and Deakin University Ethics Committees and the British Indian Ocean Territory (BIOT) Administration of the UK Foreign and Commonwealth Office. Research was endorsed through research permits (0002SE12, 0007SE15, 0002SE17, 0006SE18) from the Commissioner for BIOT and research complied with all relevant local and national legislation (**G.C.H.**).

Sea turtle tagging procedures and fieldwork were directly approved by the Centro TAMAR/IBAMA/ICMBio. Fundação ProjetoTAMAR has MMA/IICMBio/SISBIO Nº 42760 permit (**P.H.L.** and **E.A.P.S.**).

Tagging procedures for rehabilitated loggerhead sea turtles were conducted under the authorization of blanket permit from USFWS to NOAA NMFS. Loggerhead sea turtles acquired via capture or incidental capture were taken under the authority of NMFS Research permit 16134 (**G.L.**).

Green turtle tagging procedures were conducted with permission from the Administrator of Ascension Island. Leatherback turtle tagging was conducted under permits from Ezemvelo KwaZulu Natal Wildlife. Loggerhead turtle tagging was conducted with approval from the ethical committee of the University of Pisa (**P.L.**).

Tagging procedures were authorized under the Peru Instituto Nacional de Recursos Naturales (INRENA) permits 015-2002-INRENA-J-DGFFS-DCB, 070-2003-INRENA-IFFS-DCB, 068-2004-INRENA-IFFS-DCB, 025-2005-INRENA-IFFS-DCB and 002-2006-INRENA-IFFS-DCB (**J.C.M.**).

Tagging operations were authorized by the Dirección General de Sostenibilidad de la Costa y del Mar (Ref DIV/BDM/AUTSSP/58/2015, Spanish Government) (**D.M.**).

Green turtle tagging was conducted under permits of NOAA, Federated States of Micronesia, and Republic of Marshall Islands. Hawksbill turtle tagging was conducted under permits from NOAA, the USFWS, the Hawai'i Division of State Parks, and the Mexico Comisión Nacional de Áreas Naturales Protegidas (**D.M. Parker**).

Loggerhead turtles tagging procedures off of the Baja California Peninsula, Mexico, were conducted in full compliance with CARC/IACUC protocol at UC Santa Cruz and research was authorized by the Mexican government through SEMARNAP and SEMARNAT permits 150496- 213-03, 280597-213-03, 190698-213-03, 280499-213-03, 280700-213-03, SGPA/DGVS/002 4661, SGPA/DGVS/10358, and SGPA/DGVS/03501/06 (**H.P.**).

Tagging procedures were authorised by the Environment Agency Abu Dhabi, the Environment & Protected Areas Authority, Sharjah, the Environment Studies Center at Qatar University, the Qatar Ministry of Environment, the Oman Ministry of Environment and Climate Affairs, and the Department of Environment, Iran (**N.J.P.**).

Leatherback turtles tagging procedures were conducted under licence (# 27/01 and 73/08) from the Fauna Department-Ministry of Cattle, Agriculture and Fishing of Uruguay (**L.P.** and **M. Lopez Mendilaharsu**).

Tagging permissions were given by Oman's Ministry for Regional Municipalities, Environment and Water Resources (**A.F.R.**).

Tagging was performed with the permit of the Environmental Ministry of the Dominican Republic Government (**J. Tomás**).

Permissions for sea turtle rehabilitation work were given by the Dubai Wildlife Protection Office (**D.P.R.**).

Tagging procedures were conducted under approval from the National Marine Park of Zakynthos (permits from 2000–2012), the Animal Ethics Committee of Deakin University (B0X2015-17), and the Greek Ministry of Environment (Permit: 151503/162) (**G. Schofield**).

Tagging procedures were conducted under approval from the Dakshin Foundation Animal Research Ethics Review Committee. In the Andaman and Nicobar Islands, permits were issued to tag ten leatherback sea turtles with satellite transmitters from the Ministry of Environment and Forests (Wildlife Division), Government of India, on 16th December 2008 (F.No.1-4/2007 WL-I (pt-1)). Research permits from the Forest Department, Andaman and Nicobar Islands (CWLW/WL/47/393) and other relevant permits from the Andaman and Nicobar Administration were also obtained to carry out the field work in Little Andaman Island (**K.S.**).

Tagging procedures were performed in accordance with the Stanford University Protocol for the Care and Use of Laboratory Animals (APLAC no. 13848). The Costa Rican Ministry of Natural Resources and the Environment provided research permits (**G.L.S.**).

Green turtle tagging was conducted under permit approved by the Western Australian Department of Biodiversity, Conservation and Attractions. Tags were deployed by RPS Group – Perth WA (lead by former employee **D.W.**) on behalf of Woodside Energy Group Ltd.

Tagging procedures were conducted under permission obtained from the Viceconsejería de Medio Ambiente of the Gobierno de Canarias. Cape Verde did not require permission from the government at that time (**N.V.**).

Hawksbill turtle and olive Ridley turtle (*Lepidochelys olivacea*) tagging procedures were conducted under approval from Charles Darwin University Animal Ethics Committee and wildlife research permits (A4005) from Parks and Wildlife Commission of the Northern Territory (**S.D.W.**).

Research protocols for capturing and deploying satellite transmitters on flatback turtles were approved by an authorised ethics committee (SA 2015/11/531) and authority under the Nature Conservation Act 1994 (**I.B.**, **C.A.M.H.**, **A. Barnett**, **N.E.W.**).

Tracking data collection and processing

Tagging devices were deployed across more than three decades from 1985 to 2018 around the global ocean, resulting in a total of almost 11 million positions (after data curation: 6,854,440 positions) collected with different sensor systems and technologies for transmitting data. These included tagging devices using the Argos doppler-shift localization system (argos-system.org), GPS (global positioning system) and Fastloc GPS, as well as light-level geolocation tags (also termed global location sensor; GLS). Animals within taxa were captured (or tagged remotely) by different teams using a range of methods after the responsible team leader obtained all licenses and ethical permissions (see "Fieldwork and Data Collection"). All birds including penguins were mostly caught at nest sites using poles, traps, or nets, and tags generally attached dorsally or to a leg. Most cetaceans were tagged from the research vessel using crossbows, air-powered systems or poles to get tags attached to the dorsal fin or its vicinity. Fishes were mostly captured with baited hooks or purse-seine nets and tags typically attached to the first dorsal fin using a tether affixed to a dart or by fixing it with stainless steel bolts. Satellite collars were used for polar bears after immobilisation using rapid-injection darts. Seals were mostly captured with nets and sedated before tag deployment on the head or along the dorsal midline. All sirenians were tagged using a peduncle belt linked to the tag by a tether. Most turtles were captured at nesting beaches or at sea using nets or the by-hand 'rodeo' technique and tags glued to their carapace, except for leatherback turtles (*Dermochelys coriacea*) for which a harness ("backpack"), towed-tag or surgical techniques were used for attachment. All animal handling and tagging procedures were completed by trained personnel under permissions granted by ethical review bodies and in accordance with all relevant ethical regulations in the jurisdictions in which they were performed with specific approvals obtained by each data owner who was individually responsible for adhering to regulations and supervision of all procedures (details provided in "Animal Ethics Information").

Tracking datasets were collated after a lead author (representing each tagging research team) provided three csv files, each including species metadata, tracking data, and the team description. All datasets were requested with the least amount of processing possible, with all Argos, GPS and fastloc GPS data (~90% of the tracking data) provided as 'raw' position estimates. GLS positional data (for some birds and fishes only) were provided after estimation of longitude and latitude from the ambient variables recorded in the device (i.e., light intensity and elapsed time, but also depth and temperature for fishes). For birds, GLS position estimates provided were obtained in two ways: (*i*) through the Geolight package(*112*) in R(*113*) after carrying out a pre- and a post-calibration (seven days) to estimate an average value for the sun elevation parameter needed for calculations, or (*ii*) through the BASTrack software suite (British Antarctic Survey) after identifying sunrise and sunset times based on light curve thresholds and with longitude and latitude calculated from the time of local midday and day length, respectively. The exception was for the dataset for the hybrid complex of three *Pterodroma* species(*114*), referred here to as Trindade Petrel (*Pterodroma arminjoniana*), for which the GLS positions were processed with the R package *TripEstimation(115)*. For fishes, GLS tracks were obtained using pop-up satellite archival transmitters (PSAT) through satellite-relayed data or archived data from tags physically recovered. Positions were obtained after data decoding using software provided by the manufacturers (e.g., Wildlife Computers), where, similarly to bird data, longitude and latitude are calculated from estimated local time of midnight or midday and day-length, respectively. These PSAT GLS tracks were further processed with a continuous-time correlated random walk (CTCRW) Kalman filter using the crawl package(*116*) in R to produce daily positions, after filtering with the unscented Kalman filter using sea surface temperature through the UKFSST package in R and applying a bathymetric correction using the analyzepsat R add-on. PSAT data also included shark tracking data from the Tagging of Pacific Predators (TOPP) program which were downloaded from the Animal Tracking Network (ATN) hosted by the Integrated Ocean Observing System (ioos.noaa.gov/project/atn/, downloaded September 2017) for integration in the Global Shark Movement Project (GSMP; globalsharkmovement.org). These data obtained through GSMP were processed as detailed in (*62*) to determine daily position data.

All data were checked for quality-control and to standardise formats of the multiple and disparate datasets received. Poor data quality, lack of metadata, misidentified or incomplete tracks, repeated tracks, or unsolicited processing before data submission (e.g., interpolation of Argos tracked positions) led to the exclusion of 3,051 tracks from 10 species prior to analyses. All datasets were run through a speed filter using the SDAfilter package in R to remove outlier positions. Speeds used ranged for species between 5.4 – 35 $m.s^{-1}$ (20 – 126 $km.h^{-1}$) for birds, 1.6 – 7 $m.s^{-1}$ (5.8 – 25 $km.h^{-1}$) for cetaceans, 0.5 – 11.9 $m.s^{-1}$ (1.9 – 42.8 $km.h^{-1}$) for fishes, 2.1 – 4.2 $m.s^{-1}$ (7.5 – 15 $km.h^{-1}$) for penguins, 0.75 $m.s^{-1}$ (2.7 $km.h^{-1}$) for polar bears (but see (*117*)), 2.0 – 10.3 $m.s^{-1}$ (7.2 – 37 $km.h^{-1}$) for seals, 1.1 – 2.8 $m.s^{-1}$ (4.1 – 10 $km.h^{-1}$) for sirenians, and 1.4 – 2.8 $m.s^{-1}$ (5 – 10 $km.h^{-1}$) for turtles (refer to table S3 for details, and also for general morphometric data per species). During this procedure, all Argos data resulting from unsuccessful satellite uplinks (i.e., with location class Z) were removed from the dataset, keeping only location classes B, A, 0, 1, 2, and 3, which have increasing accuracy from ~160 km to 0.3 km (*118*).Visual inspection led to further removal of unrealistic GLS locations for some bird species (e.g., longitude < 43ºW or > 98ºW, latitude < 8ºN or > 73ºN for Arctic herring gull – *Larus smithsonianus*). A land mask was applied to all data using the rworldmap package in R and all locations assigned to land were excluded from analyses. We created 1° grid-cells for all area included in the world's ocean, and all grid-cells where animal tracking data were not detected have also been excluded from analyses. Because the area within each grid-cell varies considerably with latitude, all results were calculated based on area following:

$$\mathrm{A}(\theta) \;=\; 2\Delta\phi\, R^2\, [\sin(\theta_{max}) - \sin(\theta_{min})]$$

where θ is latitude, ϕ is longitude and θ_{max} and θ_{min} are the bounding latitudes of the grid-cell, and R is the average Earth's radius (6,371 km).

Addressing tracking data biases

The inherent biases in tracking datasets(*63*), such as the different data resolution and number of positions resulting from different devices, higher number of positions commonly obtained around tagging locations, and different track lengths obtained from devices deployed at the same time, make analyses challenging. To alleviate some of these potential issues, we gridded data at 1º resolution, keeping only the counts of unique individuals per species. We chose this resolution because it encompasses most of the known accuracies for most tracking devices, including most positions obtained by PSAT GLS(*62*), therefore alleviating most of the effects of position error estimates on track accuracy. This resolution has also been proposed as the best resolution to use when performing statistical analyses at large spatial scale(*63, 119*) or when using 'big data' approaches(*120*). To further reduce any potential biases in track accuracy due to the lower accuracy of GLS data and their limited daily locations (usually only 1 or 2), we repeated all spatial analyses using only one position per day for each individual, calculated as the centre of mass of all position estimates obtained per individual in a given day, and also used this dataset for all time-based calculations. We found these potential methodological biases led to no major differences in the pattern of results obtained (fig. S5). Furthermore, to avoid overestimating spatial overlaps due to the 'addition' of locations by interpolation methods – which can lead to locations being introduced where the animals were likely to have been but which were not detected by the tracking devices deployed – we considered all the positions that were detected, rather than interpolating positions for all taxa, except as detailed above (e.g., for the PSAT GLS daily position data for sharks derived from GSMP). Track interpolations, which are often calculated between positions up to 20 days apart(*61*) can result in an additional source of bias(*63*) and could inflate our globally important marine megafauna areas. By using only detected positions (rather than interpolated) and focusing on unique detections for each individual (instead of number of positions) within each 1° grid-cell, we conservatively estimated important marine megafauna areas that were also not affected by inflated detections around each tagging location (i.e., only one position was considered for each individual within 1° resolution around the tagging location). To further understand the potential effects of the tagging location bias, we also repeated our spatial analyses after removing all positions around the tagging location where the probability of finding an individual following a random trajectory from the tagging location was >10%. We did this by estimating the characteristic daily velocity (i.e., the root mean square displacement, d) for each species, and then using this value to estimate the diffusion constant (D) for a Brownian random walk, as $D = d^2/2T$ (with T = 1 day). We then compared our curated tracks with those obtained from trajectories generated through a Brownian random walk with that diffusion constant, when using similar starting locations for each track. We used these trajectories to estimate the probability of an individual randomly arriving at the same distance (or further) from each tagging location as that observed in the curated tracks, and discarded all positions where this probability was >1%. We then used our curated tracks with new starting positions matching the first location where the probability of randomly being at that location estimate was <10%, to re-compute our spatial analyses, which resulted in similar patterns obtained (fig. S6). Finally, to study the effects of spatial resolution on all our results, we repeated all the analyses at 0.5° and 2° grid-cell resolutions and found similar patterns (see fig. S7, fig. S8). All comparisons were made using the Jaccard similarity coefficient (or Jaccard index), which is calculated by dividing the size of the intersection of two datasets by the size of their union, and results in 0 for no intersection between the sets (i.e., complete dissimilarity) and in 1 for equal sets (i.e., high similarity).

Detection of key movement behaviours

To detect key movement behaviours such as migration (defining migratory corridors) or residence (potentially indicating feeding, mating or resting areas) throughout the three decades of tracking data in our multi-taxa global dataset, we used an algorithm based on statistical methods commonly applied to *big data* analyses. Our algorithm uses a time series of displacements calculated as the shortest great-circle distance, i.e., measured along the surface of the sphere, between two consecutive tracked locations separated by predetermined time-windows (*Tw*) (as done in *120*) from 1 – 10 days. We then calculated the average displacement per individual and normalised the displacements by the average displacement per species to account for disparities in speed across the 111 species considered in our study.

Detection of migratory corridors

For detecting migratory corridors captured by our tracking dataset, we calculated how *coherent* the movement direction was within each grid-cell for each species based on the displacements calculated for *Tw* = 1 – 10 days. We did this because the results obtained for movement direction can differ for long- and short-time windows, with the former likely to reflect long term movements in a specific direction (i.e., ignoring potential return trips or other shorter changes in direction, such as daily trips), and the latter likely to provide displacements that are unrepresentative of potential migration (i.e., 'noisy' data). We then defined *coherence* (*c*) per taxon, for each *Tw* and grid-cell, as the sum of the displacement vectors (w_d) in a particular direction (i.e., multiplied by the cosine and sine of the angle φ) and then divided by all displacements in all directions, as:

$$Coherence(T_w, c) = \frac{\sum_{d=1}^{D} w_d\,(\cos\varphi_d, \sin\varphi_d)}{\sum_{d=1}^{D} w_d}$$

where *D* represents all displacements observed in each grid-cell. To scale results across taxa, we multiplied the average monthly *coherence* by the ratio between the number of grid-cells with observed displacements within each time window (C_{dm}) and the maximum number of grid-cells observed over different time windows (max C_{dm}) for each taxon.

The selected taxon-specific displacements calculated for the *Tw* that resulted in the maximum number of 1° grid-cells showing coherent movement for that taxon (i.e., *'best Tw'*; refer to fig. S12) were then aggregated at temporal scales of 1, 2, 3, 4, 5, 6 and also 12 months. Considering multiple temporal scales was necessary due to the differences in movement behaviour across the many species considered in our study. For example, central place foragers return to start locations (e.g., colony) in each trip. Using multiple temporal scales is therefore useful to allow detection of movement corridors in both directions avoiding the cancellation of the displacement vectors occurring in opposite directions (e.g., trip from nest to foraging location cancelled by the reverse trip). Also, because migratory behaviour is largely unknown or incomplete for many species (e.g., sharks), we included temporal scales up to 12 months to ensure we captured any previously undetected long-term migration if present. To automate routines, these temporal scales were programmatically defined considering one month as 365 days/12 (~ 30.4 days). We then repeated the calculation of *coherence* at each temporal scale for each taxon to find sets of neighbouring grid-cells where displacements obtained from the tracking dataset indicated movement in the same direction. We did this by calculating the average direction of all observed displacements at each grid-cell within each temporal scale (e.g., for a temporal scale of 3 months, we used displacements calculated between 0 and ~ 90 days) and clustering all grid-cells that resulted in similar average direction (i.e., for which the cosine of the angle between their directions is > 0.8, i.e., indicating similar direction of movement).

The clustering of grid-cells resulted in a high number of clusters for each taxon and temporal scales. So, we computed the size distribution of clusters of grid-cells with similar average direction for each temporal scale and plotted the cumulative distribution. Then using a Lorenz curve as a parameter-free approach(*121*), we identified the intersection point between the slope of the tangent line at the maximum value (i.e., the slope where the cumulative distribution equals 1) and the *x-axis* in the Lorenz curve plot. This intersection point defines the threshold for minimum cluster size (i.e., minimum number of 1° grid-cells) defining a movement corridor at each temporal scale for each taxon (see fig. S13). All clusters with size above the defined threshold at any temporal scale were considered, and all 1° grid-cells within those clusters were aggregated and classed as corridors. Because speed is generally expected to be faster while "migrating", we confirmed speed within resulting corridors was always above average for each species.

Detection of residence areas

To determine residency-like behaviour indicative of areas where animals might be foraging, feeding, mating or resting (commonly characterised by slower speeds and greater tortuosity), we computed the z-scores (dimensionless) of the displacements starting within each grid-cell, considering the average displacements and respective standard deviations per species for the '*best Tw'* identified for each taxon. Each displacement observed in a track belonging to a species within each grid-cell was assigned a z-score by subtracting the average global displacement of that species from the calculated average displacement and dividing the result by the standard deviation of the displacements of that species. We then used these values to calculate the average z-score for each taxon in each grid-cell. If the average z-score calculated within each 1° grid-cell was lower than -1 (i.e., one standard deviation below the average displacement for that taxon), we considered it as reflecting a residency-like movement behaviour, and the corresponding grid-cells were classed as residence area. We used this approach to calculate z-scores across the same aggregated temporal scales used for detection of migratory corridors (i.e., using sets of 1, 2, 3, 4, 5, 6 and also 12 months) and, for a given taxon, observing residency-like movement behaviour in any of these scales led to the classification of the grid cell as a residence area for that taxon. To confirm that a random approach to identify areas of residence is not useful, we randomised all tracks in the dataset by changing the sequence of displacements to break their correlation but keeping the same start and end point of the trajectories (and therefore the same probability distribution function) (*122*). We then repeated the procedure to detect residence areas and see if they would be similar. We then used the Jaccard index(*123*) to measure the similarity between each randomised set of residence areas and the original per taxa. Detection of residence areas was substantially different after track randomisation, confirming space-use by animals was not random (fig. S14).

Statistical Modelling

Input Data

We modelled the probability of finding areas (grid-cells) used as residences or for migration separately for each taxon (except sirenians due to lack of data) using generalised linear models with a binomial error distribution and a logit link function. We develop these models considering as presences the locations where we have detected the described residence or migratory behaviours for each taxa and by randomly selecting equal number of locations where tracking data were available for each taxa but no behaviour was detected (see Table 2).

We then used a total of 13 environmental variables as predictors obtained from various online datasets (see Supplementary Acknowledgements). The predictors included monthly mean global sea surface temperatures (*sst*), ocean surface currents (*u* and *v*; respectively, eastward and northward ocean currents), sea surface height (*ssh*), salinity (*sal*), and mixed layer depth (*mld*) collated from the E.U. Copernicus Marine Service Information (CMEMS) Marine Data Store (MDS) Global Ocean Physics Reanalysis(*124*). Dissolved oxygen (O_2) was obtained from the CMEMS Global Ocean Biology Hindcast replaced in July 2022 by the Global Ocean Biogeochemistry Hindcast (*125*). Ocean turbidity (*turbidity*) and chlorophyll-*a* concentration (*chla*) were obtained from NASA Ocean Biology Processing Group Level-3 SeaWifs (1998-2003) (*126*) and Modis-Aqua (2003-2018) (*127*) Ocean Color Data. Atmospheric temperature at 2 m height (*temp2m*) and wind velocity at 10 m height (*u10* and *v10*, respectively representing eastward and northward direction) were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) (*128, 129*). We then used ocean surface currents to calculate eddy kinetic energy (*EKE*) as: $EKE = 0.5 * ((u - \bar{u})^2 + (v - \bar{v})^2)$, where u and v are eastward- and northward ocean currents respectively and the bar indicates the time-average. All environmental data were linearly interpolated to 1° (horizontal) resolution.

Model Set

We used the following set of seven models to explain the occurrence of residences and migratory behaviour, each including a different set of the environmental variables we collated (as described in table S8) and specifically avoiding inclusion of correlated variables in the same model:

Model 1: *Behaviour ~ sst + u + v + mld + chla + eke + bathymetry + Month*
Model 2: *Behaviour ~ ssh + u10 + v10 + turbidity + salinity + eke + bathymetry + Month*
Model 3: *Behaviour ~ O2 + vel + vel10 + mld + chla + bathymetry*
Model 4: *Behaviour ~ temp2m + u + v + mld + chla + eke + bathymetry*
Model 5: *Behaviour ~ mld + chla + sst*
Model 6: *Behaviour ~ u + v + eke + bathymetry*
Model 7 (Null model): *Behaviour ~ 1*

The response variable "*Behaviour*" corresponded to grid-cells where residence or migratory behaviour has been detected plus an equal number of grid-cells where presences were available in our tracking dataset but no behaviour was detected. The total number of grid-cells with presence and each of the residence or migratory behaviours detected per taxa are shown in Table 2. We compared the predictive ability of models containing different sets of these environmental variables using the Akaike's information criterion(*130*). According to the weight of the Akaike's Information Criteria (*wAIC*), model 2 was ranked highest for the different behaviours across all taxa, with the only exception being residency for penguins and turtles (for which the highest ranked models were model 1 and 3, respectively) (table S9). On average, the highest ranked model for corridors explained 17.8 % of the deviance (ranging from 5.2 % for turtles to 40.1 % for penguins), while for residences it explained 12 % of the deviance (ranging from 3.1 % for seals to 24.8 % for polar bears) (Table 2).

Predictions

We used the highest ranked model to predict which grid-cells are likely to be used as residence or for migration within the entire area where we had occurrence data for each taxon (see resulting maps in fig. S17). We did this after applying cross validation using a set of 10 (or 5 depending on available data for each taxon) iterations to assess the predictive ability of the highest ranked models for each taxon. We assessed the predictive ability using the Cohen's *Kappa statistics* (*K*), which measures the agreement between predicted and real (i.e., obtained) values(*131*). We then used Landis & Koch (*132*) criteria to class results into 'no agreement' ($K \leq 0$), 'slight agreement' ($0 < K \leq 0.2$), and at least 'fair agreement' ($K > 0.2$). Our *K* values for corridors averaged at 0.35 (ranging from 0.17 for turtles to 0.56 for penguins) and for residences averaged at 0.32 (ranging from 0.22 for birds and seals to 0.44 for cetaceans) (Table 2). To compute the final important marine megafauna areas across all taxa and months to be considered for the 30% protection (as shown in the right panel of Fig. 3), we used our predictions results only from models for which *K* was above 0.2 before applying the optimization algorithm.

Optimisation algorithm

To select important marine megafauna areas for protection, we first assigned a score to each grid-cell based on the detection of key movement behaviours reflecting migratory corridors or residency areas across taxa. To do this, we first defined Tc and Tr, respectively, as the number of taxa using the grid-cell as migratory corridor or residence, and then attributed a higher importance to grid-cells used as residence (i.e., where animals are likely to spend more time) when calculating the product between Tc and Tr to obtain each score per grid-cell, following:

$$Score = 2^{Tc}\ x\ 3^{Tr}$$

Using this formula, grid-cells receive scores of 2 or 3 if they are, respectively, used as: migratory corridor or residence by multiple species of only one taxon, and increasingly higher scores if they are used both as corridors and residencies across multiple taxa (e.g., we obtained a maximum score of 1944, for grid-cells used by 5 taxa as residence and 3 taxa as corridors) (fig. S15). We then ordered the grid-cells by descending scores to increasingly select, according to this ranking, grid-cells currently not (or only partially) protected, until we reached the 30% target (30% of 71.1 % area covered by our tracking dataset). The resulting selected grid-cells results in the polygons shown in Figure 3 (and the results from a sensitivity analyses changing the scores provided to migratory corridors and residences is provided in fig. S16). We repeated this procedure for the detected movement behaviours based on the probability of each grid-cell to be used as residence or for migration by each taxon obtained after our modelling procedure (detailed below). We selected important marine megafauna areas in decreasing order from the highest probabilities (closest to 1) until the threshold of 30% was reached, and similarly created the resulting polygons shown in Figure 3 (right panels).

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Compiled Raw Data for Contribution

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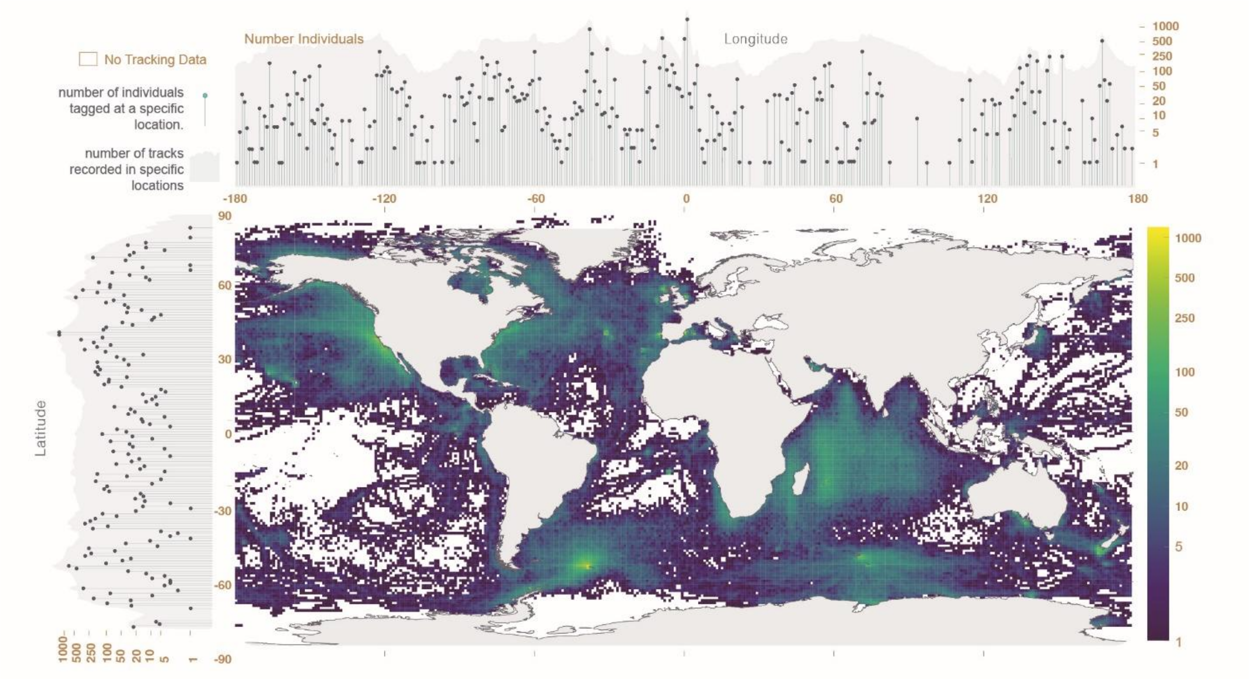

Number Individuals
Longitude
No Tracking Data
number of individuals tagged at a specific location.
number of tracks recorded in specific locations
Latitude
-180
-120
-60
0
60
120
180
90
60
30
0
-30
-60
-90
1000
500
250
100
50
20
10
5
1

Fig. S1. Total number of tracked individuals per latitude and longitude

Spatial extent of the marine megafauna tracking datasets including the 12,794 individuals in the global dataset at 1⁰ resolution, with top and left inset plots representing longitudinal and latitudinal coverage of the curated tracks with dotted histograms showing the number of individuals tagged (at tagging locations) and shaded areas indicating the number of individuals with tracked positions in the same geographical locations. These plots show that a higher number of tracked individuals is not necessarily related to tagging locations.

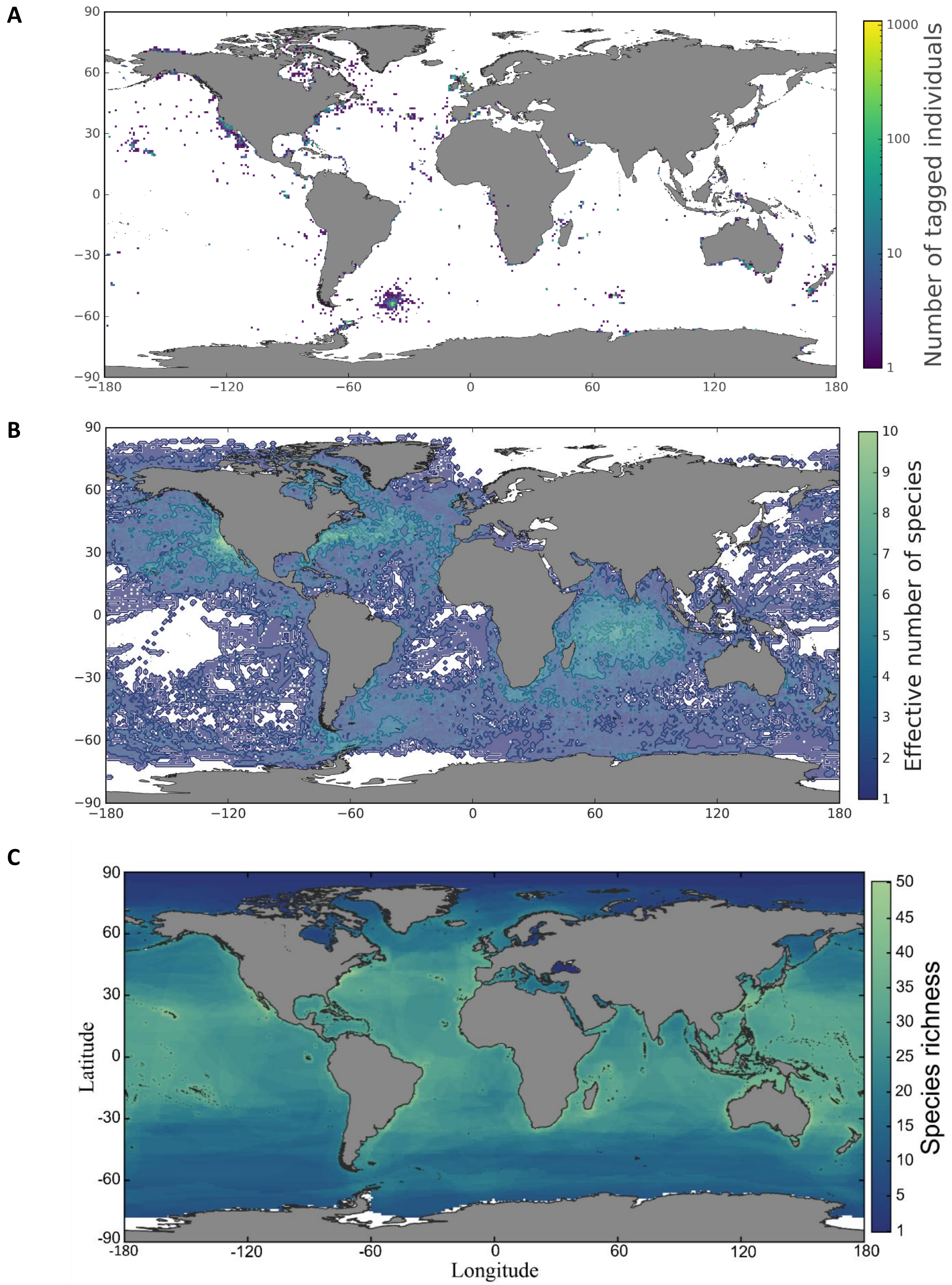

A
Number of tagged individuals
1000
100
10
1
B
Effective number of species
10
9
8
7
6
5
4
3
2
1
C
Species richness
50
45
40
35
30
25
20
15
10
5
1
Latitude
90
60
30
0
-30
-60
-90
Longitude
-180
-120
-60
0
60
120
180

Fig. S2. Biodiversity captured versus expected based on the 111 species considered in our dataset.

Map shows that our dataset captures some of the known hotspots, including in the NE Pacific, NW Atlantic, and regions of the SW Atlantic, but it misses others (e.g., Indo-Pacific and Central West Pacific regions, Gulf of Guinea, and waters around Australia and Madagascar). A) Global map depicting the first locations tracked per individual, providing a visual representation of the tagging locations. B) Effective number of species (S_{eff}) observed in each grid-cell (c) where we had tracking data based on the Shannon entropy (H)(*31*). H was calculated from the probability of observing each species among all the individuals visiting each grid-cell ($p_s(c)$), which in turn is the result of the fraction of tracked individuals $f_s(c)$ of each species (s) grid-cell with at least one location within each 1° grid-cell divided by the total number of tagged individuals of the same species. The resulting fraction is independent from the tagging effort excluding potential biases arising from the different number of tagged individuals of each species.

$$S_{\mathrm{eff}}(c) = 2^{H(c)} \text{ where } H(c) = \sum_s p_s(c)\, log_2\, p_s(c) \text{ and } p_s(c) = \frac{f_s(c)}{\sum_s f_s(c)}$$

C) Expected richness hotspots for the species considered based on species geographical range shapefiles obtained from the iucnredlist.org/ (accessed 24 Jan 2022) for all species, except for flatback turtles, which were obtained from the Recovery Plan for Marine Turtles in Australia (2017)(*133*). For comparison with global biodiversity maps see literature for birds(*134*), mammals(*51*), sharks(*14*), and also general marine biodiversity (i.e., also including plants, corals and non-migratory animals)(*135*).

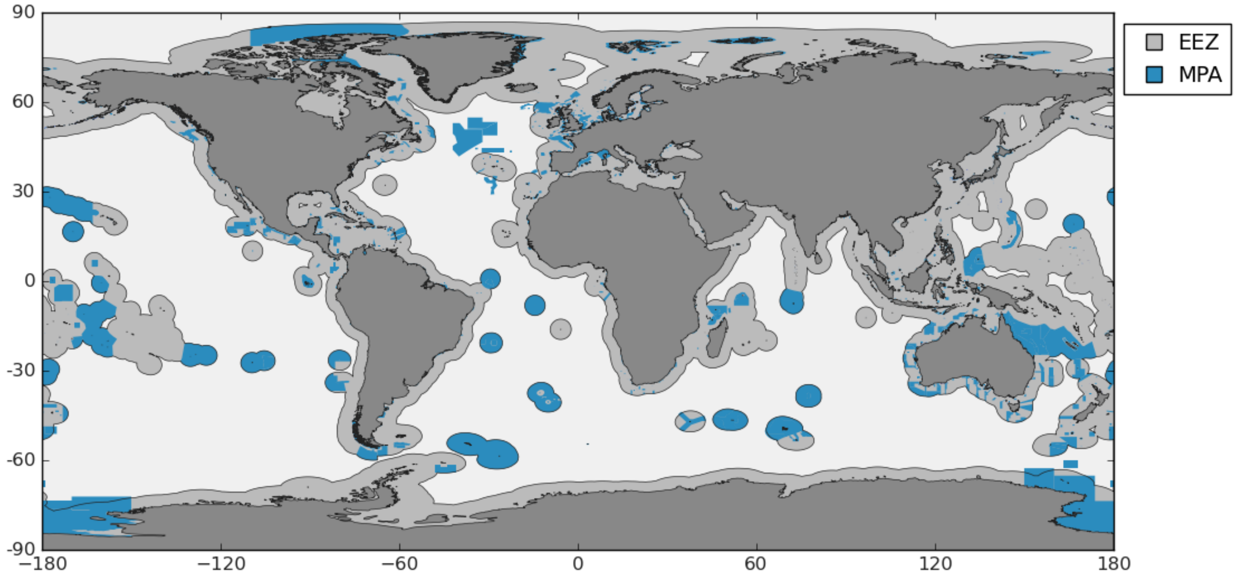

90
60
30
0
-30
-60
-90
−180
−120
−60
0
60
120
180
EEZ
MPA

Fig. S3. Marine Protected Areas (MPAs) and Exclusive Economic Zones (EEZs) in the marine environment

We obtained geographical information defining existing marine protected areas (MPAs, including marine parks; shown in blue) from protectedplanet.net (accessed 10 June 2021) (*33*) and exclusive economic zones (EEZs; shown in grey) from marineregions.org/ (accessed 28 June 2021) (*34*).

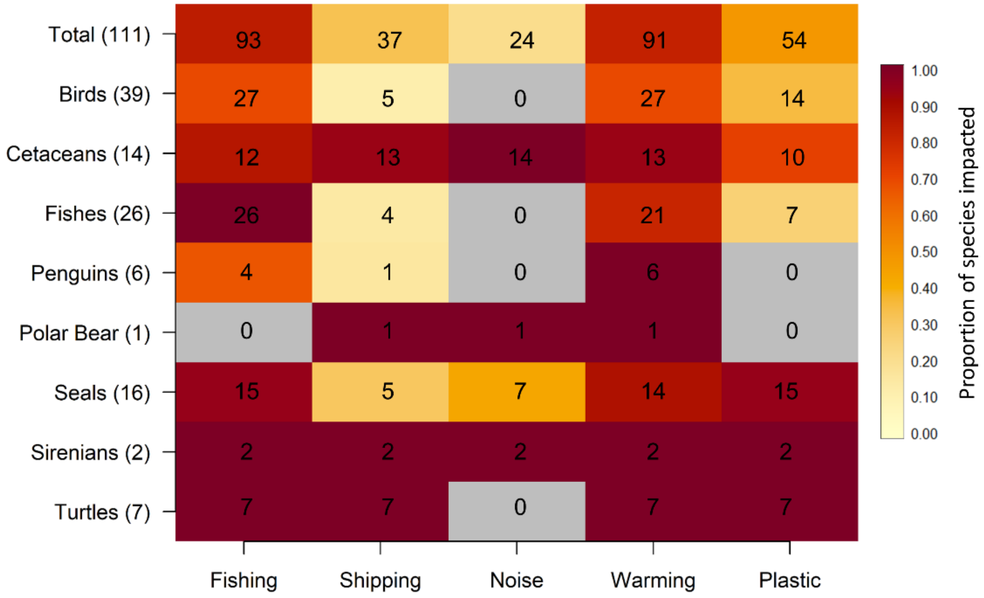


Fig. S4. Number of species affected by each anthropogenic threat considered

Summaries of the number of species known to be impacted by each threat considered in our analyses based on the listed threats and sub-threats on the IUCN Threats Classification Scheme v3.3(*50*) as detailed in table S4. Figure shows commercial fishing and climate change (represented as SST anomaly) has having impacts on the highest number of species analysed in this study, and with fixed gear and longlines fishing gears listed for most species. All sea turtles, sirenians and polar bears are affected by most of the threats. A large number of birds, cetaceans and fishes are impacted by fishing and SST anomaly, with higher number of birds and fish species being impacted by plastic, and higher number of cetacean species being the most impacted by shipping and noise. Species considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

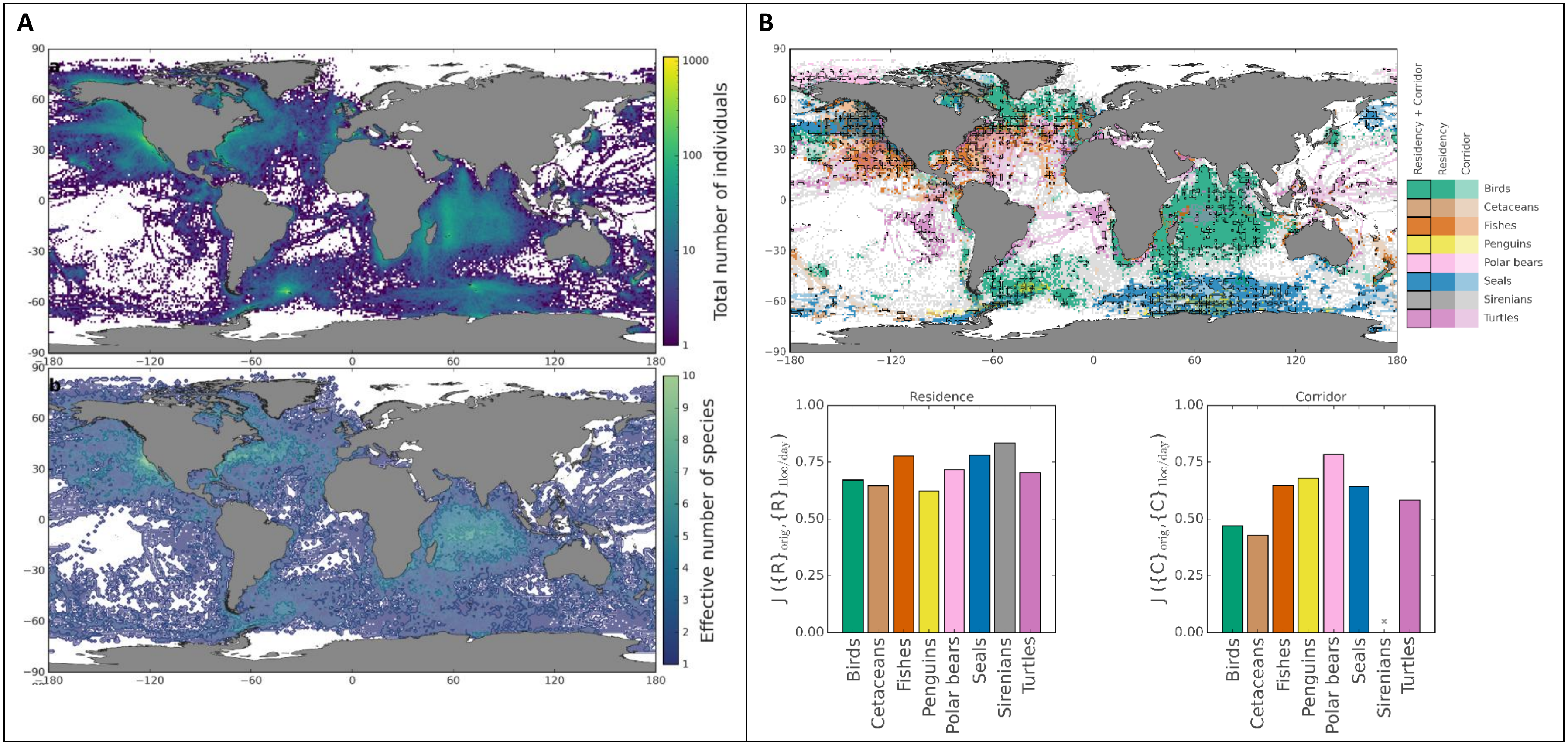

A
a
b
Total number of individuals
1
10
100
1000
Effective number of species
1
2
3
4
5
6
7
8
9
10
90
60
30
0
−30
−60
−90
−180
−120
−60
0
60
120
180
B
Residency + Corridor
Residency
Corridor
Birds
Cetaceans
Fishes
Penguins
Polar bears
Seals
Sirenians
Turtles
Residence
Corridor
$J(\{R\}_{orig}, \{R\}_{1loc/day})$
$J(\{C\}_{orig}, \{C\}_{1loc/day})$
0.00
0.25
0.50
0.75
1.00
Birds
Cetaceans
Fishes
Penguins
Polar bears
Seals
Sirenians
Turtles
×

Fig. S5. Assessment of behaviours detected when using only one position per day for each individual

Results for the final tracking dataset when considering only one position per day per individual across all taxa. All maps show similar spatial patterns to those obtained for the complete dataset (as shown in Fig. 1 and Fig. S2). A) Top: Total number of individuals for which we have tracking data in each grid-cell; Bottom: effective number of species obtained per grid-cell. B) Top: Identified migratory and residence areas when using only one position per day per individual across all taxa (greyed grid-cells indicate that no key movement behaviour was identified); Bottom: Results obtained when using the Jaccard Index to compare the results obtained here with those obtained from the original dataset. Species considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

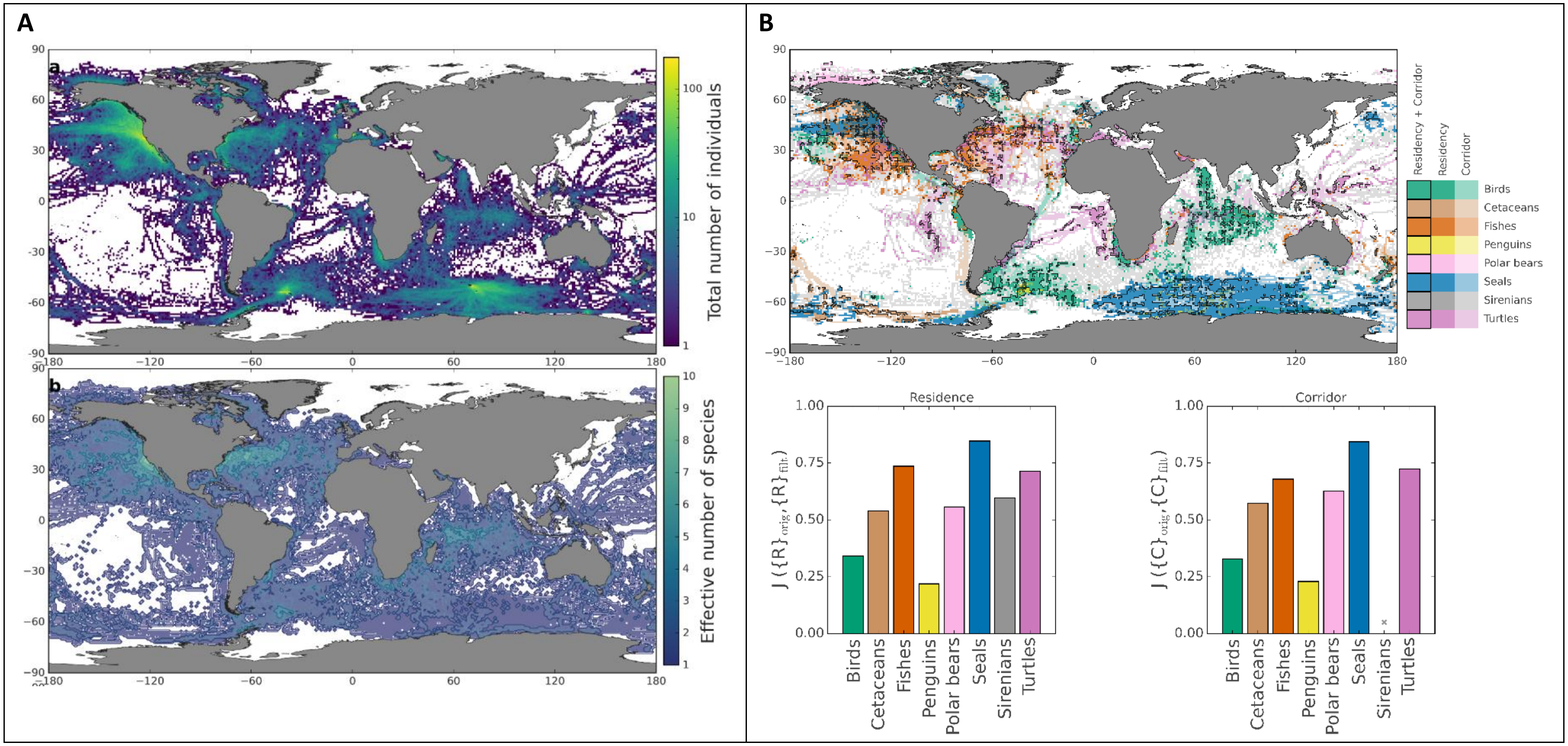

A
a
b
Total number of individuals
100
10
1
Effective number of species
10
9
8
7
6
5
4
3
2
1
90
60
30
0
−30
−60
−90
−180
−120
−60
0
60
120
180
B
Residency + Corridor
Residency
Corridor
Birds
Cetaceans
Fishes
Penguins
Polar bears
Seals
Sirenians
Turtles
Residence
Corridor
$J(\{R\}_{orig},\{R\}_{filt})$
$J(\{C\}_{orig},\{C\}_{filt})$
1.00
0.75
0.50
0.25
0.00
Birds
Cetaceans
Fishes
Penguins
Polar bears
Seals
Sirenians
Turtles
×

Fig. S6. Assessment of behaviours detected when removing the tagging location bias

Results for the final tracking dataset after removing the tagging location bias. All maps show similar spatial patterns to those obtained for the complete dataset (as shown in Fig. 1 and fig. S2). A) Top: total number of individuals for which we have tracking data in each grid-cell; Bottom: effective number of species obtained per grid-cell. B) Top: Identified migratory and residence areas when removing all locations around the tagging location for all individuals across all taxa (greyed grid-cells indicate that no key movement behaviour was identified); Bottom: Results obtained when using the Jaccard Index to compare the results obtained here with those obtained from the original dataset. Species considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

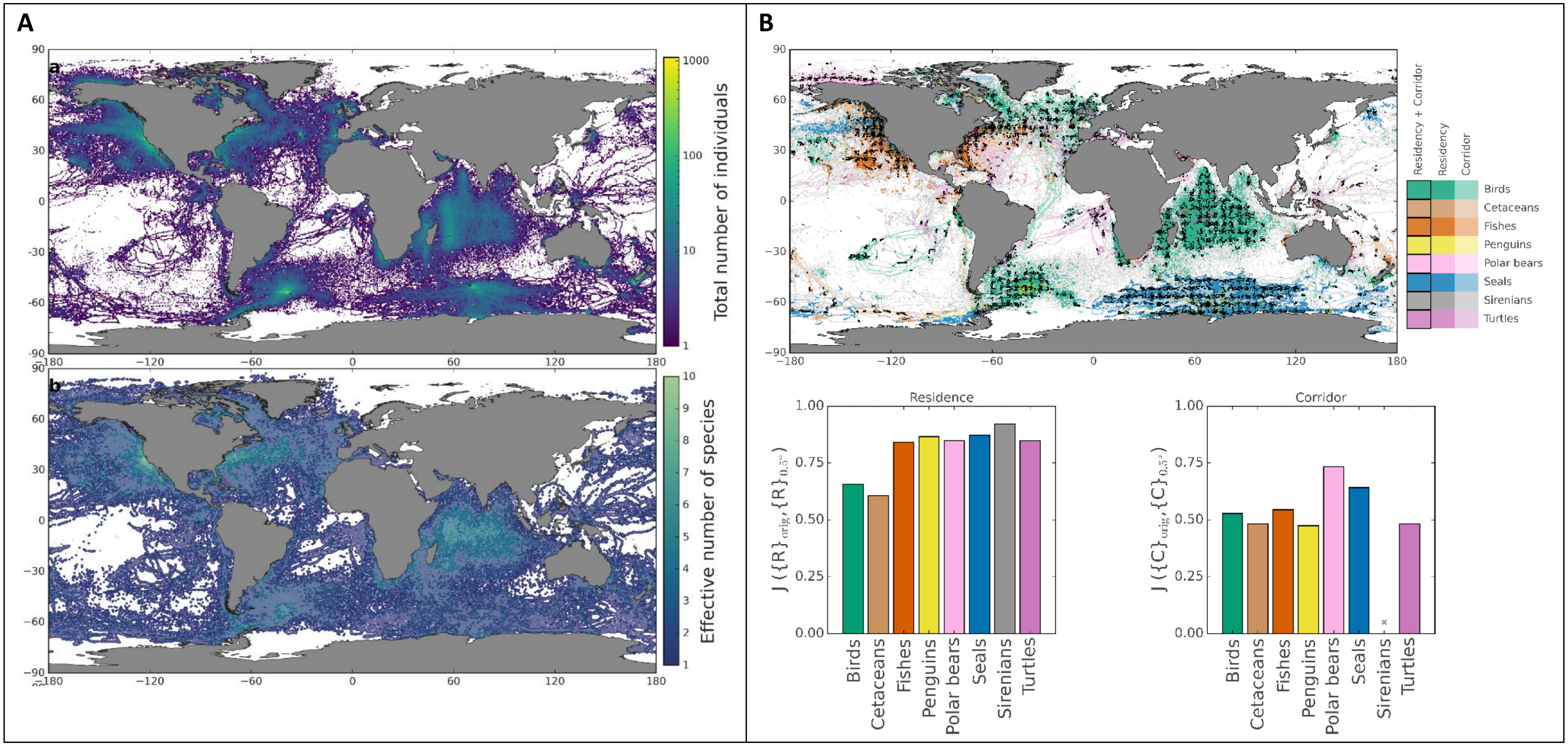

A
a
Total number of individuals
1000
100
10
1
b
Effective number of species
B
Residency + Corridor
Residency
Corridor
Birds
Cetaceans
Fishes
Penguins
Polar bears
Seals
Sirenians
Turtles
Residence
Corridor
$J(\{R\}_{orig},\{R\}_{0.5^\circ})$
$J(\{C\}_{orig},\{C\}_{0.5^\circ})$
Birds
Cetaceans
Fishes
Penguins
Polar bears
Seals
Sirenians
Turtles

Fig. S7. Assessment of behaviours detected when changing resolution to 0.5°

Results for the final tracking dataset when considering a spatial resolution of 0.5° All maps show similar spatial patterns to those obtained for the complete dataset (as shown in Fig. 1 and fig. S2). A) Top: total number of individuals for which we have tracking data in each grid-cell; Bottom: effective number of species obtained per grid-cell. B) Top: Identified migratory and residence areas when halving the spatial resolution (greyed grid-cells indicate that no key movement behaviour was identified); Bottom: Results obtained when using the Jaccard Index to compare the results obtained here with those obtained from the original dataset. Species considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

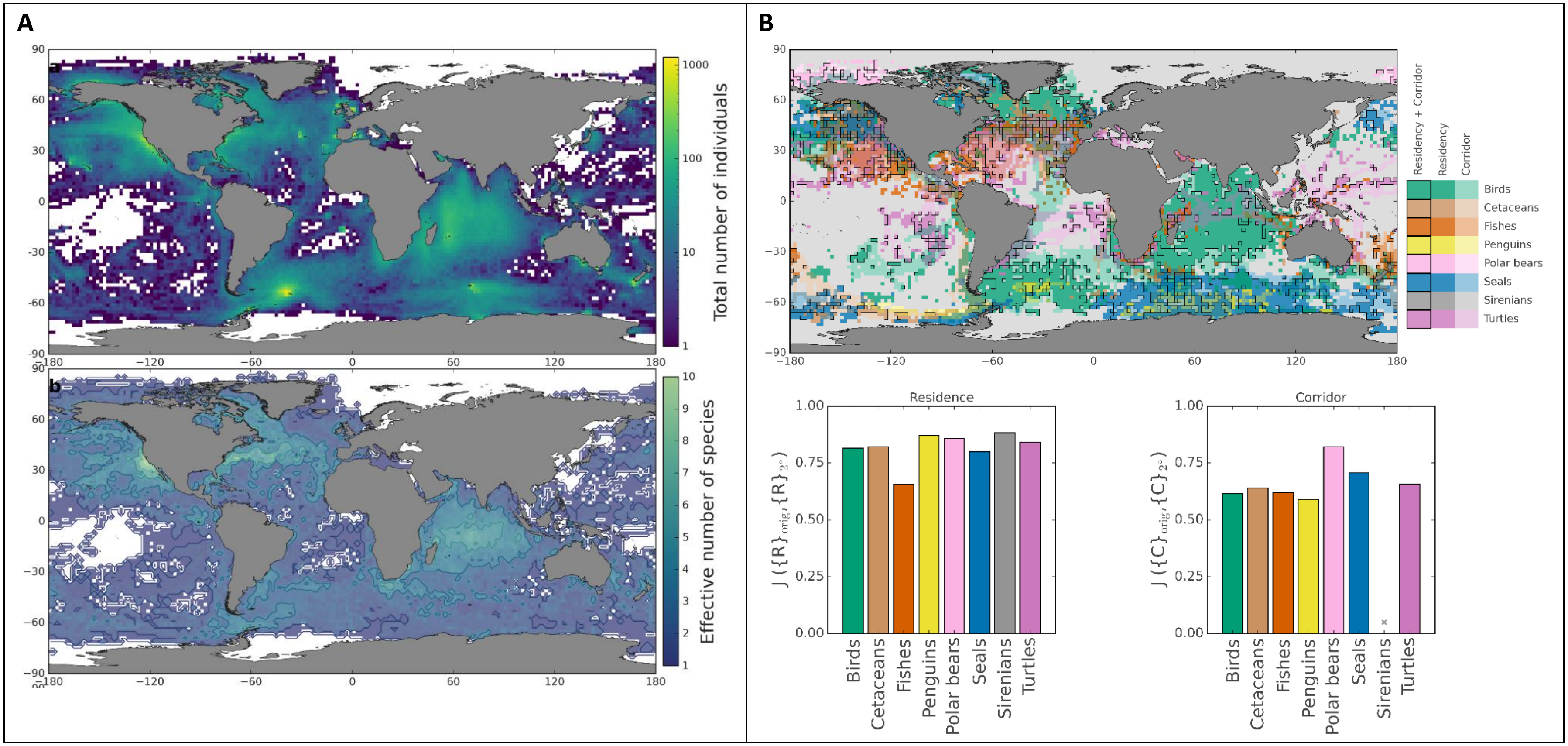

A
a
b
Total number of individuals
1000
100
10
1
Effective number of species
10
9
8
7
6
5
4
3
2
1
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
B
Residency + Corridor
Residency
Corridor
Birds
Cetaceans
Fishes
Penguins
Polar bears
Seals
Sirenians
Turtles
Residence
Corridor
J ({R}orig,{R}2°)
J ({C}orig,{C}2°)
1.00
0.75
0.50
0.25
0.00
×

Fig. S8. Assessment of ecological meaningful behaviour when changing resolution to 2°

Results for the final tracking dataset when considering a spatial resolution of 2°. All maps show similar spatial patterns to those obtained for the complete dataset (as shown in Fig. 1 and fig. S2). A) Top: total number of individuals for which we have tracking data in each grid-cell; Bottom: effective number of species obtained per grid-cell. B) Top: Identified migratory and residence areas when doubling the spatial resolution (greyed grid-cells indicate that no key movement behaviour was identified); Bottom: Results obtained when using the Jaccard Index to compare the results obtained here with those obtained from the original dataset. Species considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

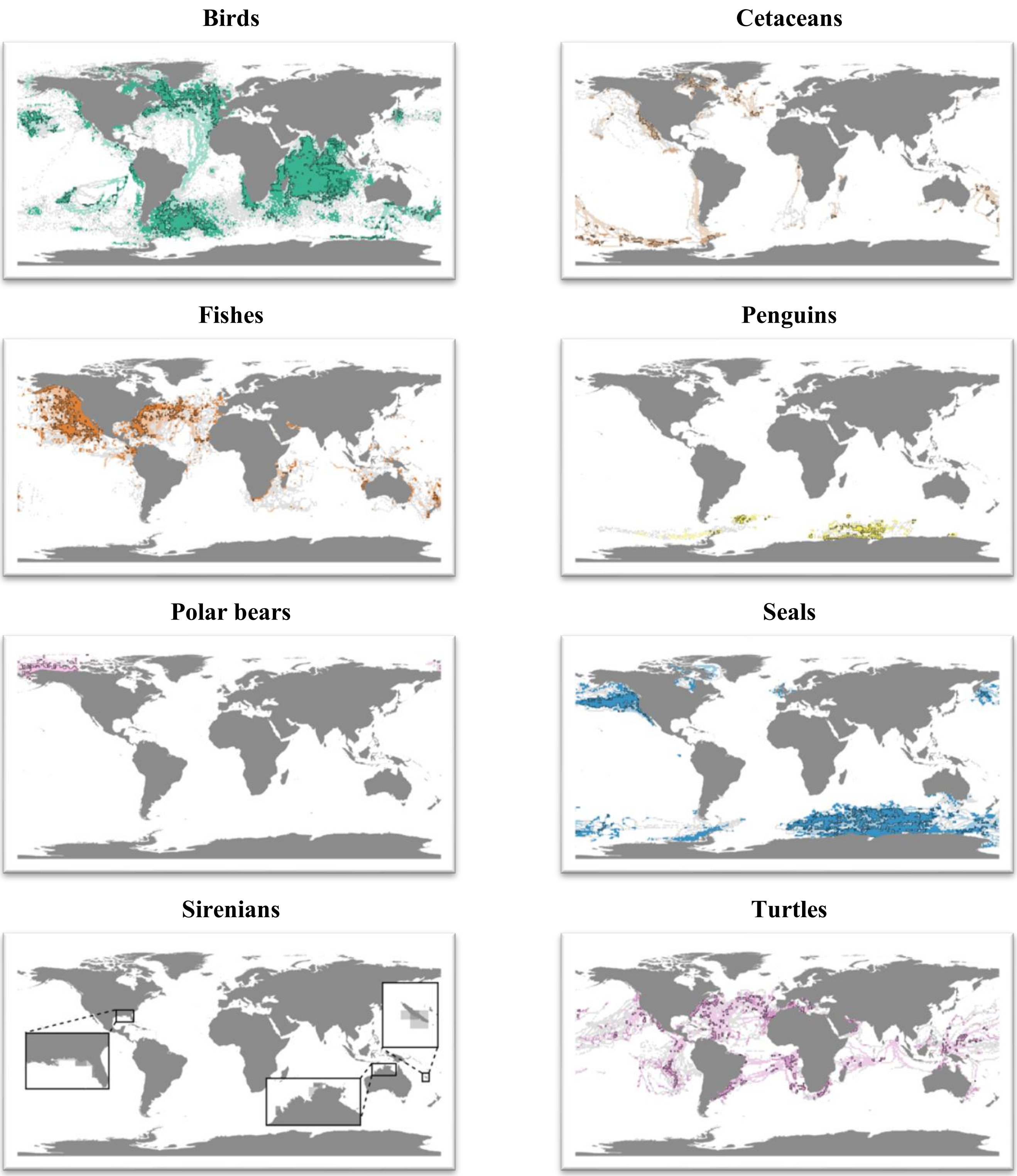

Birds
Cetaceans
Fishes
Penguins
Polar bears
Seals
Sirenians
Turtles

Fig. S9. Detected important migratory corridors and residence areas found by taxa
Spatial representation of migratory corridors and residence areas by taxa detected based on our analyses of coherence and z-scores (Methods). Results include the migratory corridors shown with faded colours for each taxon, which were obtained after detection of the time window that

resulted in the maximum number of 1° grid-cells showing coherent direction of movement within each month for each taxon (fig. S12), and after detection of hotspots of coherence clusters using on a Lorenz curve approach (fig. S13). Residence areas, indicated by grid-cells shown in stronger colours, were obtained based on z-scores of one standard deviation below the average displacement for each taxon. Where both migratory corridors and residence areas were found, grid cells include a black outline. Grey indicates grid-cells where no specific behaviour was identified. White areas depict regions without tracking data. Species considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

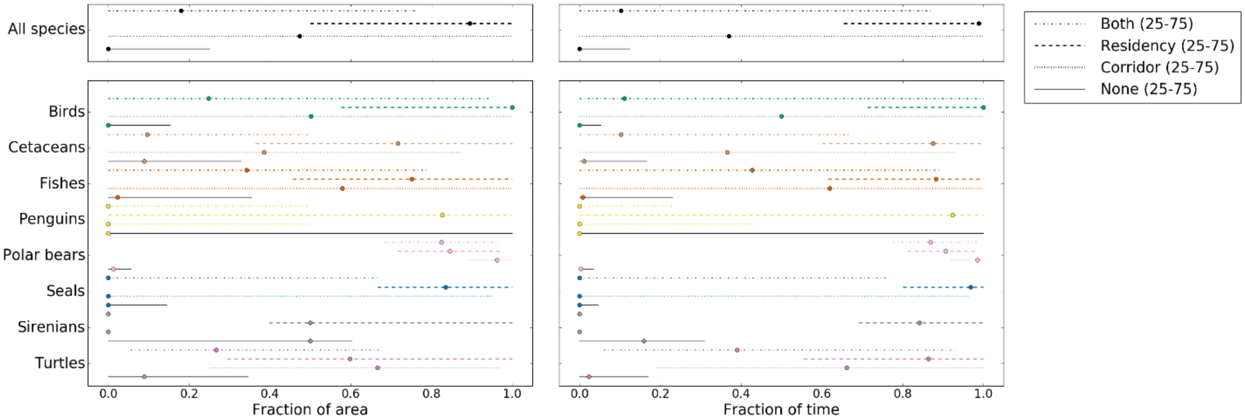


Fig. S10. Statistics of the space and time used for different behaviours per taxa

Fractions of space use (left panel) and time spent (right panel) in different behaviours calculated for each individual to show the distribution of the results obtained per taxon. Shown are the median values (percentile 50, dots) connecting the percentiles 25 and 75 obtained across individuals within each taxa. These values represent the most likely values on any sample of tracked individuals (with other values obtained outside the interval between percentiles 25 and 75). Species considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

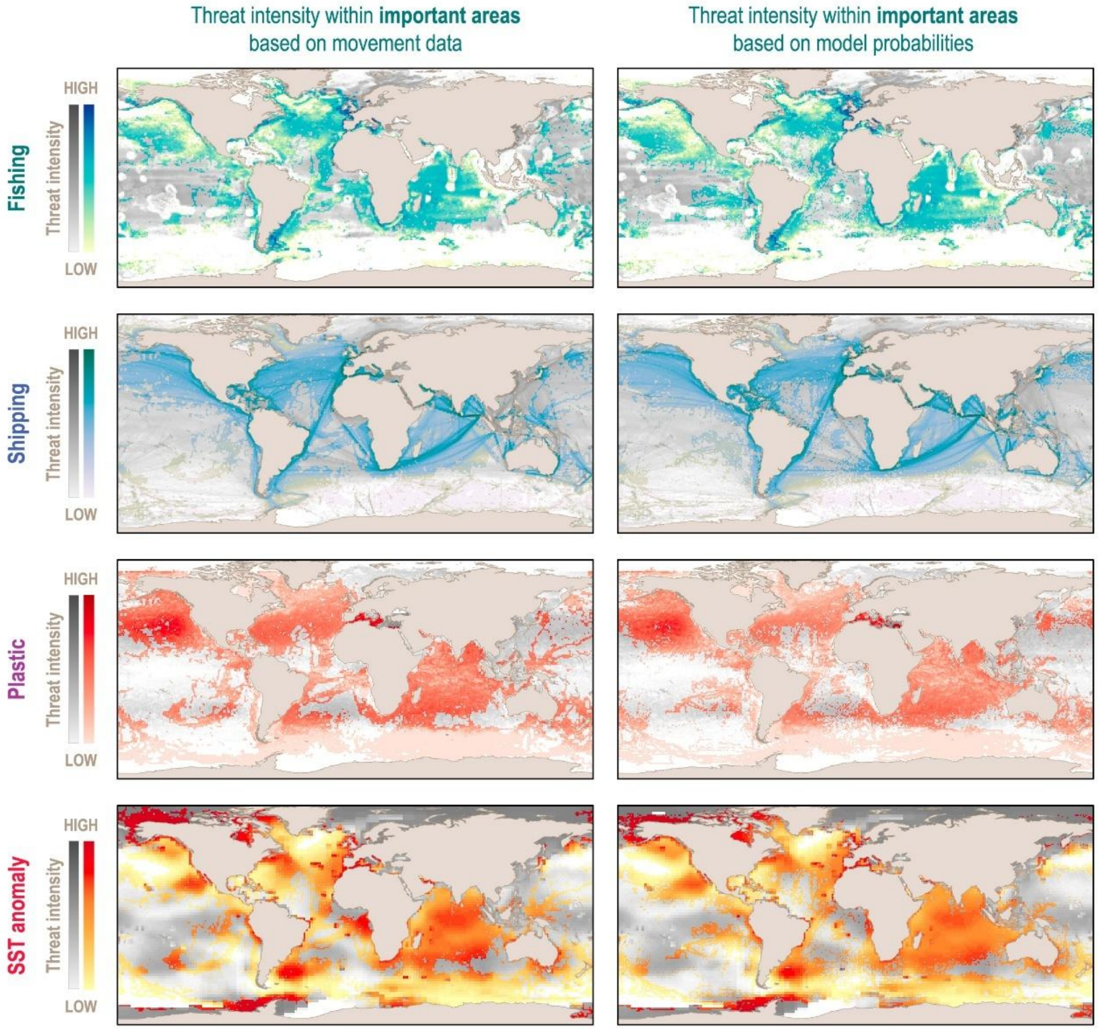

Threat intensity within **important areas** based on movement data
Threat intensity within **important areas** based on model probabilities
Fishing
Shipping
Plastic
SST anomaly
Threat intensity
HIGH
LOW

Fig. S11. Global footprint of anthropogenic threats and intensity within important areas for marine megafauna (IMMegAs)

The global footprint of anthropogenic threats is displayed as global averages per threat. Threat intensity outside the important marine megafauna areas identified in this study (left: based on the movement data, and right: based on model predictions) is indicated by the grey colour bar, and by the coloured bars per threat within important areas. Threats depicted include, from top to bottom: fishing intensity, shipping density, plastic density, and warming (according to anomalies to sea surface temperature; SST).

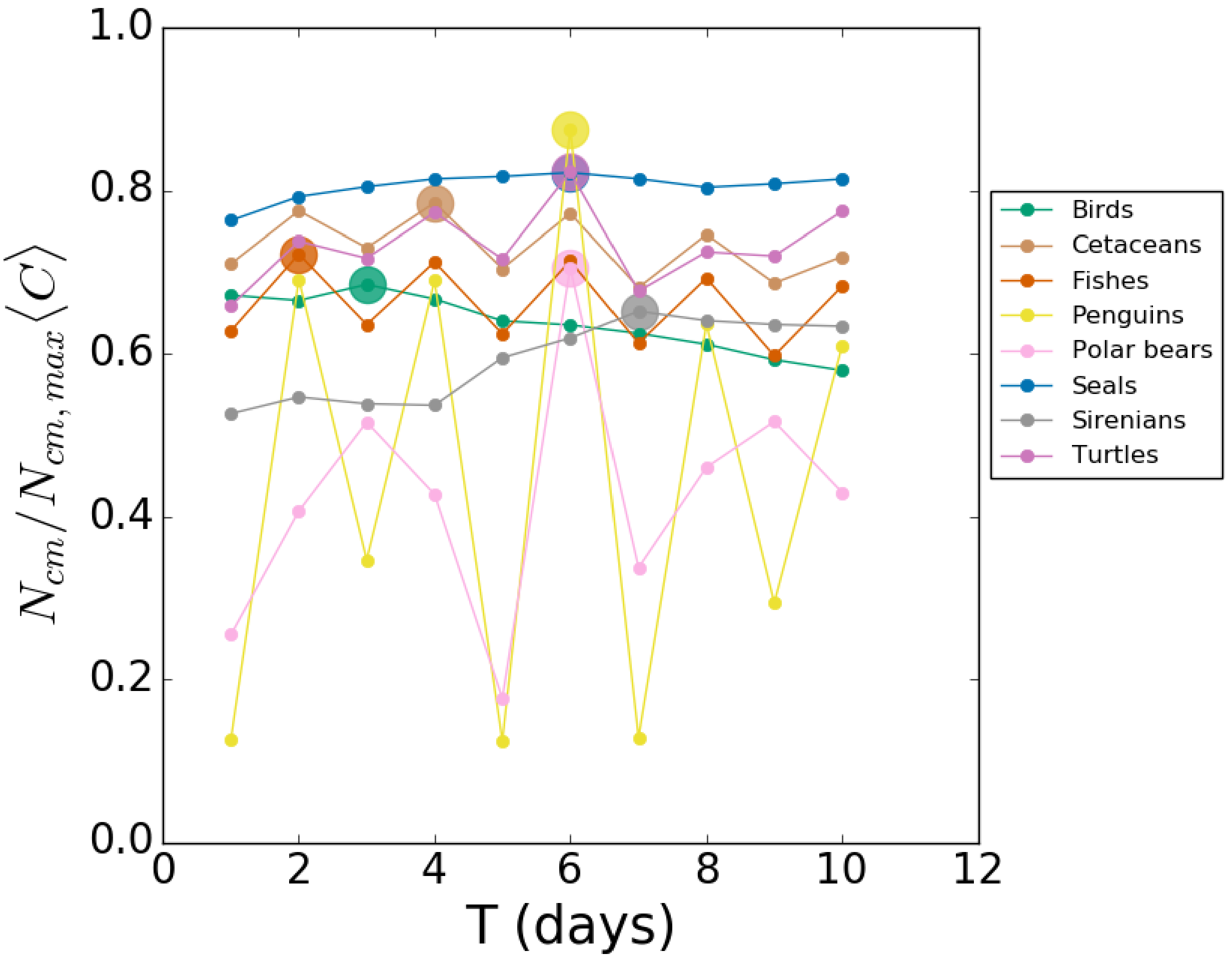


Fig. S12. Average monthly coherence results at multiple time windows for all taxa

Our analyses for detection of key movement behaviours indicated by migratory or residency-like behaviours showed that the maximum number of 1° grid-cells with coherent movement was obtained for time windows (*Tw*) < 10 days for all taxa considered: 2 days for fish, 3 days for birds, 4 days for cetaceans, 6 days for penguins, polar bears, seals, and turtles, and 7 days for sirenians. Circles indicate the time at which coherence was highest for each taxon. Species considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

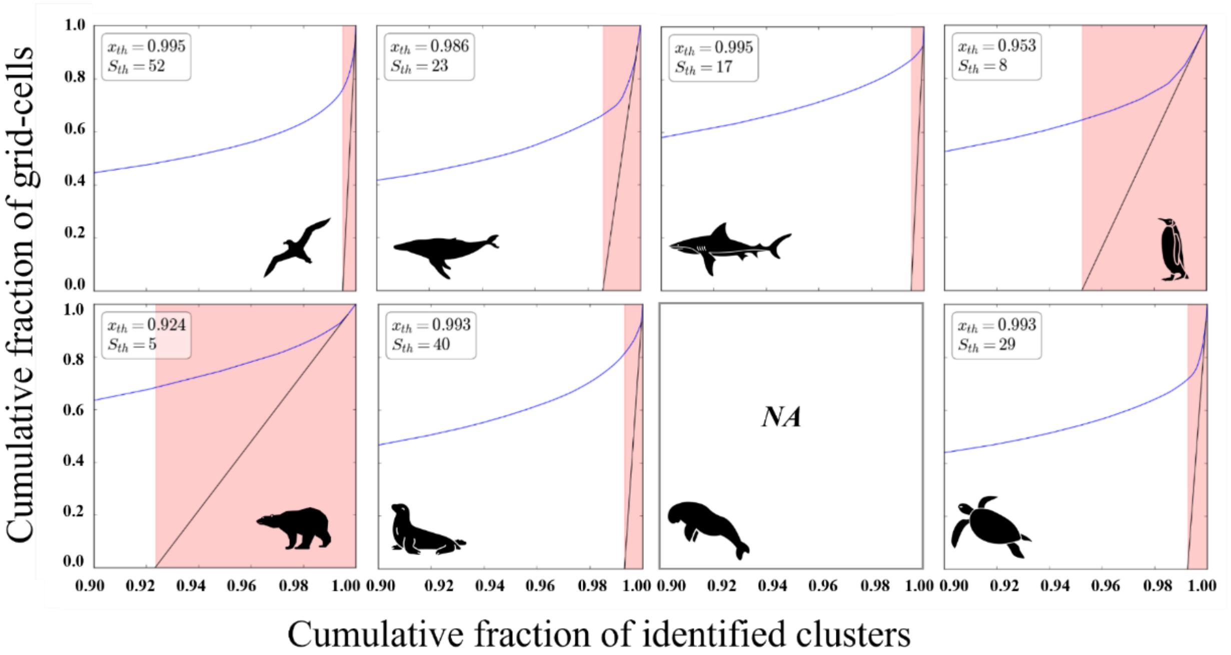


Fig. S13. Detection of cluster hotspots of coherence with the Lorenz curve

Plots show the results obtained per taxon, when considering multiple temporal scales of 1, 2, 3, 4, 5, 6, and 12 months to identify hotspots of clusters of grid-cells with coherent movement (i.e., grid-cells for which the cosine of the angle between their average directions is > 0.8) that resulted in the global migratory corridors shown in Figure 3 (also shown per taxon in Fig. S9). The threshold for minimum cluster size defining a migratory corridor at each temporal scale for each taxon was identified with a Lorenz curve (parameter free approach; *121*). For example, for birds, the hotspots for minimum cluster size were detected at the top 0.5% of the cumulative distribution (i.e., for $x_{th} = 0.995$), indicating the minimum cluster size to identify a migratory corridor was 52 connected grid-cells. Migratory corridors were therefore, defined at minimum cluster sizes (S_{th}) of 52 grid-cells for birds, 23 for cetaceans, 17 for fishes, 8 for penguins, 5 for polar bears, 40 for seals, and 29 grid-cells for turtles. No hotspots of clusters of grid-cells with coherent movement were detected for sirenians, likely due to lack of data. Species considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

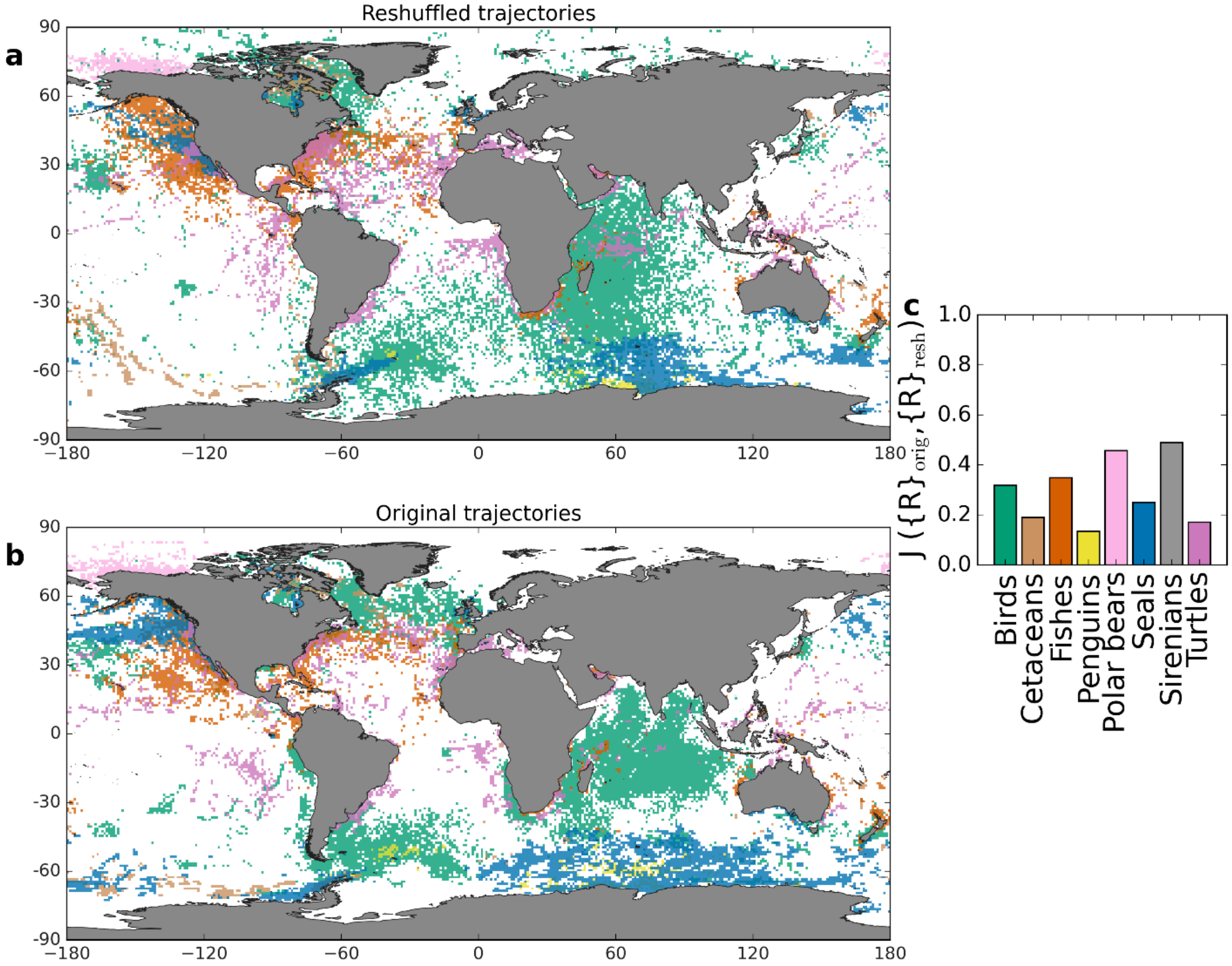

a
Reshuffled trajectories
90
60
30
0
-30
-60
-90
−180
−120
−60
0
60
120
180
b
Original trajectories
90
60
30
0
-30
-60
-90
−180
−120
−60
0
60
120
180
c
J ({R}orig, {R}resh)
1.0
0.8
0.6
0.4
0.2
0.0
Birds
Cetaceans
Fishes
Penguins
Polar bears
Seals
Sirenians
Turtles

Fig. S14. Comparison of detected residency areas across taxa after randomising tracks

Maps show the grid-cells identified as residency areas for each taxon after (a) and before (b) one example of randomised tracks (see Materials and Methods) to demonstrate animals are selectively using space. Patterns shown on the bottom map follow those identified in the original dataset and displayed in Fig. 2. (c) shows the Jaccard index (i.e., area of overlap divided by area of union) obtained for each taxon. The low values for the index across taxa confirm the independence of the results before and after randomising the dataset. Colours refer to birds (light green), cetaceans (dark yellow), fishes (red), penguins (dark green), polar bears (orange), seals (blue), sirenians (purple), and turtles (pink). Species considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

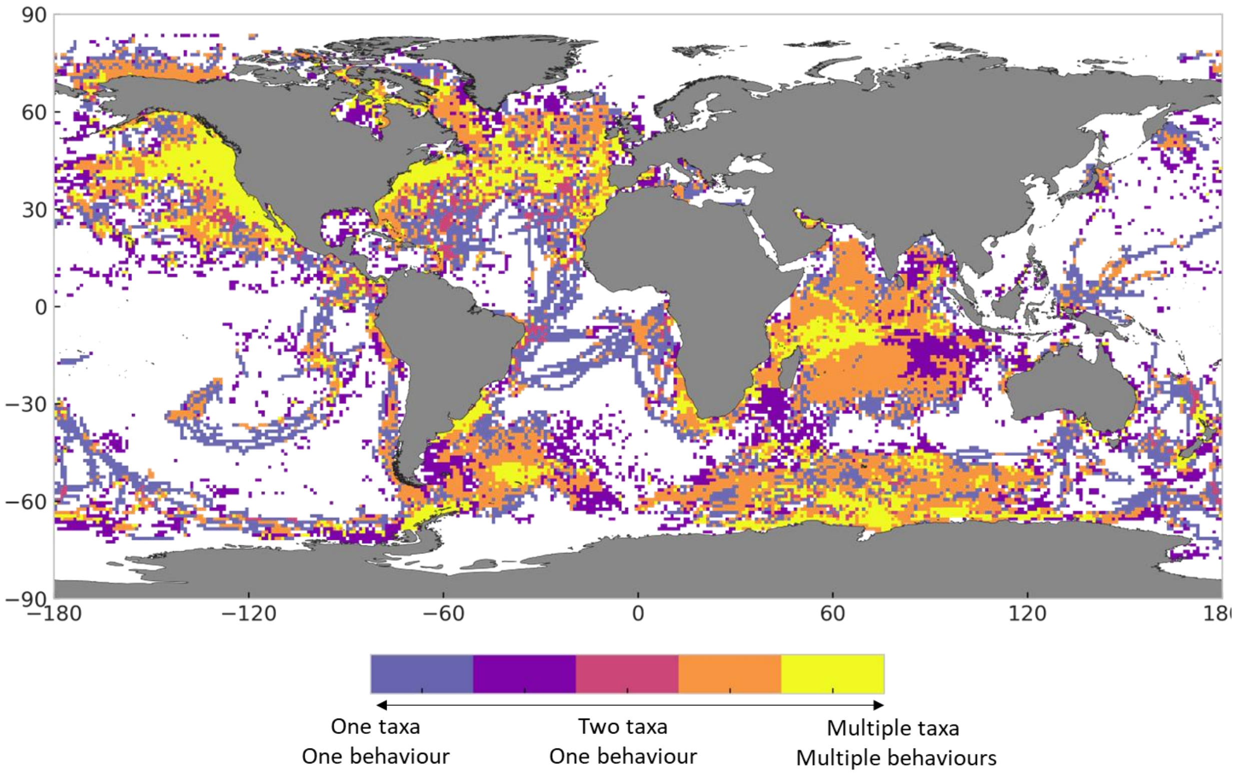

90
60
30
0
−30
−60
−90
−180
−120
−60
0
60
120
18
One taxa
One behaviour
Two taxa
One behaviour
Multiple taxa
Multiple behaviours

Fig. S15. Depiction of scores computed as part of the optimisation algorithm to select priority areas for global protection of marine megafauna

Areas used by multiple taxa (noting that each taxa group includes multiple marine megafauna species, table S1) are indicated with warmer colours (i.e., in purple, orange and red according to an increase in taxa and behaviours observed).

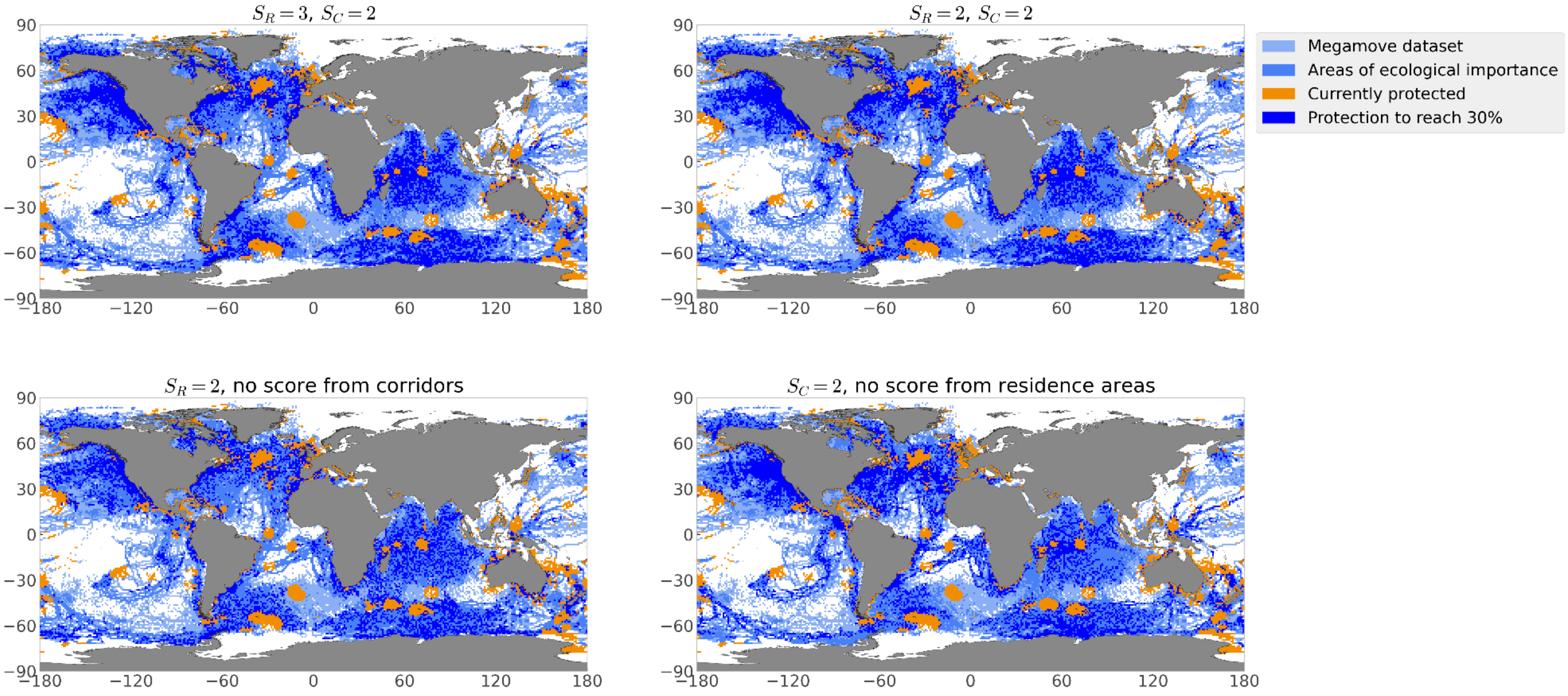
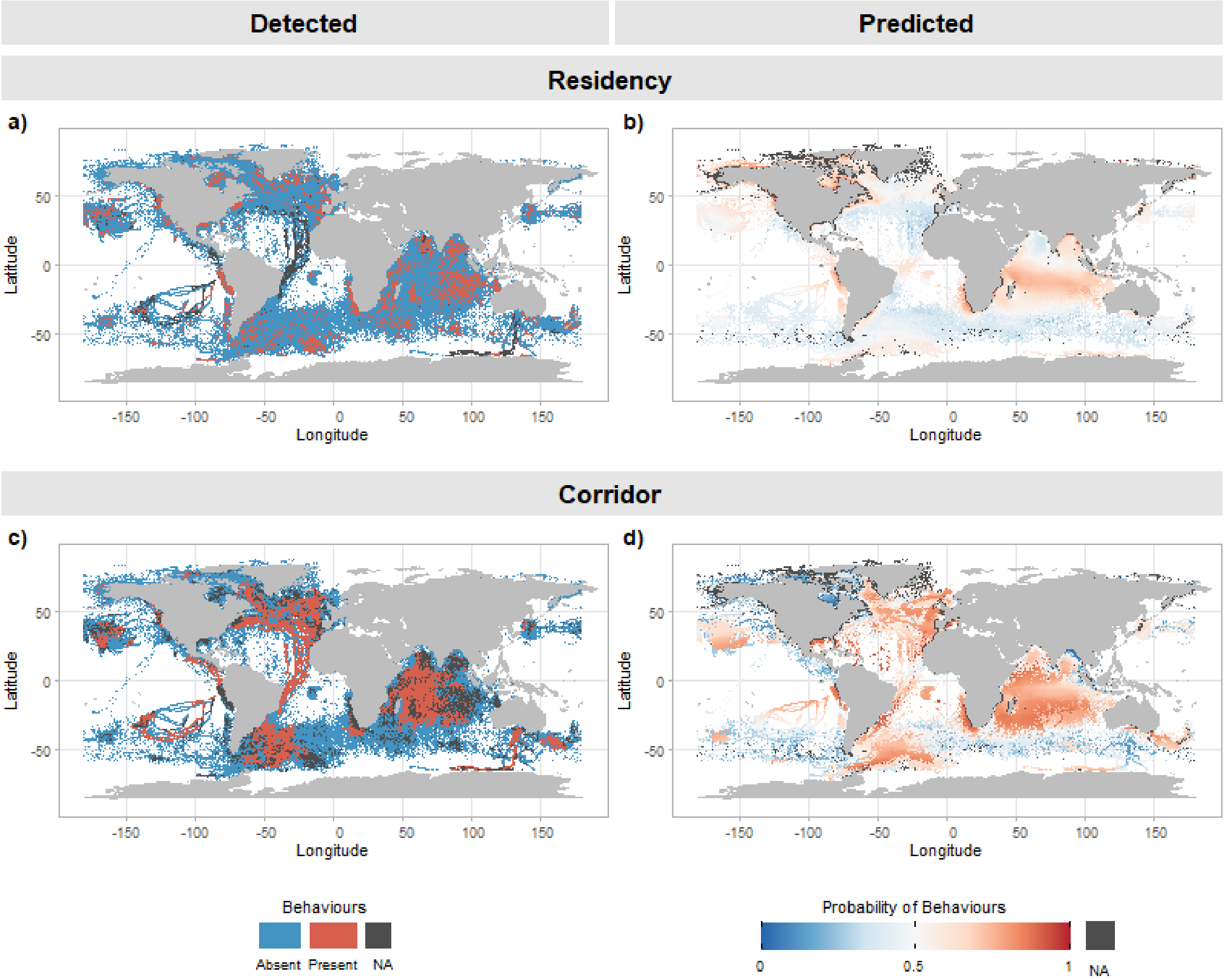

$S_R = 3,\ S_C = 2$
$S_R = 2,\ S_C = 2$
$S_R = 2$, no score from corridors
$S_C = 2$, no score from residence areas
90
60
30
0
−30
−60
−90
−180
−120
−60
0
60
120
180
Megamove dataset
Areas of ecological importance
Currently protected
Protection to reach 30%

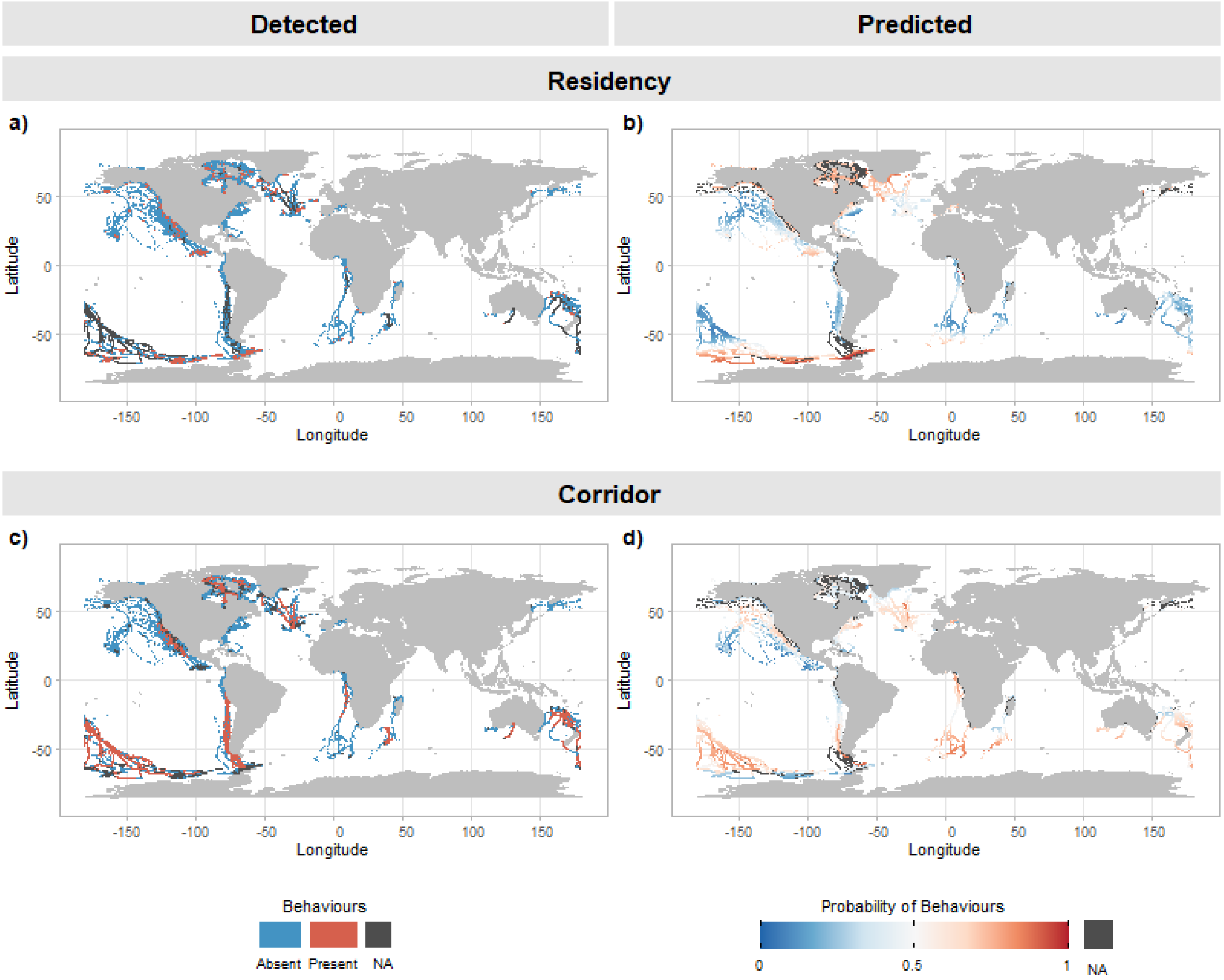
Fig S16. Sensitivity analyses on the priority areas selected by our optimisation algorithm

Results obtained when the scores for migratory corridors (S_C) and for residences (S_R) used to run the optimization algorithm were changed: (Top left) $S_R=3$ and $S_C=2$ as used throughout the manuscript, (Top rigth) $S_R=2$ and $S_C=2$, (Bottom left) $S_R=2$ with no score for corridors, and (Bottom right) $S_C=2$ with no score for residence areas (and showing the most different results as expected).

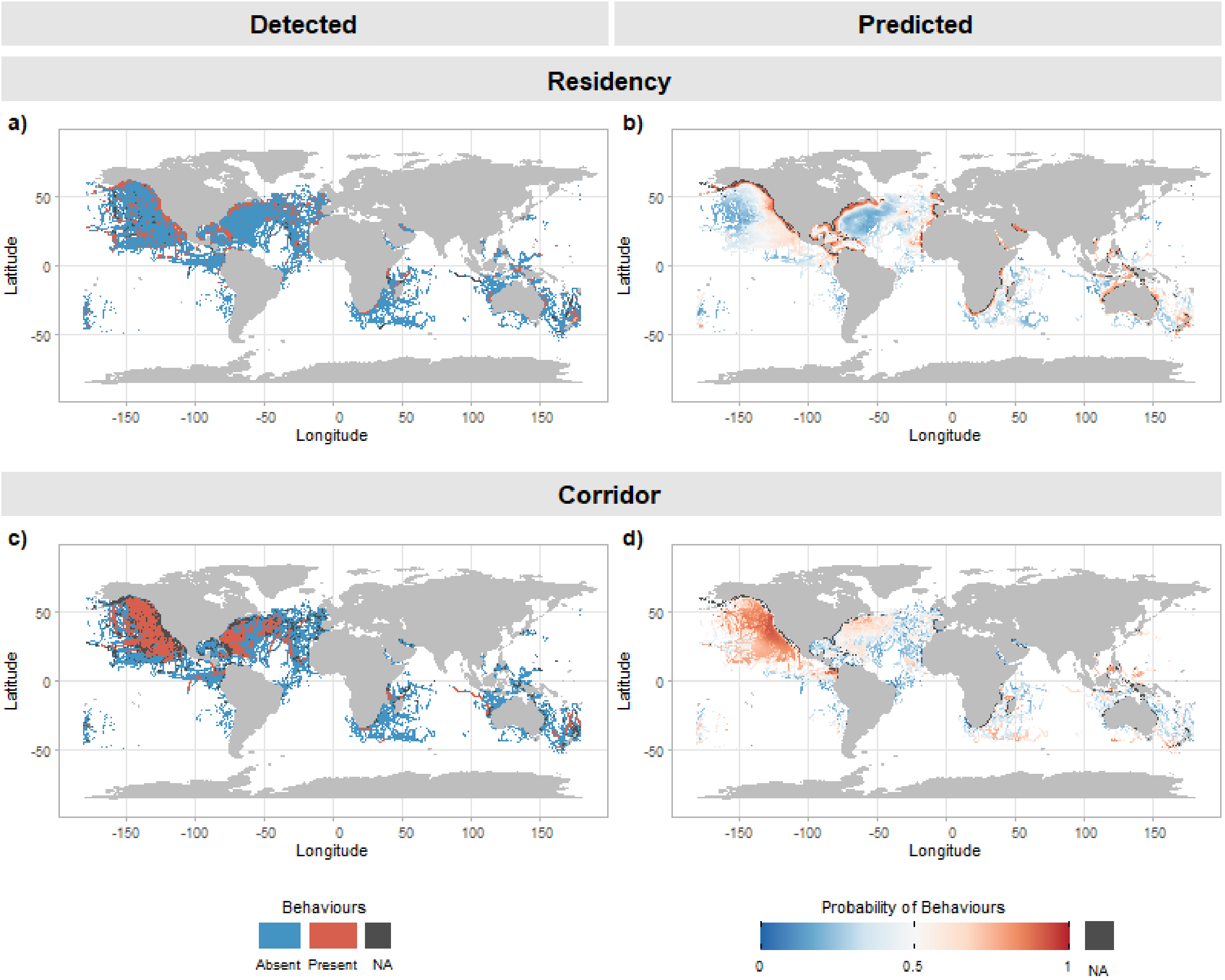
Birds


Detected
Predicted
Residency
a)
b)
Corridor
c)
d)
Latitude
Longitude
50
0
-50
-150
-100
-50
0
50
100
150
Behaviours
Absent
Present
NA
Probability of Behaviours
0
0.5
1
NA

Cetaceans

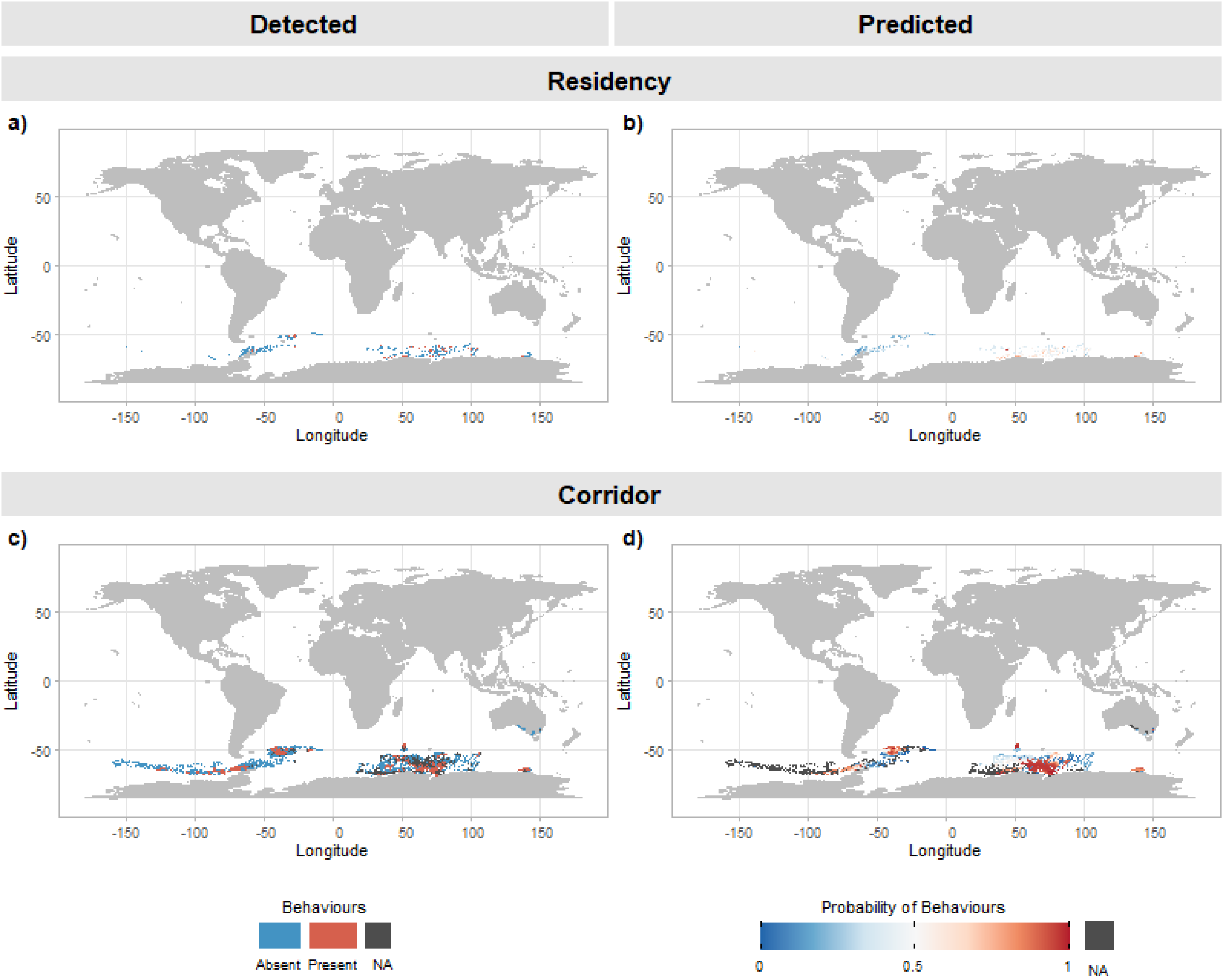

Detected
Predicted
Residency
a)
b)
Corridor
c)
d)
Latitude
Longitude
50
0
-50
-150
-100
-50
0
50
100
150
Behaviours
Absent
Present
NA
Probability of Behaviours
0
0.5
1
NA

3510 **Fishes**

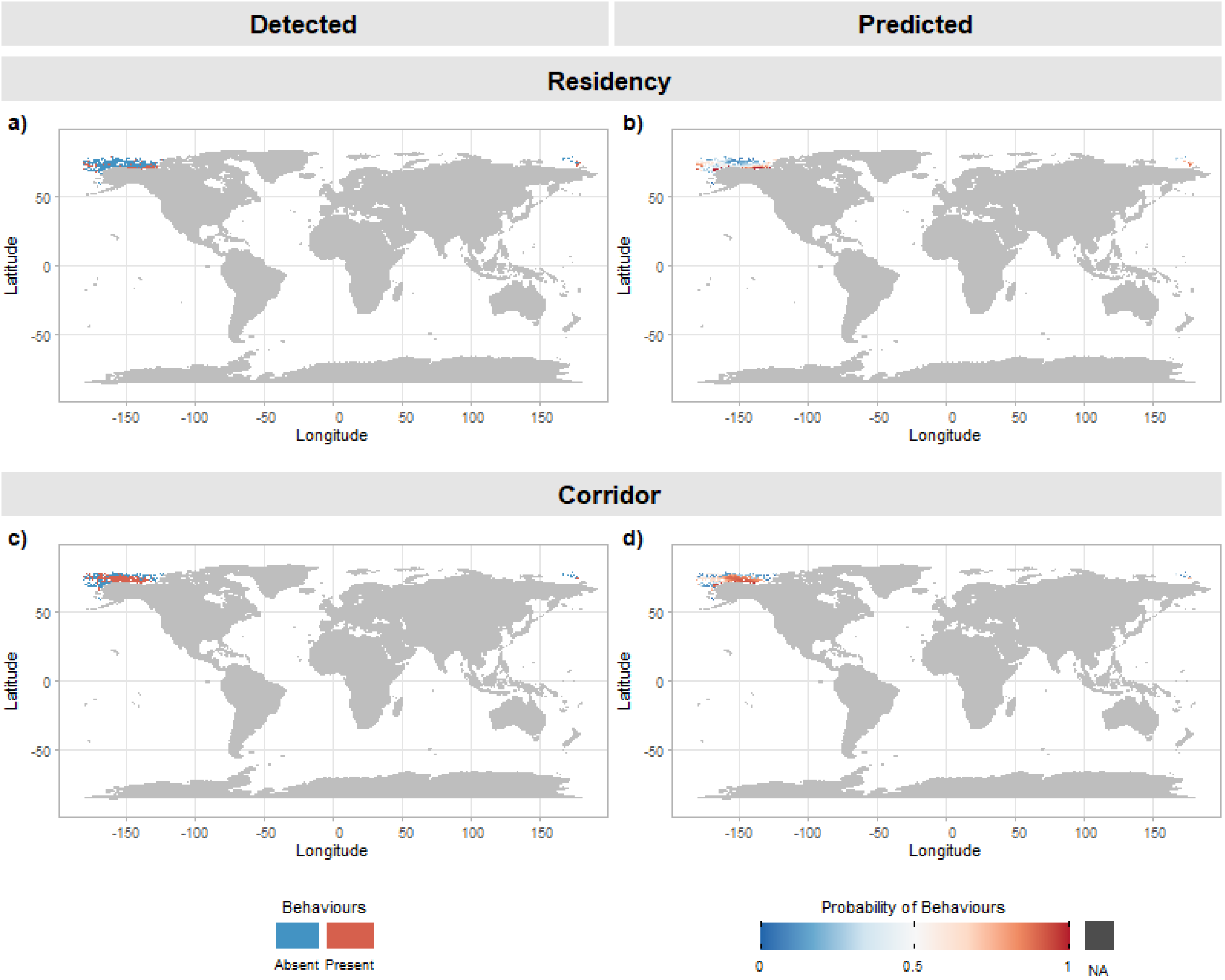

Detected
Predicted
Residency
a)
b)
Corridor
c)
d)
Latitude
Longitude
50
0
-50
-150
-100
-50
0
50
100
150
Behaviours
Absent
Present
NA
Probability of Behaviours
0
0.5
1
NA

3511

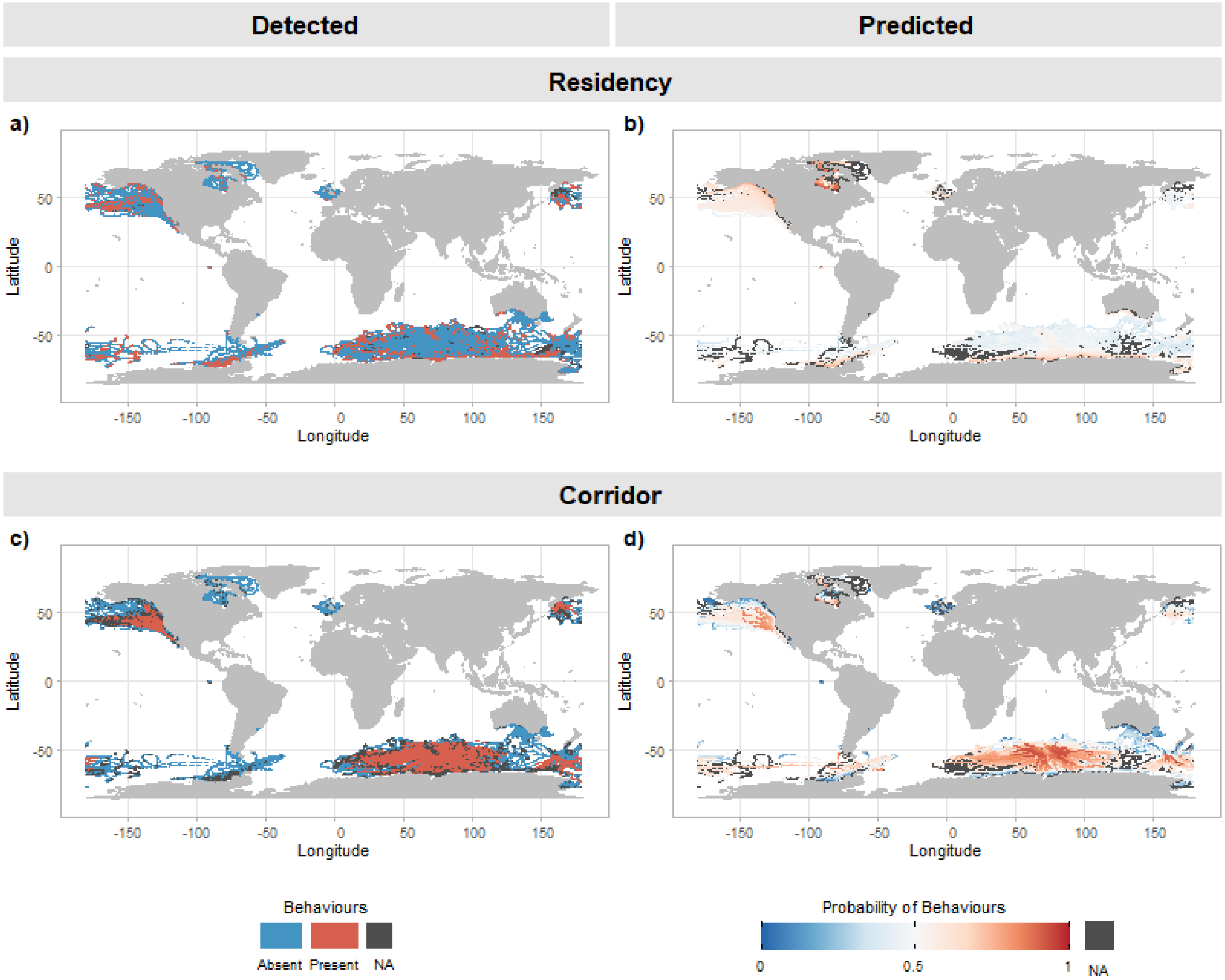
Penguins


Detected
Predicted
Residency
a)
b)
Corridor
c)
d)
Latitude
Longitude
50
0
-50
-150
-100
-50
0
50
100
150
Behaviours
Absent
Present
NA
Probability of Behaviours
0
0.5
1
NA

Polar bear


Detected
Predicted
Residency
a)
b)
Corridor
c)
d)
Latitude
Longitude
50
0
-50
-150
-100
-50
0
50
100
150
Behaviours
Absent
Present
Probability of Behaviours
0
0.5
1
NA

3516 **Seals**



Detected
Predicted
Residency
a)
b)
Corridor
c)
d)
Latitude
Longitude
50
0
-50
-150
-100
-50
0
50
100
150
Behaviours
Absent
Present
NA
Probability of Behaviours
0
0.5
1
NA

3517

Turtles

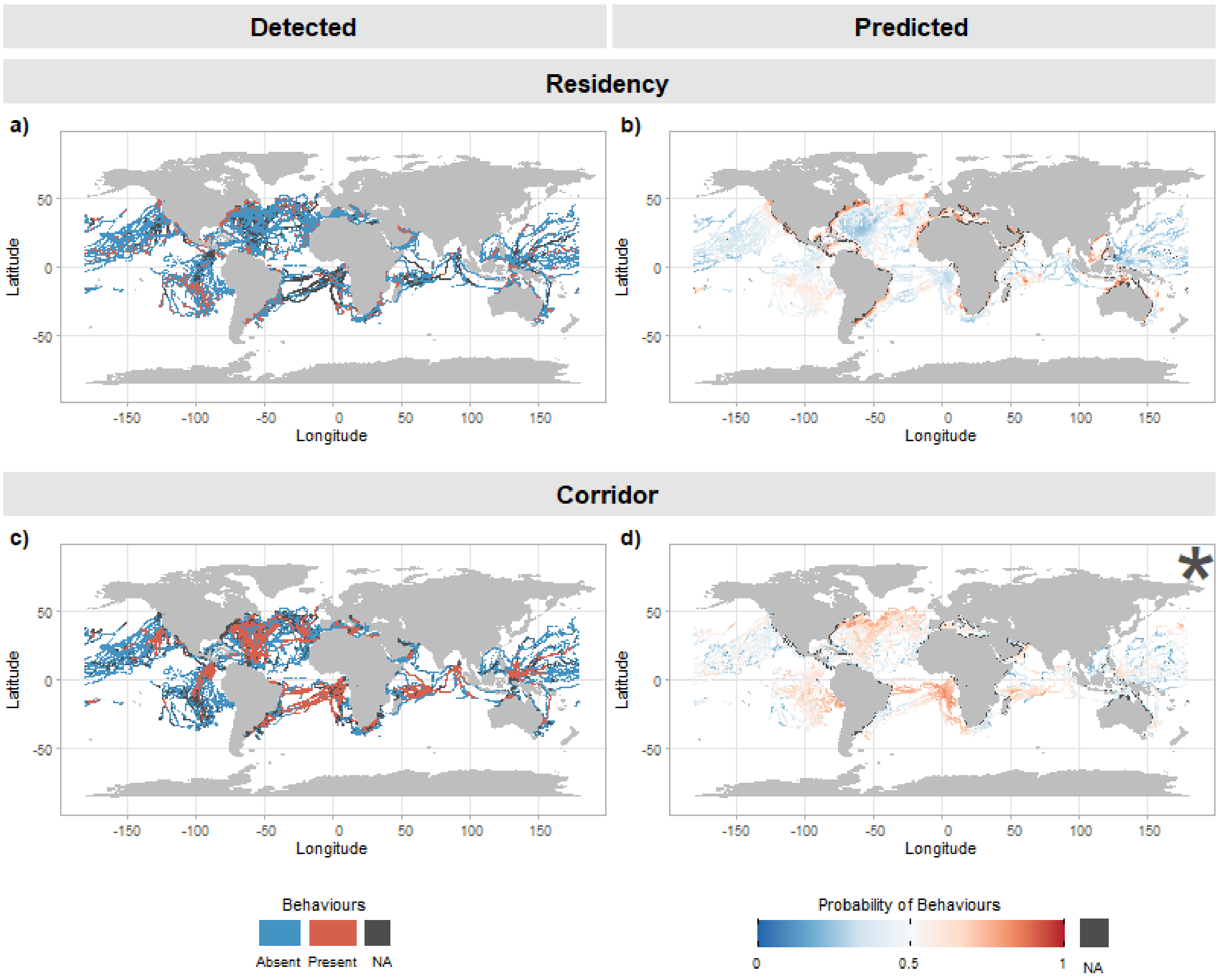

Detected
Predicted
Residency
a)
b)
Corridor
c)
d)
*
Latitude
Longitude
50
0
-50
-150
-100
-50
0
50
100
150
Behaviours
Absent
Present
NA
Probability of Behaviours
0
0.5
1
NA

Fig S17. Comparison of detected and predicted areas used for important marine megafauna behaviours

Shown are the maps we detected by our direct analyses of the tracking data (left) and those based on predicted probabilities of behaviours occurring (right) for residency (top) and migratory behaviours (bottom) for each taxon. Asterisks are included in the predicted maps for seal residences and turtle corridors because the models leading to these predictions results in a $K<0.2$ and predictions were therefore, not considered when merging important marine megafauna areas across all taxa based on modelled probabilities. Species considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.