

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%, and 61.2% 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

References (112-135)

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 1° 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.

1793

1794 **Table 1. Evidence of impacts from overlap of marine megafauna with anthropogenic**
1795 **threats.** Examples of the range of impacts derived from the overlap of marine megafauna
1796 with anthropogenic threats such as climate warming, plastic pollution, shipping, noise
1797 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 <i>Sphyrna lewini</i> 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	<i>k</i>	<i>wAIC</i>	<i>pcdev</i>	<i>Kappa</i>	Model	<i>k</i>	<i>wAIC</i>	<i>pcdev</i>	<i>Kappa</i>
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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1911

1912

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1914

1915

1916 **The PDF file includes:**

1917

1918 Materials and Methods:

- 1919 - Fieldwork and deployment of tracking devices
- 1920 - Animal ethics information
- 1921 - Tracking data collection and processing
- 1922 - Addressing tracking data biases
- 1923 - Detection of key movement behaviours
- 1924 - Statistical modelling
- 1925 - Optimisation algorithm

1926 Supplementary Acknowledgements

1927 Supplementary Author Contributions

1928 Figs. S1 to S17

1929 References (112-135)

1930

1931 **Materials and Methods**

1932 **Fieldwork and deployment of tracking devices**

1933

1934 **Birds**

1935 Birds were all caught at nest sites either whilst incubating or attending chicks, except for some
1936 northern gannets (*Morus bassanus*, immature birds at the main colony), Trindade petrels
1937 (*Pterodroma arminjoniana*, non-breeding adult birds resting at the main colony), and great
1938 shearwaters (*Ardenna gravis*, attracted to a vessel at-sea using bait). Birds were captured using
1939 noose poles, crook poles, drop traps, net launchers, nets (landing, mist, purse or handheld), or
1940 removed by hand from their burrows. Tags were typically attached to the auxiliary leg band or
1941 taped to the mantle, scapular, dorsal contour, or tail feathers. Chest or leg-loop harnesses were
1942 used for herring gulls (*Larus argentatus*), ivory gulls (*Pagophila eburnea*), some Ross's gulls
1943 (*Rhodostethia rosea*), and some northern fulmars (*Fulmarus glacialis*). For great shearwaters,
1944 tags were attached dorsally using four subcutaneous Prolene sutures. In all cases, total instrument
1945 mass was <5% of body mass to minimise effects on flight efficiency and all birds were handled
1946 for less than 20 minutes.

1947

1948 **Cetaceans**

1949 Smaller cetaceans (e.g., beluga - *Delphinapterus leucas*, bottlenose dolphins - *Tursiops*
1950 *truncatus*, narwhal - *Monodon monoceros*) were captured using seine or stationary nets. The
1951 animals were then brought to the surface, disentangled, and secured using hoop nets and loop
1952 ropes. In the case of bottlenose dolphins, animals were brought aboard the research vessel as part
1953 of capture-release health assessments. Tags were attached using nylon pins attached to the dorsal
1954 ridge or fin. Killer whales (*Orcinus orca*) were targeted from shore using crossbows and tags
1955 were attached to the dorsal fin using subdermal darts. Other cetaceans, such as blue -
1956 *Balaenoptera musculus*, bowhead - *Balaena mysticetus*, gray - *Eschrichtius robustus*, humpback
1957 - *Megaptera novaeangliae*, pilot - *Globicephala macrorhynchus* and *G. melas*, right - *Eubalaena*
1958 *glacialis* and *E. australis*, and sei whales - *Balaenoptera borealis*, were approached using a small
1959 research vessel. Tags were deployed using crossbows, air-powered applicator systems, or long
1960 fibreglass poles. Tags were attached to the dorsal fin (either anterior-to or at-the-base-of) using
1961 subdermal anchors or barbs and petals, which were sterilised and/or treated with antibiotic
1962 coatings prior to deployment.

1963

1964 **Fishes**

1965 Fish, mostly sharks, were typically captured with baited hooks, bagan lift nets, or in purse-seine
1966 nets, then brought alongside the vessel and restrained in a sling or with straps, secured to a
1967 raisable platform, or taken aboard for tagging. If brought aboard, fish were on deck an average of
1968 approximately 3 minutes; the exceptions to this were white sharks - *Carcharodon carcharias*
1969 (average duration of restraint: 12 mins) and tiger sharks - *Galeocerdo cuvier* (some were placed
1970 in tanks with running seawater and moved to deeper isobaths as part of a shark attack mitigation
1971 strategy). Manta rays - *Mobula birostris* and *M. alfredi*, and some copper - *Carcharhinus*
1972 *brachyurus*, Galapagos - *Carcharhinus galapagensis*, scalloped hammerhead - *Sphyrna lewini*,
1973 whale - *Rhincodon typus*, and white sharks were tagged whilst free-swimming in the water

1974 column using pneumatic spear guns or rubber-propelled hand spears. The majority of sunfish
 1975 (*Mola mola*) and some porbeagle sharks (*Lamna nasus*) were captured as bycatch in fisheries
 1976 targeting tuna. Tags were typically attached using a tether affixed to a dart, which was implanted
 1977 in the dorsal musculature or anchored to the first (or second in bluefin tuna - *Thunnus thynnus*;
 1978 removed from analyses) dorsal fin. For some sunfish, tags were attached to the base of the caudal
 1979 fin. For some of the blue - *Prionace glauca*, bull - *Carcharhinus leucas*, mako - *Isurus*
 1980 *oxyrinchus* and *I. paucus*, sandbar - *Carcharhinus plumbeus*, scalloped hammerhead, silky -
 1981 *Carcharhinus falciformis*, tiger, whale, and white sharks, tags were attached to the first dorsal fin
 1982 using metal bolts, neoprene and high-carbon steel washers, and steel nuts. For some white
 1983 sharks, tags were mounted on a custom-built spring clamp that was placed on the first dorsal fin.

1984

1985 Penguins

1986 Penguins were captured and released on land at nesting sites. Tags were attached to the dorsal
 1987 plumage using waterproof tape and/or epoxy glue, and in some cases secured under a bed of
 1988 feathers using a small cable tie.

1989

1990 Polar bears

1991 Adult female polar bears (*Ursus maritimus*) were located via helicopter and immobilised with a
 1992 rapid-injection dart. Tags were attached using satellite collars.

1993

1994 Seals

1995 Seals were approached whilst onshore or in shallow waters surrounding haul-out sites and
 1996 captured using hoop nets, tangle nets, beach seine nets, and/or remote syringe darts. Once
 1997 captured, seals were manually restrained, sedated, or anaesthetised. Tags were attached to the
 1998 head or along the dorsal midline using quick-setting epoxy glue.

1999

2000 Sirenians

2001 Manatees (*Trichechus manatus*) were located via an aerial observer and individuals were
 2002 captured in a net deployed from a specialised capture boat. Dugongs (*Dugong dugon*) were
 2003 captured using a 'rodeo' technique, where a personal watercraft is used to closely pursue an
 2004 individual dugong until fatigued. The dugong is then caught around the peduncle region by a
 2005 catcher leaping off the boat, and the animal is restrained at the water surface by several people.
 2006 For all sirenians, tags were tethered to the animal using a peduncle belt.

2007

2008 Turtles

2009 Turtles were primarily adult females captured at nesting beaches after a successful nesting event.
 2010 In some cases, adult and juvenile turtles were captured at sea (both in the vicinity of nesting
 2011 beaches or at foraging grounds) using tangle nets, dip nets, a "rodeo" technique, or by hand as
 2012 they rested at the surface. Some turtles were found stranded or were incidentally captured by
 2013 local fishers, then handed into conservation organisations for tagging and release. For hard-
 2014 shelled turtles, tags were attached to the carapace or head with quick-setting epoxy glue, a
 2015 fiberglass and polyester resin, or in the case of flatback turtles (*Natator depressus*), by using a

2016 specially-designed harness. Leatherback turtles (*Dermochelys coriacea*) were tagged via direct
2017 attachment surgical technique (tags were directly attached by drilling into the central-dorsal ridge
2018 and affixing with nylon or metal ties), tow technique (hole drilled in caudal peduncle and tag
2019 towed), or harness technique. Where post-hatchlings were used, they were collected from the
2020 nest, reared by head-starting programs, and then selected for tagging based on their size and
2021 swimming abilities. Post-hatchlings were tagged using an acrylic-silicone-neoprene attachment
2022 method, which for larger individuals sometimes also included drilling through the keratin part of
2023 the carapace crest and securing the tag with nylon ties.

2024 **Animal ethics information**

2025 Data providers obtained all licenses and ethical permissions required for data collection in their
2026 jurisdictions and ensured that each animal was handled and tagged by trained personnel. Details
2027 per taxon are presented below with name initials indicating the responsible co-author.

2028

2029 Birds (flying)

2030 Tagging of black-browed albatrosses (*Thalassarche melanophris*) at Diego Ramirez Islands was
2031 conducted under a permit provided by the Chilean Antarctic Institute (**J.A.A.**).

2032 Audouin's gull (*Ichthyaeetus audouinii*) tagging was conducted with permission from the Catalan
2033 and Balearic Islands Governments, and Scopoli's shearwater (*Calonectris diomedea*) tagging
2034 was conducted with permission from the Balearic and Valencian Governments, as well as the
2035 Spanish Government (**J.M.A.**).

2036 The sooty tern (*Onychoprion fuscatus*) tracking project in Seychelles was approved by the
2037 Seychelles Bureau of Standards and supported by the owners of Bird Island (**C.F.**).

2038 Tagging procedures on little penguins (*Eudyptula minor*), crested terns (*Thalasseus bergii*), and
2039 short-tailed shearwaters (*Ardenna tenuirostris*) off South Australia were conducted under
2040 approval by the South Australian Department of Primary Industry and Regions (PIRSA) Animal
2041 Ethics Committee (32-12) and the South Australian Department for Environment and Water
2042 (DEW) (Scientific Permit A24684) (**S.D.G.**).

2043 Broad-billed prion (*Pachyptila vittata*) fieldwork on Rangatira was conducted with the
2044 permission and cooperation of the New Zealand Department for Conservation and would not
2045 have been possible without the support of the Chatham Island Area Office. Northern gannets
2046 were ringed and loggers deployed with permits and approval from the British Trust for
2047 Ornithology (BTO) and Scottish Natural Heritage (**W.J.G.**).

2048 All tracking of northern gannets, razorbills (*Alca torda*), Atlantic puffins (*Fratercula arctica*),
2049 and Manx shearwaters (*Puffinus puffinus*) in the Republic of Ireland were approved by the
2050 University College Cork (UCC) Animal Ethics Committee (2013/032 and 2019/001) and
2051 conducted under permits by the BTO (C/6143) and Irish National Parks and Wildlife Service
2052 (26/2010, 011/2013, 018/2014, 016/2015, 025/2016, 082/2017, C051/2011, C116/2012,
2053 C039/2013, C075/2014, C087/2015, C100/2016, C87/2017) (**M.J.**).

2054 Barau's petrel (*Pterodroma baraui*) tracking work was authorized by Centre de Recherches sur
2055 la Biologie des Populations d'Oiseaux (CRBPO) permit number PP609, Ethic Committee of
2056 Réunion Island, Parc National de La Réunion, and direction de l'environnement, de
2057 l'aménagement et du logement de La Réunion (DEAL-Réunion). Red-tailed tropic bird
2058 (*Phaethon rubricauda*) tagging was authorized by Permit Le Corre PP616, Terres Australes et
2059 Antarctiques Françaises (TAAF), Mauritius National Park, and Madagascar National Parks.
2060 White-tailed tropicbird (*Phaethon lepturus*) tracking was conducted with research approval by
2061 CRBPO (PP616) and the Seychelles Bureau of Standard (SBS). Sooty tern tagging was
2062 authorized by PP616 M. Le Corre, Seychelles Bureau of Standard, and TAAF. Wedge-tailed
2063 shearwater (*Ardenna pacifica*) tagging was authorized by CRBPO permit PP616, Ethical
2064 committee of Réunion Island, Institutional Authorizations from DEAL-Réunion, Conservatoire
2065 du Littoral Réunion, Mauritius National Parks and Conservation Service, and Seychelles Bureau
2066 of Standard (**M.L.C.**).

2067 Common eider (*Somateria mollissima*) tagging was conducted under Environment Canada
 2068 (ECCC) Animal Care Permits, Canadian Wildlife Service (CWS) Scientific Permit NUN-SCI-
 2069 04-02, and Nunavut Wildlife Research Permit WL1028. Herring gull tagging was conducted
 2070 under Nunavut Wildlife Research Permit WL2008–1028; CWS Scientific Permit NUN-SCI-08-
 2071 04, SC2761; and ECCC Animal Care permits EC-PN-08-026. Ivory gull tagging was conducted
 2072 under CWS Banding Permit number 10694; CWS Scientific Permit NUN-SCI-09-02; and
 2073 Nunavut Wildlife Research License WL2010-032. Northern fulmar collections were in
 2074 accordance with Canadian Council on Animal Care guidelines, and were conducted under the
 2075 following permits: research (NUN-SCI-03-02, WL000190, WL000714), animal care
 2076 (2003PNR017, 2004PNR021, 2005PNR021), and land use (59A/7-2-2). Parasitic jaeger
 2077 (*Stercorarius parasiticus*) tagging was conducted under CWS Banding Permit 10694; Animal
 2078 Care EC-PNR-11-020, Scientific Permit NUN-SCI-09-01, and Territorial Permit WL 2010-042.
 2079 Ross’s gull tagging was conducted under CWS Banding Permit 10694; Animal Care Permit EC-
 2080 PNR-11-020; Scientific Permit NUN-SCI-09-01; and Territorial Permit WL 2010-042. Sabine’s
 2081 gull (*Xema sabini*) tagging was conducted under permits CWS Animal Care EC-PN-11-020,
 2082 CWS Scientific Permit NUN-SCI-09-01, Government of Nunavut Wildlife Research Licence
 2083 WL 2010-042, Nunavut Water Board licence 3BC-TER0811, Indian and Northern Affairs Land
 2084 Use Reserve 068H16001, and CWS Banding Permit 10694. Thick-billed murre (*Uria lomvia*)
 2085 tagging was conducted under Canadian scientific and access permits (NUN-SCI-08-55, NUN-
 2086 MBS-12-03, NUN-SCI-12-04, WRP2013040), banding permit (10694, 10322), and animal care
 2087 (0800AG01) (**M.L. Mallory**).
 2088 Tagging work followed the ethical standards set out by the Mauritian Wildlife Foundation and its
 2089 partner and consulting organisations, the North of England Zoological Society, the Durrell
 2090 Wildlife Conservation Trust, and the International Zoo Vet Group (**M.A.C.N.**).
 2091 Permission to capture and tag Ascension frigatebirds (*Fregata aquila*) was granted by the
 2092 Conservation Department of the Ascension Island Government. The attachment of devices met
 2093 the ethical guidelines of the Special Methods Panel of the BTO. King eiders (*Somateria*
 2094 *spectabilis*) were handled with approval by the University of Alaska Fairbanks Institutional
 2095 Animal Care and Use Committee (IACUC) (protocol #05-29) and CWS Animal Care Committee
 2096 (permit #PNR007). Masked booby (*Sula dactylatra*) tagging was carried out under permission
 2097 and with collaboration of the St Helena Environmental Management Directorate. The capture
 2098 and handling of birds and attachment of unconventional marks was carried out under licence
 2099 from the BTO. Permission to capture and tag birds was granted by the Environmental
 2100 Management Directorate on St Helena. The attachment of GPS devices met the ethical guidelines
 2101 of the Special Methods Panel of the BTO. Tagging of Murphy’s petrels (*Pterodroma ultima*)
 2102 followed all applicable international, national, and/or institutional guidelines for the care and use
 2103 of animals. Permission to access Henderson Island in order to conduct scientific research in 2015
 2104 was granted by the Government of the Pitcairn Islands (**S. Oppel**).
 2105 Tagging work was conducted under approval by the Portuguese Government Instituto de
 2106 Conservação da Natureza e Florestas (ICNF) under licenses 188/2010/ CAPT, 152/2011/CAPT,
 2107 101/2012/CAPT, 99/2013/CAPT, 203/2014/CAPT, 169/2015/CAPT, and 89/2011/CAPT
 2108 (**V.H.P.**).
 2109 Tagging work was authorized by the Government of South Georgia and the South Sandwich
 2110 Islands (**R.A.P.**).

2111 Tagging procedures were conducted under approval by the Portuguese Government ICNF
 2112 (permit 89/2011/CAPT) and in compliance with Portuguese laws No. 140/99, No. 49/2005, No.
 2113 316/89, and No. 180/2008 (**J.A.R.**).

2114 Buller's albatross (*Thalassarche bulleri*) tagging was approved by the Southland Conservancy,
 2115 Department of Conservation, New Zealand (**P.M.S.**).

2116 Sooty shearwater (*Ardenna grisea*) ethics was approved by the IACUC at the University of
 2117 California Santa Cruz and approval for the research was provided by the Whenua Hou
 2118 Management Committee, Rakiura Titi Islands Administering Body, and Southland Department
 2119 of Conservation in New Zealand. Black-footed (*Phoebastria nigripes*) and Laysan albatross
 2120 (*Phoebastria immutabilis*) tagging in the Hawaiian Islands was approved by the University of
 2121 California Santa Cruz and San Jose State University IACUCs under Master Bird Banding permit
 2122 23411. Laysan albatross tagging on Guadalupe Island, Mexico was approved by University of
 2123 California Santa Cruz IACUC under Master Banding Permit 20768. Western gull (*Larus*
 2124 *occidentalis*) tagging was conducted under permission granted by Año Nuevo State Park,
 2125 California State Parks, California Department of Fish and Wildlife, and the US Fish and Wildlife
 2126 Farallon Islands National Wildlife Refuge (SUP# 81641). All research protocols were approved
 2127 by the San Jose State University IACUC (protocol 979) (**S.A.S.**).

2128 Common murre (*Uria aalge*) field work was conducted under Kukulget Inc. land crossing
 2129 permits, University of Alaska Fairbanks IACUC protocol #471022, US Fish and Wildlife Service
 2130 (USFWS) scientific collection permit #MB70337A, A. Kitaysky's Master Banding permit
 2131 #23350, and Alaska Department of Fish and Game's permits #19-140, 18-131, 17-104, 16-089.
 2132 Streaked shearwater (*Calonectris leucomelas*) tagging procedures were approved by the Animal
 2133 Experimental Committee of the University of Tokyo and conducted in accordance with the
 2134 Guidelines for the Care of Experimental Animals, with fieldwork conducted under permits from
 2135 the Ministry of the Environment and the Agency for Cultural Affairs. Thick-billed murre tagging
 2136 was conducted under Kukulget Inc. land crossing permits, UAF IACUC protocol #471022,
 2137 USFWS scientific collection permit #MB70337A, A. Kitaysky's Master Banding permit #23350,
 2138 and Alaska Department of Fish and Game's permits #19-140, 18-131, 17-104, 16-089. (**A.**
 2139 **Takahashi**).

2140 Capture and tagging of Northern fulmar in Scotland was carried out under licences from the
 2141 BTO (Licence No: AO/4939) and UK Home Office (Licence No: PIL 60/698) following review
 2142 by the University of Aberdeen ethics committee (**P.M.T.**).

2143 Northern gannet capture and tagging on St Kilda was carried out with permission from the
 2144 National Trust for Scotland and Scottish Natural Heritage and under licence from BTO (Licence
 2145 No: A2332 with a specific unconventional methods endorsement) (**S. Wanless**).

2146 Tagging procedures were conducted with approval from the US Department of the Interior
 2147 #21963, Massachusetts Division of Fisheries and Wildlife #058.19SCB, Stellwagen Bank
 2148 National Marine Sanctuary Permit # SBNMS-2019-001, and the Long Island University IACUC
 2149 (**D.N.W.**).

2150 Northern gannet capture and tagging was carried out under licences from the BTO and Natural
 2151 England, with approval of the Royal Society of the Protection of Birds (**L.J.W.**).

2152 Tagging work was conducted with permits from the Ministry of the Environment: No.060609001
 2153 for Sangan Island and No.18-340 for Mikura Island (**T.Y.**).

2154
2155 Cetaceans

2156 Tagging was undertaken under US National Marine Fisheries Service (NMFS) Scientific
2157 Research Permits No. 17096, 731-1774, and 15330. Tagging was undertaken under protocols
2158 approved by the Cascadia Research Collective IACUC (**R.W.B.**).

2159 Tagging was conducted under University of Auckland Animal Ethics AEC001587, New Zealand
2160 Department of Conservation Permit #44388-MAR, and approval from local Maori tribes (iwi)
2161 Ngāti Kuri and Te Aupōuri (**R.C.**).

2162 Tagging was undertaken with the permission of the Environment Department of the province
2163 Sud of New Caledonia and of the Government of New Caledonia under permits 383-
2164 2010/ARR/DENV, 33313-2010/ARR/DENV, 3616-2011/ARR/DENV, 3157-2012/ARR/DENV,
2165 1045-2014/ARR/DENV, 151-2015/ARR/DENV, 1105-2016/ARR/DENV, 899-
2166 2017/ARR/DENV, 2220-2018/ARR/DENV, 2016-1391/GNC, 2017-1107/GNC and 2018-
2167 923/GNC (**C. Garrigue**).

2168 Tagging procedures were approved by Fisheries and Oceans Canada (DFO) Freshwater Institute
2169 Animal Care Committee (AUP # FWI-ACC-2002, 2003, 2004, 2005, 2006 and 2007) and under
2170 DFO License to Fish for Scientific Purposes #S-02/03 to 05/06-1019-NU and #S-12/13-1024-
2171 NU, S-13/14-1009-NU and S-16/17 1005-NU (**S.H.F.**).

2172 Tagging was conducted under permits 11-101/VP/MPEEIA:SG and 12-100/VP/MPEEIA:SG
2173 issued by the Secretary-General of the Union of the Comoros, permits 105/DEAL//SEPR/2012
2174 and 148/DEAL/SEPR/2012 issued by Direction de l'Environnement, de l'Aménagement et du
2175 Logement de Mayotte, and permit FR1397600001-E issued by Direction de l'environnement, de
2176 l'aménagement et du logement (DEAL) Mayotte (**S.F.**).

2177 Tagging was conducted under NMFS permits (numbers 14907, 14809, and 14856) and ACA
2178 Permits (2009-013 and 2015-011). All animal work was approved and conducted under Duke
2179 University IACUC A049-122-02 and the Oregon State University Animal Care and Use Protocol
2180 (ACUP) 4513 (**A.S.F.**).

2181 Beluga tagging was carried out with Animal Care Approval and Research Permits issued by the
2182 Canadian Government (**M.O.H.**).

2183 Deployment of satellite tags on southern right whales at the Head of Bight, South Australia were
2184 conducted under approval by the South Australian Department of Primary Industries and
2185 Regions (PIRSA) Animal Ethics Committee (32-12), and under the following permits: PIRSA
2186 Fisheries Exemption (ME9902712), Department of Environment Water and Natural Resources
2187 (DEWNR) Permit and Licence to Undertake Scientific Research (A24684-12), Environment
2188 Protection and Biodiversity Conservation Act Cetacean Permit (20014-0004), Access to
2189 Biological Resources in a Commonwealth Area for Non-commercial Purposes (AU-COM2014-
2190 248), Approval for Activity in Commonwealth Marine Reserve (CMR-14-000196) and DEW
2191 Marine Parks Permit (MO00024-2) (**A.I.M., S.D.G., and R.H.**).

2192 Beluga tagging was carried out under Animal Use Protocol permit number FWI-ACC-2015-018
2193 and DFO license S-12/13-1022-NU. Narwhal tagging was carried out under Animal Use
2194 Protocol number FWI-ACC-2016-030 from the DFO Animal Care Committee (under the
2195 Canadian Council on Animal Care) and a DFO License to Fish for Scientific Purpose License S-
2196 16/17-1037-NU (**M. Marcoux**).

2197 Sei whale fieldwork and tagging was approved by the Regional Directorate of the Environment/
 2198 Regional Government of the Azores under research permit 7/CN/2005, issued to the Department
 2199 of Oceanography and Fisheries of the University of the Azores (**E.O.**).

2200 Whale tagging was authorized by the NMFS under permit numbers 841 (for blue, bowhead,
 2201 gray, and humpback whales), 369-1440 (for blue, fin - *Balaenoptera physalus*, gray, humpback
 2202 and northern right whales), and 369-1757 (for blue, gray, and southern right whales). Tagging in
 2203 Mexican waters was conducted under permits issued by the Secretaría de Medio Ambiente y
 2204 Recursos Naturales, Mexico (permit number DOO 02.8319 and SGPA/DGVS 0576). Southern
 2205 right whale tagging was also authorised under a permit issued by the South African Department
 2206 of Environmental Affairs and Tourism in terms of Regulation 58 of the Marine Living Resources
 2207 Act (no. 18 of 1998). Sperm whale (*Physeter macrocephalus*) tagging was conducted under
 2208 permits # 08159 and SGPA/DGVS 01102 by the Secretaría de Medio Ambiente y Recursos
 2209 Naturales of Mexico, and the NMFS under permit numbers 369-1757. For all eight species,
 2210 research was approved by the Oregon State University IACUC (**D.M. Palacios** and **B.M.**).

2211 Tagging was approved by the University of Pretoria's Ethics Committee (EC023-10; EC077-15)
 2212 and permitted by the Prince Edward Islands Management Committee (PEIMC 17/12, 1/2013 and
 2213 1/2014) (**R.R.R.** and **P.J.N.B.**).

2214 Blue, fin and sei whale fieldwork and tagging were approved by the Regional Directorate of the
 2215 Environment/Regional Government of the Azores, under research permits: 20/2009/DRA (blue,
 2216 fin and sei whales), 16/2010/DRA (blue and fin whales), 51/2011/DRA (blue and fin whales),
 2217 30/2015/DRA (blue whale), 37/2016/DRA (blue whale), 31/2012/DRA (fin whale),
 2218 20/2013/DRA (fin whale), 34/2014/DRA (fin whale), 76/2007/DRA (sei whale) (**M.A. Silva**).

2219 Short-finned pilot whales were tagged under authorization from NMFS. Bottlenose dolphin
 2220 tagging was conducted under NMFS Scientific Research Permit No. 15543 and approved by
 2221 Mote Marine Laboratory's IACUC (**R.S.W.**).

2222

2223 Fishes

2224 Tagging procedures were approved by the Committee on Ethics for the Use of Animals of the
 2225 Universidade Federal Rural de Pernambuco (CEUA #23082.009679/2009 and
 2226 #23082.025519/2014). Work permits granted by the Instituto Chico Mendes para a Conservação
 2227 da Biodiversidade (ICMBio #43305-6 and #15083-8) (**A.S.A.**).

2228 Tagging in the Philippines was performed in collaboration with the respective Regional Offices
 2229 of the Department of Environment and Natural Resources, the Department of Agriculture-Bureau
 2230 of Fisheries and Aquatic Resources and the Palawan Council for Sustainable Development
 2231 (Wildlife Gratuitous Permit 2017-13). All research in Tubbataha Reefs Natural Park was done in
 2232 collaboration with the Tubbataha Management Office (**G.A.**).

2233 Tagging procedures in the Bay of Biscay followed established guidelines that met ethical
 2234 reviews, with scientists limiting handling time and stress as much as possible during attachment
 2235 (**I.A.**).

2236 Tagging procedures were approved and conducted under Australian Fisheries Management
 2237 Authority Scientific Permit #901193 and Great Barrier Reef Marine Park Authority G11/33231.1
 2238 (**A. Barnett**).

2239 All procedures for whale shark tagging in the Red Sea were approved by the Institutional
 2240 Biosafety and Bioethics Committee (IBEC) of the King Abdullah University of Science and
 2241 Technology. KAUST IBEC serves as the registered (HAP-02-J-042) local committee for all
 2242 National Committee of Bioethics (NCBE)-regulated activities including animal-related research.
 2243 (**M.L. Berumen** and **J.E.M.C.**).

2244 Tagging was conducted with the permission of Chico Mendes Institute for Biodiversity
 2245 Conservation (number 50119-1), of the Brazilian Ministry of the Environment. Shark capture
 2246 and tagging methods were approved by the Commission of Ethics on the Usage of Animals of
 2247 Federal Rural University of Pernambuco (licence number 054/2013, protocol number
 2248 23082.022567/2012) (**N.P.A.B.**).

2249 Tagging procedures were approved by Stanford University IACUC, the National Oceanic and
 2250 Atmospheric Administration (NOAA), and the California Department of Fish and Wildlife
 2251 (**B.A.B.**).

2252 Tagging of blue, porbeagle and shortfin mako sharks in the northwest Atlantic was conducted in
 2253 accordance with the animal care guidelines of DFO and the Canadian Council on Animal Care
 2254 (**S.E.C.**).

2255 Tagging was conducted with approval by the Province Sud of New Caledonia under permit
 2256 6024-4916/DENV/SMer and authorization issued by Affaires Maritimes for Chesterfield field
 2257 trips (C110-3510-263/MM) (**E.E.G.C.**).

2258 Tagging was conducted with approval by South African Institute for Aquatic Biodiversity
 2259 Animal Ethics (Ref#25/4/1/7/5_2019-04) (**R.D.**).

2260 Whale sharks in Madagascar were tagged by Centre National de Recherches Océano- graphiques
 2261 (CNRO) in July 2016 under permit number No 16-12-CNRO-N (**S. Diamant**).

2262 Tagging was conducted under permit from the St Helena Government (SHG 20-SRE-01)
 2263 (**A.D.M.D.**).

2264 Blue sharks (tagged in Irish waters) were tagged under license AE191130/I007 AE19130/P002
 2265 and issued by the Irish Health Products Regulatory Authority (HPRA) and complied with the EU
 2266 Directive 2010/63/EU for scientific research on animals (**T.K.D.**).

2267 Manta ray tagging procedures were approved by the Raja Ampat Marine Protected Area
 2268 Management Authority and were in accordance with the protocols established by Conservation
 2269 International Indonesia's and University of Auckland's Animal Ethics Committees (University of
 2270 Auckland AEC approval #002228). Whale shark tagging was conducted under permits issued by
 2271 the Cendrawasih Bay National Park Authority (SIMAKSI SI.18/BBTNTC-2/TEK/2015,
 2272 SIMAKSI SI.46/BBTNTC-2/TEK/2015, and SIMAKSI SI.05/BBTNTC-2/TEK/2016). Tagging
 2273 procedures were approved by the Cenderawasih Bay National Park Authority and are in
 2274 accordance with the protocols established by Conservation International Indonesia's animal
 2275 ethics review committee (**A. Sianipar, E.S. and M.V.E.**).

2276 Great white sharks were tagged in New Zealand waters according to the protocols specified in
 2277 Department of Conservation Animal Ethics Committee approvals AEC278, AEC216 and
 2278 AEC260. Mako and porbeagle sharks were tagged according to the code of practice for ethical
 2279 conduct of tagging carried out by the National Institute of Water and Atmospheric Research
 2280 (NIWA Animal Ethics Committee 2009) (**M.P.F., B.F. and C.A.D.**).

2281 Tagging was approved by Griffith University ethics (ENV/16/08/AEC) and Ocean and Coast
 2282 Research animal ethics approval (CA 2010/11/482), with fieldwork conducted under permits
 2283 6024-4916/DENV/SMer (New Caledonia), G10 33187.2 (Great Barrier Reef Marine Park
 2284 Authority), 143005 (Queensland Fisheries), QS2010 GS065 (Great Sandy Marine Park) and
 2285 LHIMP/R/2012/009 (Lord Howe Island) (**J.G.** and **J.M.W.**).

2286 Tagging was conducted under permit MAF/LIA/22 to conduct scientific marine animal research
 2287 supplied by the Department of Marine Resources, Bahamas to Bimini Biological Field Station
 2288 Foundation (**T.L.G.**).

2289 Tagging was conducted under permits from the NMFS Highly Migratory Species Division and
 2290 under the University of Miami IACUC. Additionally, blacktip shark tagging was conducted
 2291 under permits from Florida Fish and Wildlife, Everglades National Parks; bull shark tagging was
 2292 conducted under permits from the Florida Keys National Marine Sanctuary, Florida Fish and
 2293 Wildlife, and the Biscayne and Everglades National Parks; and great hammerhead shark and
 2294 tiger shark tagging was conducted under permits from the Florida Keys National Marine
 2295 Sanctuary, Florida Fish and Wildlife, Bahamas Department of Marine Resources, and the
 2296 Biscayne and Everglades National Parks (**N.H.**).

2297 Tagging procedures were conducted under Galapagos National Park Permits PC-13-01, PC-37-
 2298 11. PC-01-14, PC-51-15, PC-69-16, PC-34-17, and MAE-PNG/CDS-2012-0020. Field methods
 2299 were also approved under University of California, Davis IACUC #16022 (**A.R.H.**).

2300 Tagging procedures were approved by the University of Windsor Animal Care Committee with a
 2301 permit through Coastal Oceans Research and Development – Indian Ocean (CORDIO) (**N.E.**
 2302 **Hussey**).

2303 Tagging was conducted under Flinders University Animal Welfare Ethics Permits E349 and
 2304 E360, and was authorised by the Victorian Department of Primary Industries under General
 2305 Research Permit RP1048 and PIRSA Ministerial Exemptions Section 115: 9902064 and 9902094
 2306 (**C.H.**).

2307 Tagging procedures for scalloped hammerhead and Galapagos sharks were approved by the
 2308 Zoological Society of London’s ethics committee under the project code BPE/0708. Research
 2309 tagging activities around Mikomoto Island, Japan, were communicated to and approved by
 2310 fisheries officers within the Japanese government (a formal research permit was not required)
 2311 (**D.M.P.J.**).

2312 For South African white sharks, all research methods were approved and conducted under the
 2313 South African Department of Environmental Affairs: Oceans and Coasts permitting authority
 2314 (Permit #RES2012/OCEARCH/umbrella-project) (**A.A.K.**).

2315 Tagging was conducted with the full approval of the Instituto Chico Mendes de Conservação da
 2316 Biodiversidade of the Brazilian Ministry of the Environment (permit no. 14124) (**B.C.L.M.**).

2317 Tagging procedures were reviewed and approved by the Seychelles Bureau of Standards, the
 2318 Seychelles Ministry of Environment, Energy and Climate Change, and The University of
 2319 Western Australia (RA/3/100/1480) (**L.R.P.**).

2320 Tagging was conducted under Direccção-Geral de Alimentação e Veterinária ethics approvals
 2321 from Decreto-lei N° 129/92 (6 de julho); Portaria N° 1005/92 (23 de outubro) (**N.Q.**).

2322 Tagging was carried out under the general auspices of Consejo Nacional de Ciencia y Tecnología
 2323 (CONACYT), Dirección General de Vida Silvestre (DGVs), Secretaría del Medio Ambiente y
 2324 Recursos Naturales (SEMARNAT), and Comisión Natural de Áreas Naturales Protegidas
 2325 (CONANP). These are the relevant Mexican authorities governing all research actions on
 2326 wildlife and protected animals and areas in Mexico. CONACYT registration: RENIECYT No.
 2327 030 (currently 1602199) and 13920. DGVs authorization numbers are: SGPA/DGVs/02677/08,
 2328 SGPA/DGVs/02888/09, SGPA/DGVs/03848/10, SGPA/DGVs/03155/11,
 2329 SGPA/DGVs/03362/12, SGPA/DGVs/05555/16 and SGPA/DGVs/05970/17 (**D.R.**).
 2330 All tagging was conducted under animal ethics approvals from Murdoch University's Animal
 2331 Ethics Committee (permit numbers: W2058/7; W2402/11; R2926/17) and an animal ethics
 2332 permit from The University of Queensland: SBS/085/18/WA/INTERNATIONAL. Permits to
 2333 conduct research on wildlife in Western Australia were issued by the Western Australian
 2334 Department of Environment and Conservation (DEC) (permit numbers: SF007471; SF007949;
 2335 SF008572) and Department of Parks and Wildlife (DPaW) (permit numbers: SF009184;
 2336 SF009897; SF010414; SF010781; 08-000533-2; 08-002082-2) (**S.D.R.**).
 2337 Tagging was conducted with permission by the Qatar Ministry of Environment (**D.P.R.**).
 2338 Tagging in Mozambique was compliant with ethics guidelines from the University of
 2339 Queensland's Animal Ethics Committee and was conducted under their approval certificate
 2340 GPEM/186/10/MMF/WCS/SF. Madagascan fieldwork was conducted with the approval of and
 2341 in partnership with the CNRO in Madagascar. Filipino fieldwork was performed in collaboration
 2342 with the respective Regional Offices of the Department of Environment and Natural Resources,
 2343 the Department of Agriculture-Bureau of Fisheries and Aquatic Resources and the Palawan
 2344 Council for Sustainable Development (Wildlife Gratuitous Permit 2017-13) (**C.A.R.**).
 2345 Tagging methods for broadnose sevengill sharks (*Notorynchus cepedianus*) were approved by
 2346 the University of Tasmania Animal Ethics Committee (Approval No A0011590) (**J.M.S.**).
 2347 Tagging procedures were approved by the Marine Biological Association of the UK (MBA)
 2348 Animal Welfare Ethical Review Body (AWERB) and licensed by the UK Home Office through
 2349 Personal and Project Licences under the Animals (Scientific Procedures) Act 1986 (**D.W.S.**).
 2350 Smooth hammerhead shark (*Sphyrna zygaena*) tagging was approved by the Massachusetts
 2351 Division of Marine Fisheries. Porbeagle shark tagging was approved by the University of
 2352 Massachusetts, Dartmouth IACUC (Protocol #05-07). White shark tagging was conducted under
 2353 Exempted Fishing Permits (SHK-EFP-11-04, SHK-EFP-12-08, SHK-EFP-13-01, SHK-EFP-14-
 2354 03) issued to the Massachusetts Division of Marine Fisheries by the NMFS Highly Migratory
 2355 Species Management Division (**G. Skomal**).
 2356 Tagging procedures were approved by the University of California, San Diego IACUC (protocol
 2357 S12116) (**J.D. Stewart**).
 2358 Whale shark tagging procedures were approved by the University of Western Australia
 2359 (RA/3/100/1110; RA/3/100/1437), University of Adelaide (S-2009-109), or Charles Darwin
 2360 University Animal Ethics Committees (**M.T.** and **M.G.M.**).
 2361 Tagging data according to protocols approved by the South African Department of
 2362 Environmental Affairs: Oceans and Coasts (now the Department of Forestry, Fisheries and the
 2363 Environment) and adhered to the legal requirements of South Africa. All research methods were

2364 approved and conducted under the South African Department of Environmental Affairs: Oceans
 2365 and Coasts permitting authority (Permit #RES2012/OCEARCH/KOCK) (**A. Towner**).

2366 Tagging procedures were approved by the Nova Southeastern University IACUC (#064-398-15-
 2367 0203) (**B.M.W.**).

2368 Tagging was conducted under permits given by the Subsecretaría de Pesca y Acuicultura de
 2369 Chile. Resolución exenta (Undersecretary of Fishing and Aquaculture) (**P.M.Z.**).

2370
 2371 Penguins
 2372

2373 Tagging procedures for little penguins from Montague Island were approved by the Macquarie
 2374 University Animal Ethics Committee (Animal Research Authority 2014/057), and work was
 2375 conducted under Office of Environment and Heritage NSW Scientific Licence SL100746 (**G.C.**
 2376 and **R.H.**).

2377 Tagging procedures were conducted under approval from Monash University Animal Ethics
 2378 Committee (approval numbers BSCI/2006/12, BSCI/2010/22, BSCI/2011/33), Phillip Island
 2379 Animal Experimentation Ethics Committee (approval numbers 3.2007, 2.2010, 3.2011, 2.2014,
 2380 7.2017), and research permit issued by the Department of Sustainability and Environment of
 2381 Victoria, Australia (permit numbers 10003848, 10004360, 10005601, 10005605, 10006148,
 2382 10007320, 10008506) (**A. Chiaradia**).

2383 Tagging procedures on little penguins off South Australia, were conducted under approval by the
 2384 South Australian Department of Primary Industries and Regions (PIRSA) Animal Ethics
 2385 Committee (32-12), and Department for Environment and Water (DEW) (Scientific Permit
 2386 A24684) (**S.D.G.**).

2387 Tagging procedures were approved by the Australian Animal Ethics Committee (Department for
 2388 the Environment and Heritage) and the University of Tasmania Animal Ethics Committee Work
 2389 was carried out under Macquarie Island special permits M1/3/95 and MI/13/96 (**M.A.H.**).

2390 Tagging procedures were permitted under US Antarctic Conservation Act Permits (Permit
 2391 #2017-012). Field protocols were approved by the University of California San Diego IACUC
 2392 (S05480) (data used courtesy of Jefferson T. Hinke).

2393 Adelle penguin (*Pygoscelis adeliae*) tagging procedures were approved by the TAAF ethic
 2394 committee and the French regional ethic committee. King penguin (*Aptenodytes patagonicus*)
 2395 handling procedures were approved by the Ethical Committee of the French Polar Institute
 2396 (Institut Polaire Paul-Emile Victor). Authorizations to enter the king penguin breeding site
 2397 (permits nos. 2005–191, 2006–67) and handle birds (permits nos. 99/346/AUT, 00/240/AUT,
 2398 01/315/AUT, 01/322/AUT, 2003–113, 2003–114, 2004–182, 2004–183, 2005–203 and 2006–73)
 2399 were delivered by the French Ministère de l'Aménagement du Territoire et de l'Environnement
 2400 (MATE) and TAAF (**Y.R.**).

2401 Animal handling procedures were approved by the joint University of Cambridge / British
 2402 Antarctic Survey Animal Ethics Committee (**P.N.T.**).

2403 Tagging procedures were approved by the Animal Ethics Committee of the Australian Antarctic
 2404 Division (ATEP-12-13-4086-4088-SUMMER) (**B.W.**).

2405

2406 Polar bears

2407 Tagging procedures were conducted under USFWS research permit MA 690038 Animal Care
 2408 and Use Committees of the US Geological Survey (assurance no. 2010–3) (**A.M.P.**).

2409

2410 Seals

2411 Tagging was permitted by the Russian Federal Veterinary and Agricultural Control Service
 2412 (Rosselkhoznadzor, Kamchatka and Koryakia regions, Permit No. 1194) and was approved by
 2413 the Alaska Sea Life Center IACUC (**R.D.A.**).

2414 Tagging procedures were approved by the Adelaide University Animal Ethics (permit S80-2004)
 2415 and South Australia Department for Environment and Heritage (permit A24684-3) (**A.M.M.B.**).

2416 Weddell seals (*Leptonychotes weddellii*) tagged in Dumont d'Urville, Adélie Land by LOCEAN
 2417 laboratory were treated in accordance with the Institut Paul-Emile Victor (IPEV) ethical and
 2418 Polar Environment Committees guidelines (**J. Charrassin**).

2419 Animal use protocols for northern elephant seal tagging was reviewed and approved by the
 2420 University of California at Santa Cruz IACUC and followed the guidelines established by the
 2421 ethics committee of the Society of Marine Mammalogy. Research was carried out under NMFS
 2422 permits: #786-1463 and #87-143. Southern elephant seal (*Mirounga leonina*) captures were
 2423 conducted under NMFS permit No. 87-1851-00. All animal procedures were approved by the
 2424 IACUC at University of California Santa Cruz. Weddell seal handling protocols were approved
 2425 by the University of Alaska Anchorage and University of California Santa Cruz's IACUCs.
 2426 Research and sample import to the United States were authorized under the Marine Mammal
 2427 permit No. 87-1851-04 issued by the Office of Protected Resources, NMFS. Research activities
 2428 on southern elephant seals and Weddell seals were also approved through Antarctic Conservation
 2429 Act permits while at McMurdo Station (**D.P.C.** and **P.W.R.**).

2430 Ringed seal (*Pusa hispida*) handling and tagging was approved by the University of Windsor
 2431 Animal Care Committee (AUPP #12-12,13-10) and a DFO License to Fish for Scientific
 2432 Purposes (S-12/13-1019-NU) (**S.H.F.** and **D.J.Y.**).

2433 Australian sea lion (*Neophoca cinerea*) tagging procedures were approved by the PIRSA Animal
 2434 Ethics Committee (32-12), South Australian DEW (Scientific Permit A24684), and Western
 2435 Australian Department of Environment and Conservation (Licence to Take Fauna for Scientific
 2436 Purposes SF009529). Long-nosed fur seal tagging procedures were approved by the PIRSA
 2437 Animal Ethics Committee (32-12) South Australian DEW, Scientific (Permit A24684) (**S.D.G.**).

2438 Tagging procedures for Australian fur seal (*Arctocephalus pusillus doriferus*) and New Zealand
 2439 fur seal (*Arctocephalus forsteri*) were approved by the Macquarie University Animal Ethics
 2440 Committee (Animal Research Authority 2014/057), and work conducted under Office of
 2441 Environment and Heritage NSW Scientific Licence SL100746. Weddell seal tagging procedures
 2442 were approved by Macquarie University (#3223) ARA 2014_057 (**R.H.**) or approved by the
 2443 New Zealand Department of Conservation, Ministry of Foreign Affairs and Trade, and NIWA
 2444 Animal Ethics Panel (DOC-69331-MAR) (**M.P.**).

2445 Animal Ethics were obtained from NIWA to manipulate New Zealand sea lions (*Phocarctos*
 2446 *hookeri*) at Campbell Island, with the proviso that all work was undertaken with approval from
 2447 the Department of Conservation and the NZ Department of Conservation permit issued under the

2448 Marine Mammal Protection Act (1978). Southern elephant seal tagging procedures were
 2449 approved by University of Tasmania Animal Ethics (permit A0014523) (**M.A.H.**).

2450 All animal captures and procedures were authorised under NMFS permits (numbers 87-1593 and
 2451 87-1851-00) and approved by the University of California, Santa Cruz IACUC. Fieldwork in
 2452 Antarctica was approved by the Antarctic Conservation Act (**L.A. Huckstadt**).

2453 Tagging procedures were approved by the UCC Animal Ethics Committee, Irish National Parks
 2454 & Wildlife Service, and HPRA (**M.J.**).

2455 Southern elephant seals, Antarctic fur seals (*Arctocephalus gazella*), Weddell seals, crabeater
 2456 seals (*Lobodon carcinophaga*) and leopard seals (*Hydrurga leptonyx*) were tagged under ethics
 2457 and permits provided by the Brazilian Antarctic Programme "in lieu" of SCAR as their local
 2458 representatives for all the field work conducted on pinnipeds at Elephant Island, South Shetlands
 2459 (**M.M.C.M.**).

2460 Tagging procedures were conducted under the permit #572/208 approved by the National
 2461 Administration of Aquatic Resources, Ministry of Livestock, Agriculture and Fisheries
 2462 (DINARA), Uruguay (**F.G.R.**).

2463 Tagging procedures were approved by the Dirección Nacional del Antártico, Buenos Aires,
 2464 Argentina, and were carried out according to the Scientific Committee on Antarctic Research
 2465 Code of Conduct for Animal Experiments under University of New South Wales Animal Care
 2466 and Ethics Committee (Protocols 08/103B and 11/112A), and the Animal Care and Ethics
 2467 Committee of the Antarctic Science Advisory Committee (permit number 1144) (**T.L.R.**).

2468 Northern fur seal (*Callorhinus ursinus*) tagging in the Pacific North East and Pacific East Central
 2469 was conducted in accordance with and under the authority of the United States Marine Mammal
 2470 Protection Act (NMFS Permits 782–1455 and 782–1708). At the time this work was conducted
 2471 there was no additional requirement for review of these procedures by an institutional review
 2472 board or ethics committee. In 2010, a NMFS IACUC was established for the Alaska Fisheries
 2473 and Northwest Fisheries Science Centers and the capture and handling protocols were reviewed
 2474 and approved by this committee (**J.T.S.** and **R.R.**).

2475 Harbor seal (*Phoca vitulina*) studies in Scotland were carried out under UK Home Office licence
 2476 under the Animal (Scientific Procedures) Act 1986 (PIL nos. 60/3303, 60/4009 and 70/7806),
 2477 following approval by the University of St Andrews animal welfare and ethics committee.
 2478 Licences to capture and release animals in the wild for research were also granted by Marine
 2479 Scotland Licensing (**P.M.T.**).

2480 Animal handling and instrumentation complied with animal care regulations and applicable
 2481 national laws of Ecuador. This research was approved by the Chancellor's Animal Research
 2482 Committee at University of California, Santa Cruz. The appropriate animal use and care
 2483 committee of Ecuador (Parque Nacional Galapagos) approved all research protocols. This work
 2484 was performed under the permit No PC-11-08 and PC-043-09 and authorization No. 084/06
 2485 PNG of the National Park service, Galapagos (**S.V.**).

2486 Grey (*Halichoerus grypus*) and harbor seals were caught under licenses Number 05/475/AUT,
 2487 05/485/AUT, 06/82/AUT, 07/481/AUT, 08/346/DEROG, 08/347/DEROG, 10/102/DEROG,
 2488 11/873/DEROG, 11/874/DEROG, and 13/422/DEROG delivered by the French ministry of the
 2489 environment (**C.V.**).

2490 California sea lion (*Zalophus californianus*) capture and procedures were approved by the
 2491 University of California Santa Cruz Chancellor's Animal Research Committee (CARC) protocol
 2492 (COST 01.10) and authorized under National Marine Fisheries Service permit number 87-1593-
 2493 05 (**M.J. Weise**)

2494
 2495 Sirenians

2496 Dugong tagging was conducted under the conditions of ethics permit DEC AEC 2009/11
 2497 (**R.A.C.**).

2498 Permits required to capture and satellite track dugongs were obtained from the James Cook
 2499 University Animal Ethics Committee (Permits A1735 and A1936) and the North (60912155-
 2500 2013/JJC) and South (3157- 2012/ARR/DENV) Provinces of New Caledonia (**C.C.**).

2501 Tagging procedures were approved by the Charles Darwin University Animal Ethics Committee
 2502 and wildlife research permits were obtained from the Parks and Wildlife Commission of the
 2503 Northern Territory (**S.D.W.**).

2504 Manatee tagging procedures were carried out in accordance with the USFWS Permits
 2505 MA107933-1 and MA37808A-0, Alabama Department of Conservation and Natural Resources,
 2506 and Alabama Division of Wildlife and Freshwater Fisheries annual permits. Approvals obtained
 2507 by the University of South Alabama IACUC for protocols 581568 and 1038636 (**R.H.C.**).

2508
 2509 Turtles

2510 Tagging was conducted under permits from Dirección General del Medi Natural de la
 2511 Generalitat Valenciana, Generalitat de Catalunya, Consejería de Medio Ambiente y Ordenación
 2512 del Territorio de la Junta de Andalucía, and Región de Murcia. A general permit for tagging
 2513 adult females was obtained from Ministerio para la Transición Ecológica y el Reto Demográfico
 2514 (GPM/BDM/AUTSPP/23/2020) (**S.A. and E.J. Belda**).

2515 The Indonesian Institute of Sciences provided research permits for telemetry deployments at the
 2516 nesting beaches. Telemetry deployments at California foraging grounds were conducted under
 2517 Endangered Species Act permit nos. 1159, 1227, and 1596 (**S.R.B.**).

2518 Queensland Scientific purposes permit and a University of Queensland Animal Ethics permit
 2519 (**H.A.C.**).

2520 Tagging procedures were conducted under permits granted by the Commonwealth of Dominica
 2521 Ministry of Agriculture and Forestry to Domenicia's Sea Turtle Conservation Organisation Inc
 2522 (**R.W.C.**).

2523 Green turtle (*Chelonia mydas*) tagging procedures were carried out in compliance with Mexican
 2524 regulations (permit SGPADGVS/SEMARNAT, Mexico, No.09583/15). Hawksbill turtle
 2525 (*Eretmochelys imbricata*) tagging was carried out in compliance with Mexican regulations
 2526 (permit SGPADGVS/SEMARNAT Mexico, No.09583/15) (**E. Cuevas-Flores**).

2527 Loggerhead turtles (*Caretta caretta*) were handled under license "Nº 04/IFCN/2018- FAU
 2528 MAO" and previous licenses issued by the Government of the Autonomous Region of Madeira
 2529 (**T.D.**).

2530 Leatherback turtle tagging procedures were conducted under NMFS Endangered Species Act
 2531 Section 10 Permits #1557 and #15672, University of New Hampshire IACUC #060501 and

2532 #090402, and University of Massachusetts IACUC #2010-0019. Turtle disentanglement was
 2533 conducted under the authority of NOAA 50 CFR Part 222.310 (**K.L.D.**).

2534 All sea turtle research was conducted under NMFS Permit 1260 and 16733 to take protected
 2535 species for scientific purposes and USFWS permits TE-676379-4 and TE676379-5 issued to the
 2536 NMFS Southeast Fisheries Science Centre (SEFSC) and according to IACUC-reviewed
 2537 procedures outlined in the NMFS SEFSC Sea Turtle Research Techniques Manual (**L.L.D.**).

2538 Loggerhead and green turtle tagging procedures were conducted under permit issued by the
 2539 wildlife agencies of Buenos Aires and Río Negro provinces and the National Wildlife Agency of
 2540 Argentina (**V.G.C.**).

2541 Green turtle tagging procedures were conducted within the Statia National Marine Park
 2542 programme and complied with all relevant national legislation. Hawksbill turtle tagging was
 2543 conducted within the Statia National Marine Park and St Maarten Marine Park programmes and
 2544 complied with all relevant national legislation (**N.E.**).

2545 Leatherback turtle tagging procedures were reviewed by the University of New Hampshire
 2546 IACUC (060501) (**B.J.G.**).

2547 Leatherback turtle were tagged under permit number SGPA/DGVS/08562/17. Green and
 2548 hawksbill turtle tagging procedures were authorized by the SEMARNAT (permit numbers
 2549 150496–213–03, 280597–213–03, 190698–213–03, 280499–213–03, SGPA/DGVS/002m
 2550 SGPA/DGVS/05137/12, SGPA/GDVS/02259/14, and SGPA/DGVS/04478/15) (**C.E.H.**).

2551 Tagging procedures were approved by Swansea University and Deakin University Ethics
 2552 Committees and the British Indian Ocean Territory (BIOT) Administration of the UK Foreign
 2553 and Commonwealth Office. Research was endorsed through research permits (0002SE12,
 2554 0007SE15, 0002SE17, 0006SE18) from the Commissioner for BIOT and research complied with
 2555 all relevant local and national legislation (**G.C.H.**).

2556 Sea turtle tagging procedures and fieldwork were directly approved by the Centro
 2557 TAMAR/IBAMA/ICMBio. Fundação ProjetoTAMAR has MMA/IICMBio/SISBIO N° 42760
 2558 permit (**P.H.L.** and **E.A.P.S.**).

2559 Tagging procedures for rehabilitated loggerhead sea turtles were conducted under the
 2560 authorization of blanket permit from USFWS to NOAA NMFS. Loggerhead sea turtles acquired
 2561 via capture or incidental capture were taken under the authority of NMFS Research permit 16134
 2562 (**G.L.**).

2563 Green turtle tagging procedures were conducted with permission from the Administrator of
 2564 Ascension Island. Leatherback turtle tagging was conducted under permits from Ezemvelo
 2565 KwaZulu Natal Wildlife. Loggerhead turtle tagging was conducted with approval from the
 2566 ethical committee of the University of Pisa (**P.L.**).

2567 Tagging procedures were authorized under the Peru Instituto Nacional de Recursos Naturales
 2568 (INRENA) permits 015-2002-INRENA-J-DGFFS-DCB, 070-2003-INRENA-IFFS-DCB, 068-
 2569 2004-INRENA-IFFS-DCB, 025-2005-INRENA-IFFS-DCB and 002-2006-INRENA-IFFS-DCB
 2570 (**J.C.M.**).

2571 Tagging operations were authorized by the Dirección General de Sostenibilidad de la Costa y del
 2572 Mar (Ref DIV/BDM/AUTSSP/58/2015, Spanish Government) (**D.M.**).

2573 Green turtle tagging was conducted under permits of NOAA, Federated States of Micronesia,
 2574 and Republic of Marshall Islands. Hawksbill turtle tagging was conducted under permits from
 2575 NOAA, the USFWS, the Hawai'i Division of State Parks, and the Mexico Comisión Nacional de
 2576 Áreas Naturales Protegidas (**D.M. Parker**).

2577 Loggerhead turtles tagging procedures off of the Baja California Peninsula, Mexico, were
 2578 conducted in full compliance with CARC/IACUC protocol at UC Santa Cruz and research was
 2579 authorized by the Mexican government through SEMARNAP and SEMARNAT permits
 2580 150496-213-03, 280597-213-03, 190698-213-03, 280499-213-03, 280700-213-03,
 2581 SGPA/DGVS/002 4661, SGPA/DGVS/10358, and SGPA/DGVS/03501/06 (**H.P.**).

2582 Tagging procedures were authorised by the Environment Agency Abu Dhabi, the Environment
 2583 & Protected Areas Authority, Sharjah, the Environment Studies Center at Qatar University, the
 2584 Qatar Ministry of Environment, the Oman Ministry of Environment and Climate Affairs, and the
 2585 Department of Environment, Iran (**N.J.P.**).

2586 Leatherback turtles tagging procedures were conducted under licence (# 27/01 and 73/08) from
 2587 the Fauna Department-Ministry of Cattle, Agriculture and Fishing of Uruguay (**L.P. and M.**
 2588 **Lopez Mendilaharsu**).

2589 Tagging permissions were given by Oman's Ministry for Regional Municipalities, Environment
 2590 and Water Resources (**A.F.R.**).

2591 Tagging was performed with the permit of the Environmental Ministry of the Dominican
 2592 Republic Government (**J. Tomás**).

2593 Permissions for sea turtle rehabilitation work were given by the Dubai Wildlife Protection Office
 2594 (**D.P.R.**).

2595 Tagging procedures were conducted under approval from the National Marine Park of Zakynthos
 2596 (permits from 2000–2012), the Animal Ethics Committee of Deakin University (B0X2015-17),
 2597 and the Greek Ministry of Environment (Permit: 151503/162) (**G. Schofield**).

2598 Tagging procedures were conducted under approval from the Dakshin Foundation Animal
 2599 Research Ethics Review Committee. In the Andaman and Nicobar Islands, permits were issued
 2600 to tag ten leatherback sea turtles with satellite transmitters from the Ministry of Environment and
 2601 Forests (Wildlife Division), Government of India, on 16th December 2008 (F.No.1-4/2007 WL-I
 2602 (pt-1)). Research permits from the Forest Department, Andaman and Nicobar Islands
 2603 (CWLW/WL/47/393) and other relevant permits from the Andaman and Nicobar Administration
 2604 were also obtained to carry out the field work in Little Andaman Island (**K.S.**).

2605 Tagging procedures were performed in accordance with the Stanford University Protocol for the
 2606 Care and Use of Laboratory Animals (APLAC no. 13848). The Costa Rican Ministry of Natural
 2607 Resources and the Environment provided research permits (**G.L.S.**).

2608 Green turtle tagging was conducted under permit approved by the Western Australian
 2609 Department of Biodiversity, Conservation and Attractions. Tags were deployed by RPS Group –
 2610 Perth WA (lead by former employee **D.W.**) on behalf of Woodside Energy Group Ltd.

2611 Tagging procedures were conducted under permission obtained from the Viceconsejería de
 2612 Medio Ambiente of the Gobierno de Canarias. Cape Verde did not require permission from the
 2613 government at that time (**N.V.**).

2614 Hawksbill turtle and olive Ridley turtle (*Lepidochelys olivacea*) tagging procedures were
2615 conducted under approval from Charles Darwin University Animal Ethics Committee and
2616 wildlife research permits (A4005) from Parks and Wildlife Commission of the Northern
2617 Territory (**S.D.W.**).

2618 Research protocols for capturing and deploying satellite transmitters on flatback turtles were
2619 approved by an authorised ethics committee (SA 2015/11/531) and authority under the Nature
2620 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 $5.4 - 35 \text{ m.s}^{-1}$ ($20 - 126 \text{ km.h}^{-1}$) for birds, $1.6 - 7 \text{ m.s}^{-1}$ ($5.8 - 25 \text{ km.h}^{-1}$) for cetaceans, $0.5 - 11.9 \text{ m.s}^{-1}$ ($1.9 - 42.8 \text{ km.h}^{-1}$) for fishes, $2.1 - 4.2 \text{ m.s}^{-1}$ ($7.5 - 15 \text{ km.h}^{-1}$) for penguins, 0.75 m.s^{-1} (2.7 km.h^{-1}) for polar bears (but see (117)), $2.0 - 10.3 \text{ m.s}^{-1}$ ($7.2 - 37 \text{ km.h}^{-1}$) for seals, $1.1 - 2.8 \text{ m.s}^{-1}$ ($4.1 - 10 \text{ km.h}^{-1}$) for sirenians, and $1.4 - 2.8 \text{ m.s}^{-1}$ ($5 - 10 \text{ km.h}^{-1}$) 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 $\sim 160 \text{ km}$ to 0.3 km (118). Visual inspection led to further removal of unrealistic GLS locations for some bird species (e.g., longitude $< 43^\circ\text{W}$ or $> 98^\circ\text{W}$, latitude $< 8^\circ\text{N}$ or $> 73^\circ\text{N}$ 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:

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

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 ($6,371 \text{ km}$).

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 1° 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 (T_w) (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.

2755
2756 *Detection of migratory corridors*

2757 For detecting migratory corridors captured by our tracking dataset, we calculated how *coherent*
2758 the movement direction was within each grid-cell for each species based on the displacements
2759 calculated for $Tw = 1 - 10$ days. We did this because the results obtained for movement direction
2760 can differ for long- and short-time windows, with the former likely to reflect long term
2761 movements in a specific direction (i.e., ignoring potential return trips or other shorter changes in
2762 direction, such as daily trips), and the latter likely to provide displacements that are
2763 unrepresentative of potential migration (i.e., ‘noisy’ data). We then defined *coherence* (c) per
2764 taxon, for each Tw and grid-cell, as the sum of the displacement vectors (w_d) in a particular
2765 direction (i.e., multiplied by the cosine and sine of the angle φ) and then divided by all
2766 displacements in all directions, as:

2767
$$Coherence(T_w, c) = \frac{\sum_{d=1}^D w_d (\cos \varphi_d, \sin \varphi_d)}{\sum_{d=1}^D w_d}$$

2768 where D represents all displacements observed in each grid-cell. To scale results across taxa, we
2769 multiplied the average monthly *coherence* by the ratio between the number of grid-cells with
2770 observed displacements within each time window (C_{dm}) and the maximum number of grid-cells
2771 observed over different time windows (max C_{dm}) for each taxon.

2772 The selected taxon-specific displacements calculated for the Tw that resulted in the maximum
2773 number of 1° grid-cells showing coherent movement for that taxon (i.e., ‘best Tw ’; refer to fig.
2774 S12) were then aggregated at temporal scales of 1, 2, 3, 4, 5, 6 and also 12 months. Considering
2775 multiple temporal scales was necessary due to the differences in movement behaviour across the
2776 many species considered in our study. For example, central place foragers return to start
2777 locations (e.g., colony) in each trip. Using multiple temporal scales is therefore useful to allow
2778 detection of movement corridors in both directions avoiding the cancellation of the displacement
2779 vectors occurring in opposite directions (e.g., trip from nest to foraging location cancelled by the
2780 reverse trip). Also, because migratory behaviour is largely unknown or incomplete for many
2781 species (e.g., sharks), we included temporal scales up to 12 months to ensure we captured any
2782 previously undetected long-term migration if present. To automate routines, these temporal
2783 scales were programmatically defined considering one month as 365 days/12 (~ 30.4 days). We
2784 then repeated the calculation of *coherence* at each temporal scale for each taxon to find sets of
2785 neighbouring grid-cells where displacements obtained from the tracking dataset indicated
2786 movement in the same direction. We did this by calculating the average direction of all observed
2787 displacements at each grid-cell within each temporal scale (e.g., for a temporal scale of 3
2788 months, we used displacements calculated between 0 and ~ 90 days) and clustering all grid-cells
2789 that resulted in similar average direction (i.e., for which the cosine of the angle between their
2790 directions is > 0.8 , i.e., indicating similar direction of movement).

2791 The clustering of grid-cells resulted in a high number of clusters for each taxon and temporal
2792 scales. So, we computed the size distribution of clusters of grid-cells with similar average
2793 direction for each temporal scale and plotted the cumulative distribution. Then using a Lorenz
2794 curve as a parameter-free approach(121), we identified the intersection point between the slope
2795 of the tangent line at the maximum value (i.e., the slope where the cumulative distribution equals
2796 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 T_w ’ 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 ($\bar{u}$ and $\bar{v}$; 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 (*chl_a*) were obtained from NASA Ocean Biology Processing Group Level-3 SeaWiifs (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* + *chl_a* + *eke* + *bathymetry* + *Month*
- Model 2: *Behaviour* ~ *ssh* + *u10* + *v10* + *turbidity* + *salinity* + *eke* + *bathymetry* + *Month*
- Model 3: *Behaviour* ~ O_2 + *vel* + *vel10* + *mld* + *chl_a* + *bathymetry*
- Model 4: *Behaviour* ~ *temp2m* + *u* + *v* + *mld* + *chl_a* + *eke* + *bathymetry*
- Model 5: *Behaviour* ~ *mld* + *chl_a* + *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).

2883 *Predictions*

2884 We used the highest ranked model to predict which grid-cells are likely to be used as residence
2885 or for migration within the entire area where we had occurrence data for each taxon (see
2886 resulting maps in fig. S17). We did this after applying cross validation using a set of 10 (or 5
2887 depending on available data for each taxon) iterations to assess the predictive ability of the
2888 highest ranked models for each taxon. We assessed the predictive ability using the Cohen's
2889 *Kappa statistics* (K), which measures the agreement between predicted and real (i.e., obtained)
2890 values(131). We then used Landis & Koch (132) criteria to class results into 'no agreement' ($K \leq$
2891 0), 'slight agreement' ($0 < K \leq 0.2$), and at least 'fair agreement' ($K > 0.2$). Our K values for
2892 corridors averaged at 0.35 (ranging from 0.17 for turtles to 0.56 for penguins) and for residences
2893 averaged at 0.32 (ranging from 0.22 for birds and seals to 0.44 for cetaceans) (Table 2). To
2894 compute the final important marine megafauna areas across all taxa and months to be considered
2895 for the 30% protection (as shown in the right panel of Fig. 3), we used our predictions results
2896 only from models for which K was above 0.2 before applying the optimization algorithm.
2897

2898 **Optimisation algorithm**

2899 To select important marine megafauna areas for protection, we first assigned a score to each
2900 grid-cell based on the detection of key movement behaviours reflecting migratory corridors or
2901 residency areas across taxa. To do this, we first defined T_c and T_r , respectively, as the number of
2902 taxa using the grid-cell as migratory corridor or residence, and then attributed a higher
2903 importance to grid-cells used as residence (i.e., where animals are likely to spend more time)
2904 when calculating the product between T_c and T_r to obtain each score per grid-cell, following:

2905
$$Score = 2^{T_c} \times 3^{T_r}$$

2906 Using this formula, grid-cells receive scores of 2 or 3 if they are, respectively, used as: migratory
2907 corridor or residence by multiple species of only one taxon, and increasingly higher scores if
2908 they are used both as corridors and residencies across multiple taxa (e.g., we obtained a
2909 maximum score of 1944, for grid-cells used by 5 taxa as residence and 3 taxa as corridors) (fig.
2910 S15). We then ordered the grid-cells by descending scores to increasingly select, according to
2911 this ranking, grid-cells currently not (or only partially) protected, until we reached the 30% target
2912 (30% of 71.1 % area covered by our tracking dataset). The resulting selected grid-cells results in
2913 the polygons shown in Figure 3 (and the results from a sensitivity analyses changing the scores
2914 provided to migratory corridors and residences is provided in fig. S16). We repeated this
2915 procedure for the detected movement behaviours based on the probability of each grid-cell to be
2916 used as residence or for migration by each taxon obtained after our modelling procedure
2917 (detailed below). We selected important marine megafauna areas in decreasing order from the
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3307 S.A., F.J.A., K.A., F.A.A., A.S.A., S.Å., R.D.A., J.A.A., G.A., I.A., H. Arrizabalaga, M. Auger-
3308 Méthé, F.B., R.W.B., W.B., A.M.M.B., A. Beard, J.B., A. Bennison, S.R.B., D.B., S. Bessudo,
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3311 Couto, M.C., E. Cuevas-Flores, I.C., P.J.N.B., S. Derville, A.D., K.L.D., M.C.D., P.H.D.,
3312 E.W.J.E., L.D.E., N.E., F.F., J. Filmlalter, M.P.F., A.S.F., M.F., S.D.G., V.G.C., W.J.G., C.
3313 Guinet, C.E.H., G.H., G.C.H., A.R.H., R.W.H.I., M.A.H., B.J.H., L.A. Howey, L.A. Huckstadt,
3314 R.E.H., N.E. Humphries, N.E. Hussey, C.H., P.H.L., D.T.I., D.M.P.J., A.J., M.Y.J., M.J., I.D.J.,
3315 L.K.B.J., S.J.J., J.T.K., F.O.L., J.V.L., J.L., O.A.L., G.L., G.G.L., M. Lopez Mendilaharsu,
3316 A.D.L., P.L., W.S.L., B.C.L.M., A.I.M., J.C.M., D.M., D.A., H. Marshall, B.M., J.D.M., R.L.M.,
3317 L.M., C.R.M., M.M.C.M., W.J.N., M.A.C.N., B.M.N., E.O., S. Oppel, S. Orłowski, A.M.P.,
3318 B.P., V.H.P., D.M. Palacios, D.M. Parker, C.P., L.R.P., C.R.P., J.G.P., R.A.P., S.K.P., N.J.P.,
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3321 Sheaves, G.L.S., J.R.D.S., M.A. Silva, S.J.S., D.W.S., L.L.S., J. Stahl, J.D. Stevens, J.D.
3322 Stewart, A. Swaminathan, A. Takahashi, V.T., M.T., L.G.T., P.N.T., J.P.T., R.P.V.D., F.V.,

3323 N.V., J.J.V., M. Vedor, S.V., C.V., S.B.W., M.J. Weise, R.S.W., B.M.W., A.U.W., N.E.W.,
3324 M.W., S. Wischnewski, M.J. Witt, F.C.W., A.G.W., L.J.W., T.Y., D.J.Y., A.N.Z..
3325

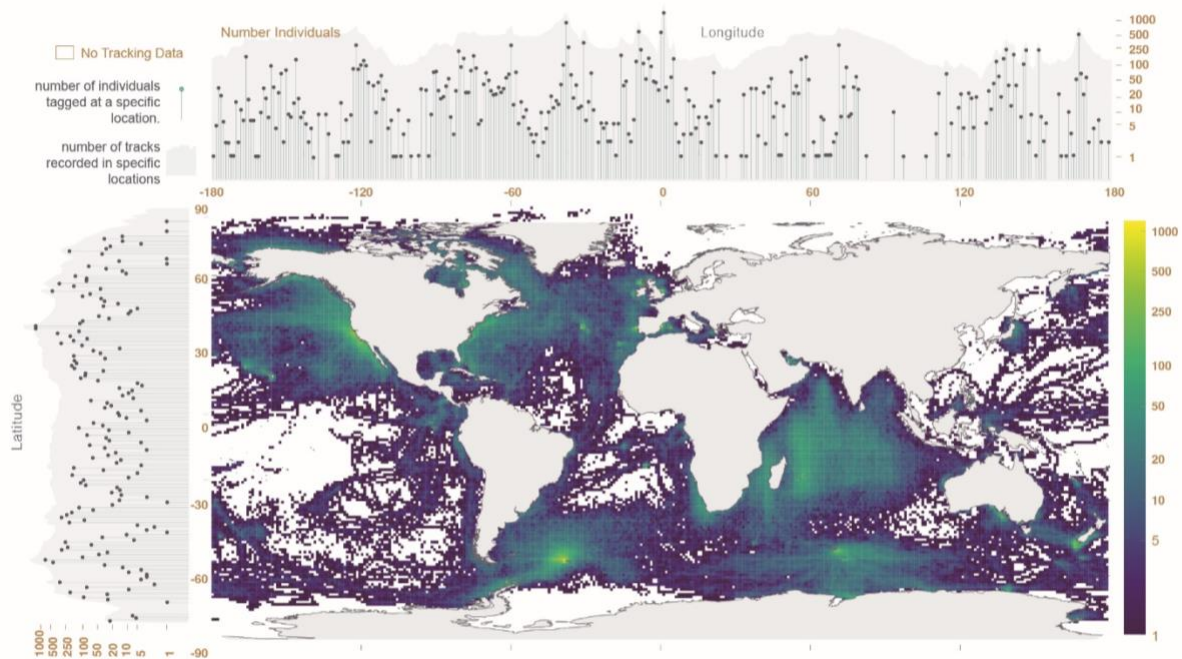


Fig. S1. Total number of tracked individuals per latitude and longitude

Spatial extent of the marine megafauna tracking datasets including the 12,794 individuals in the global dataset at 1° 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.

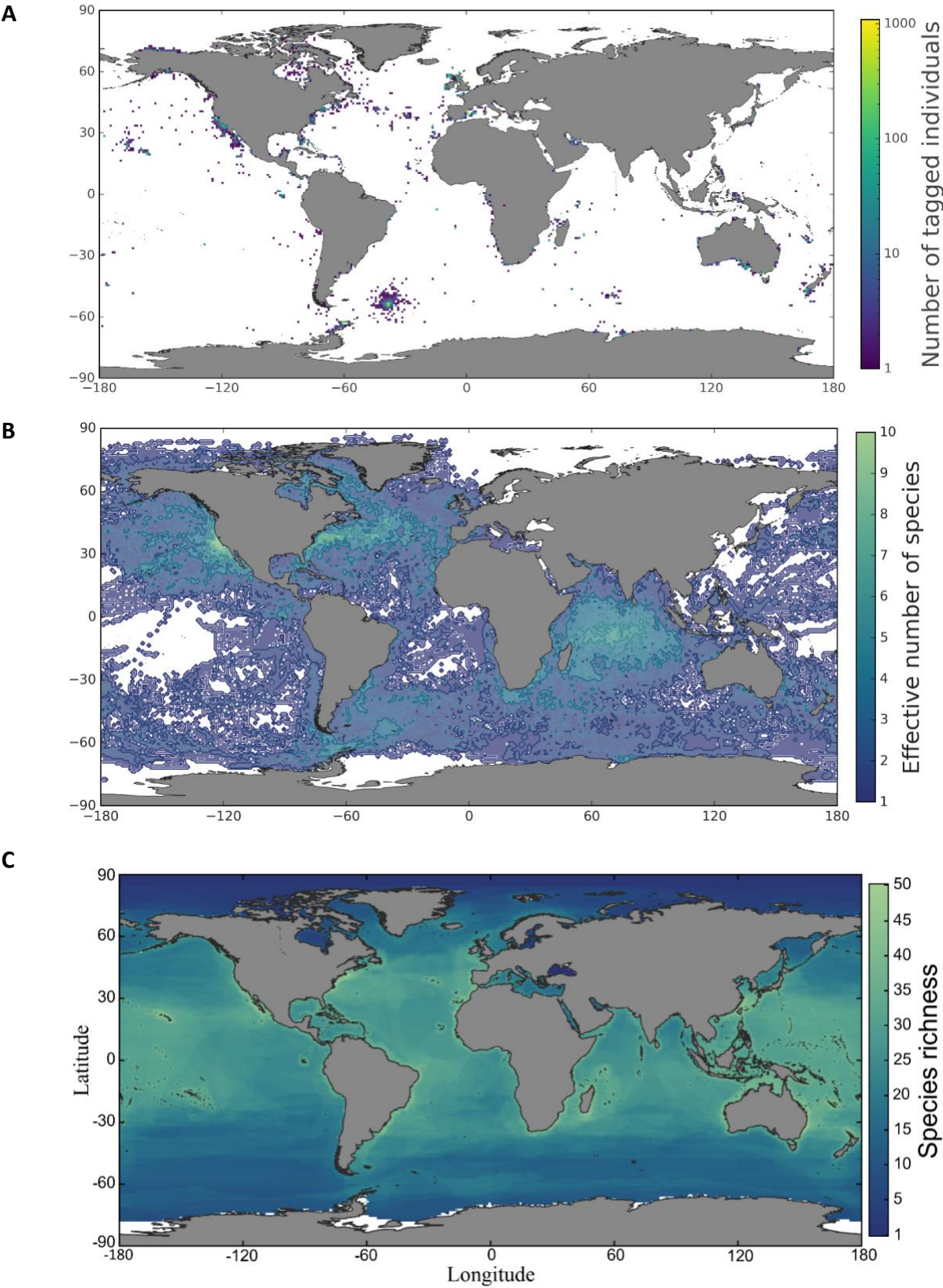


Fig. S2. Biodiversity captured versus expected based on the 111 species considered in our dataset.

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.

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

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).

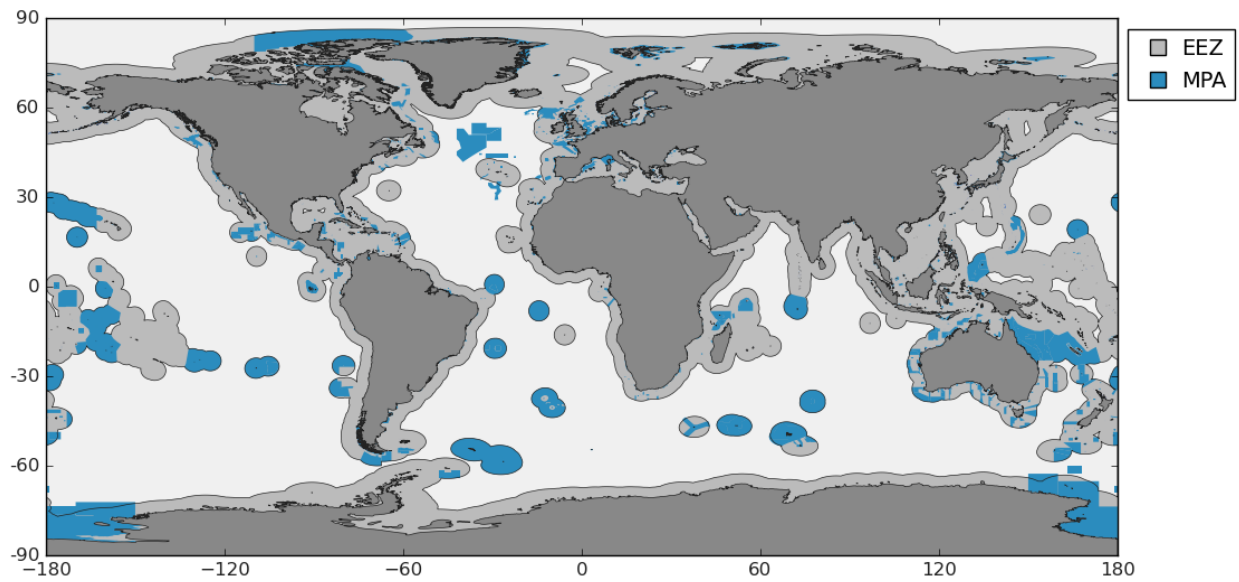


Fig. S3. Marine Protected Areas (MPAs) and Exclusive Economic Zones (EEZs) in the marine environment

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).

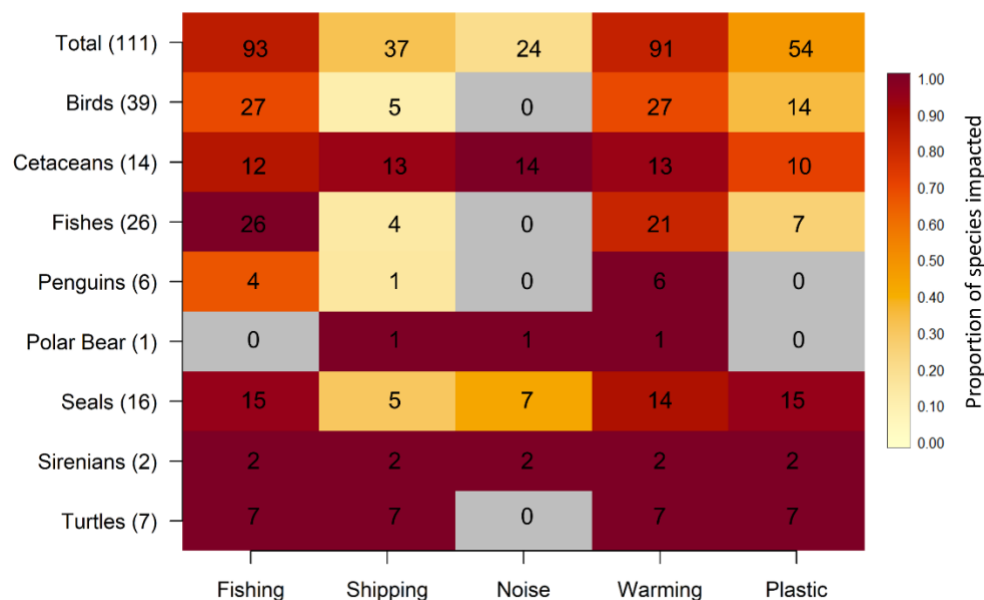
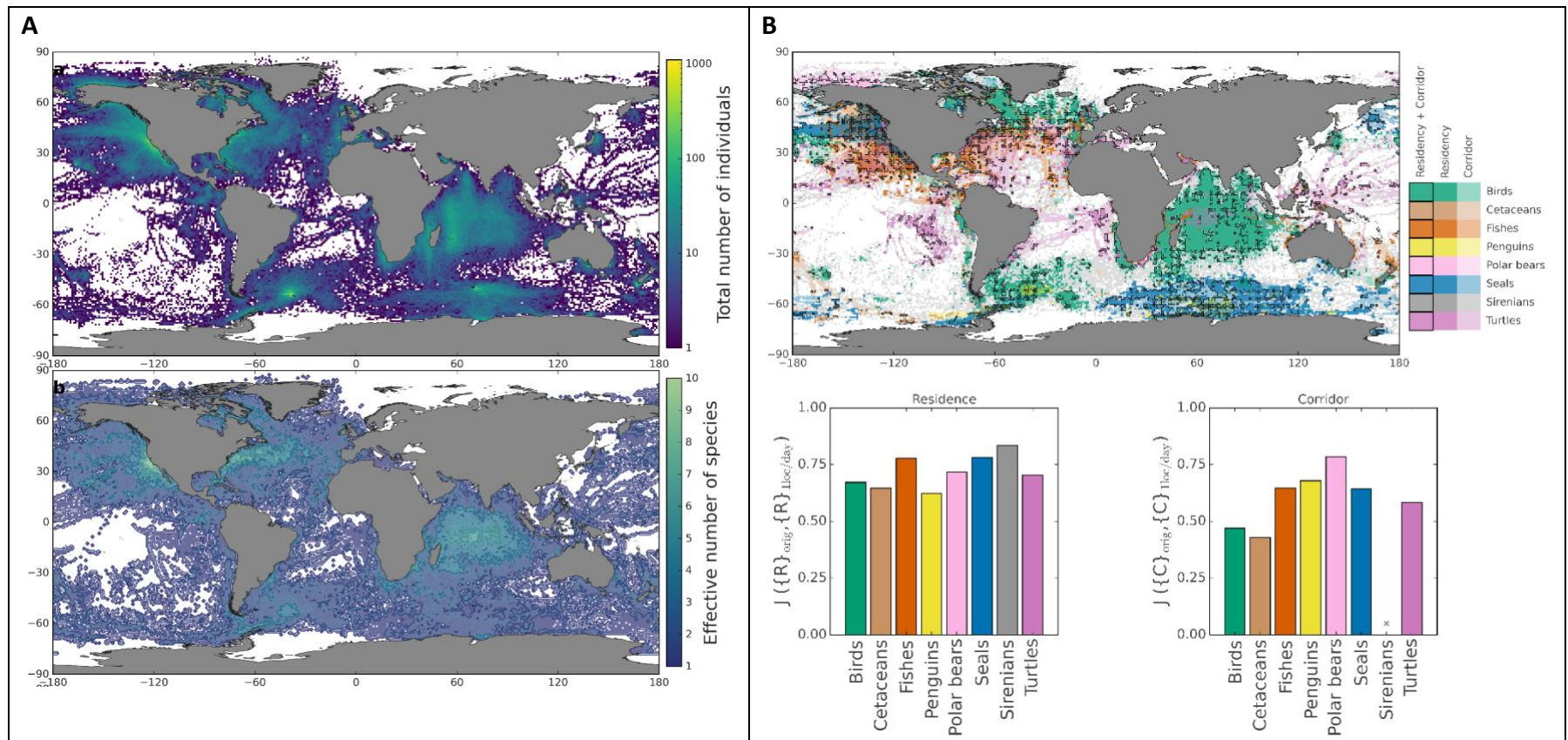


Fig. S4. Number of species affected by each anthropogenic threat considered

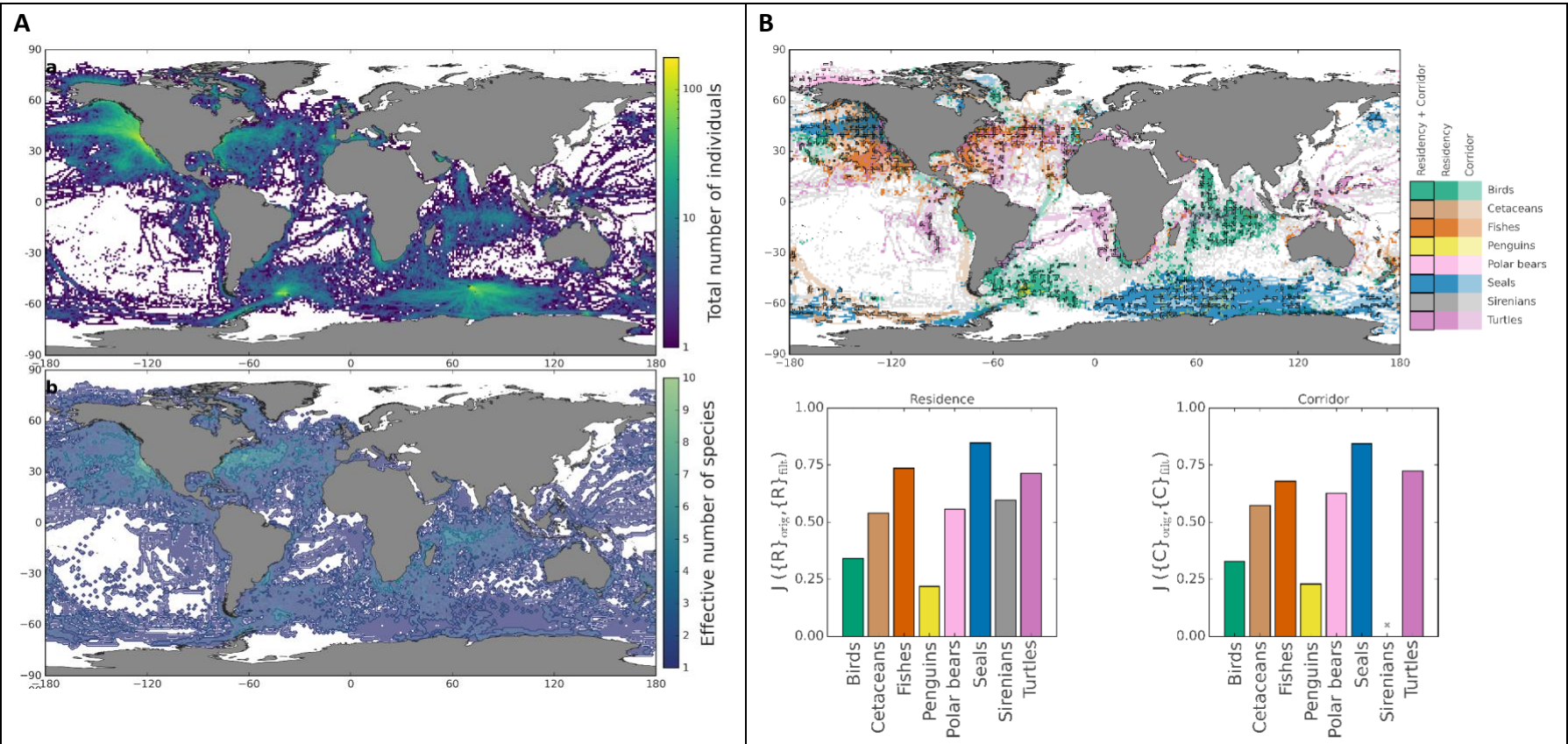
Summaries of the number of species known to be impacted by each threat considered in our analyses based on the listed threats and sub-threats on the IUCN Threats Classification Scheme v3.3(50) as detailed in table S4. Figure shows commercial fishing and climate change (represented as SST anomaly) has 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.



3381 **Fig. S5. Assessment of behaviours detected when using only one position per day for each individual**

3382 Results for the final tracking dataset when considering only one position per day per individual across all taxa. All maps show similar
 3383 spatial patterns to those obtained for the complete dataset (as shown in Fig. 1 and Fig. S2). A) Top: Total number of individuals for
 3384 which we have tracking data in each grid-cell; Bottom: effective number of species obtained per grid-cell. B) Top: Identified
 3385 migratory and residence areas when using only one position per day per individual across all taxa (greyed grid-cells indicate that no
 3386 key movement behaviour was identified); Bottom: Results obtained when using the Jaccard Index to compare the results obtained here
 3387 with those obtained from the original dataset. Species considered in each taxon group include flying birds (listed as birds), cetaceans
 3388 (mostly whales but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and
 3389 manatees), and turtles.

3390



3391 **Fig. S6. Assessment of behaviours detected when removing the tagging location bias**

3392 Results for the final tracking dataset after removing the tagging location bias. All maps show similar spatial patterns to those obtained
3393 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
3394 grid-cell; Bottom: effective number of species obtained per grid-cell. B) Top: Identified migratory and residence areas when removing
3395 all locations around the tagging location for all individuals across all taxa (greyed grid-cells indicate that no key movement behaviour
3396 was identified); Bottom: Results obtained when using the Jaccard Index to compare the results obtained here with those obtained from
3397 the original dataset. Species considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also
3398 dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

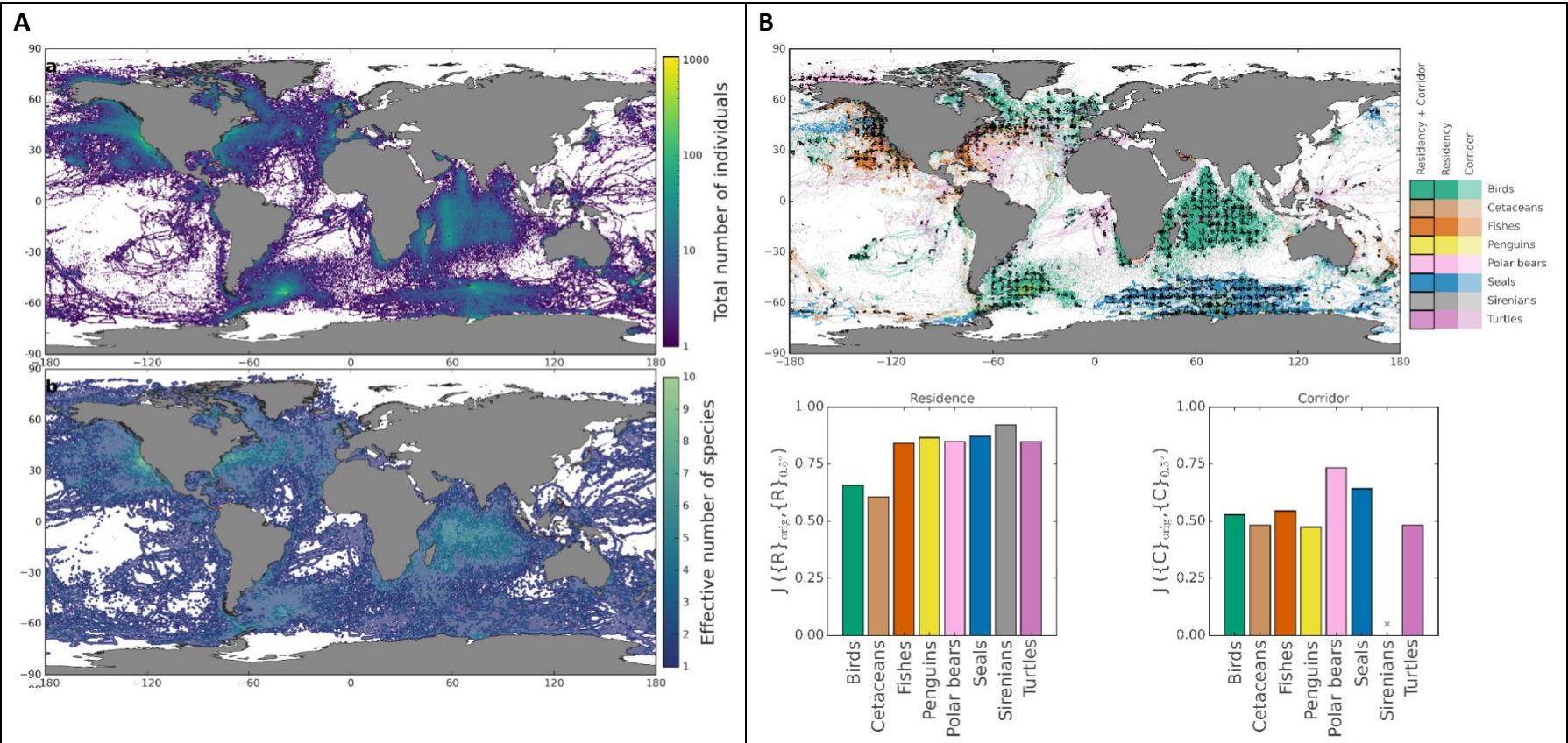
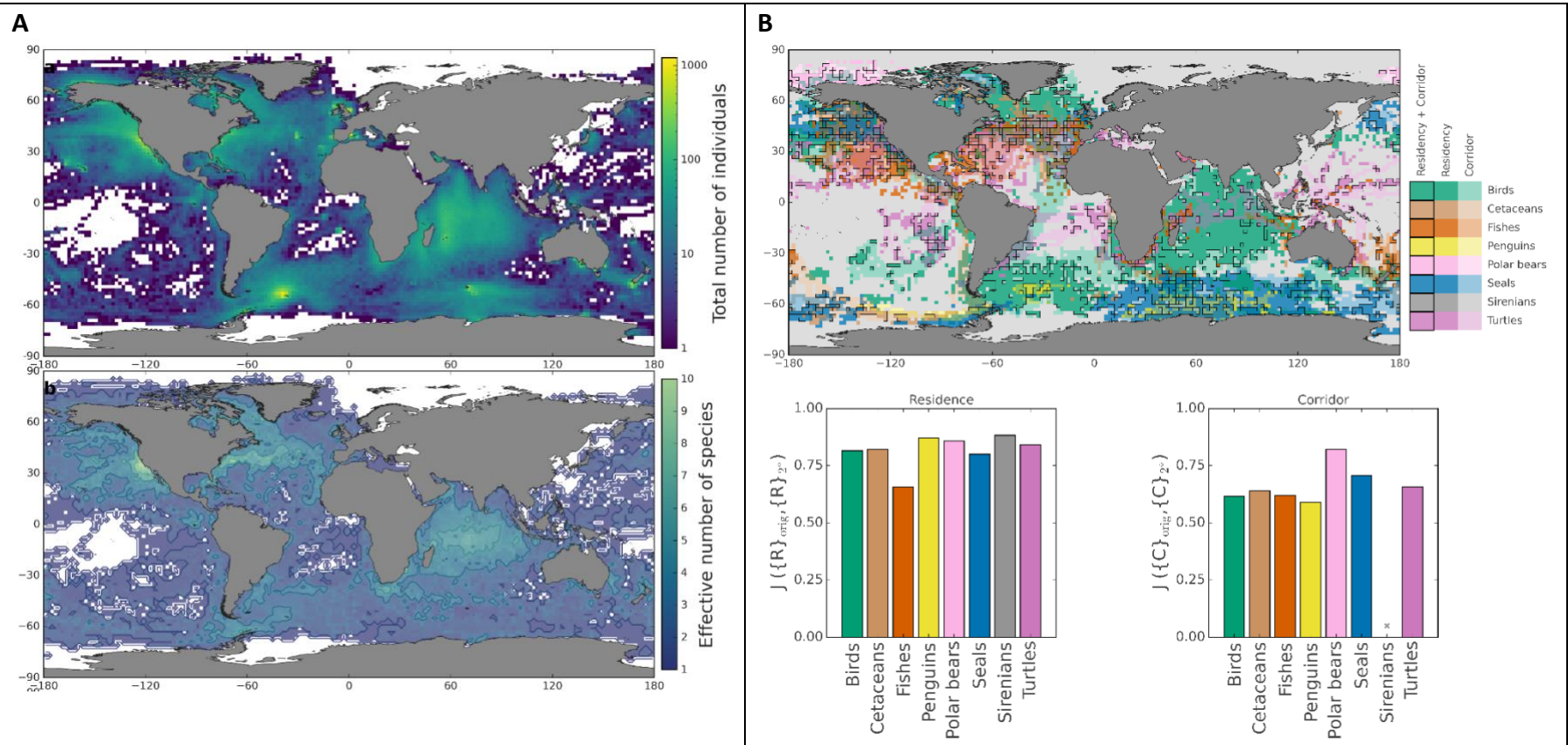


Fig. S7. Assessment of behaviours detected when changing resolution to 0.5°

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.

3408



3409 **Fig. S8. Assessment of ecological meaningful behaviour when changing resolution to 2°**

3410 Results for the final tracking dataset when considering a spatial resolution of 2°. All maps show similar spatial patterns to those
3411 obtained for the complete dataset (as shown in Fig. 1 and fig. S2). A) Top: total number of individuals for which we have tracking
3412 data in each grid-cell; Bottom: effective number of species obtained per grid-cell. B) Top: Identified migratory and residence areas
3413 when doubling the spatial resolution (greyed grid-cells indicate that no key movement behaviour was identified); Bottom: Results
3414 obtained when using the Jaccard Index to compare the results obtained here with those obtained from the original dataset. Species
3415 considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes (mostly
3416 sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and manatees), and turtles.

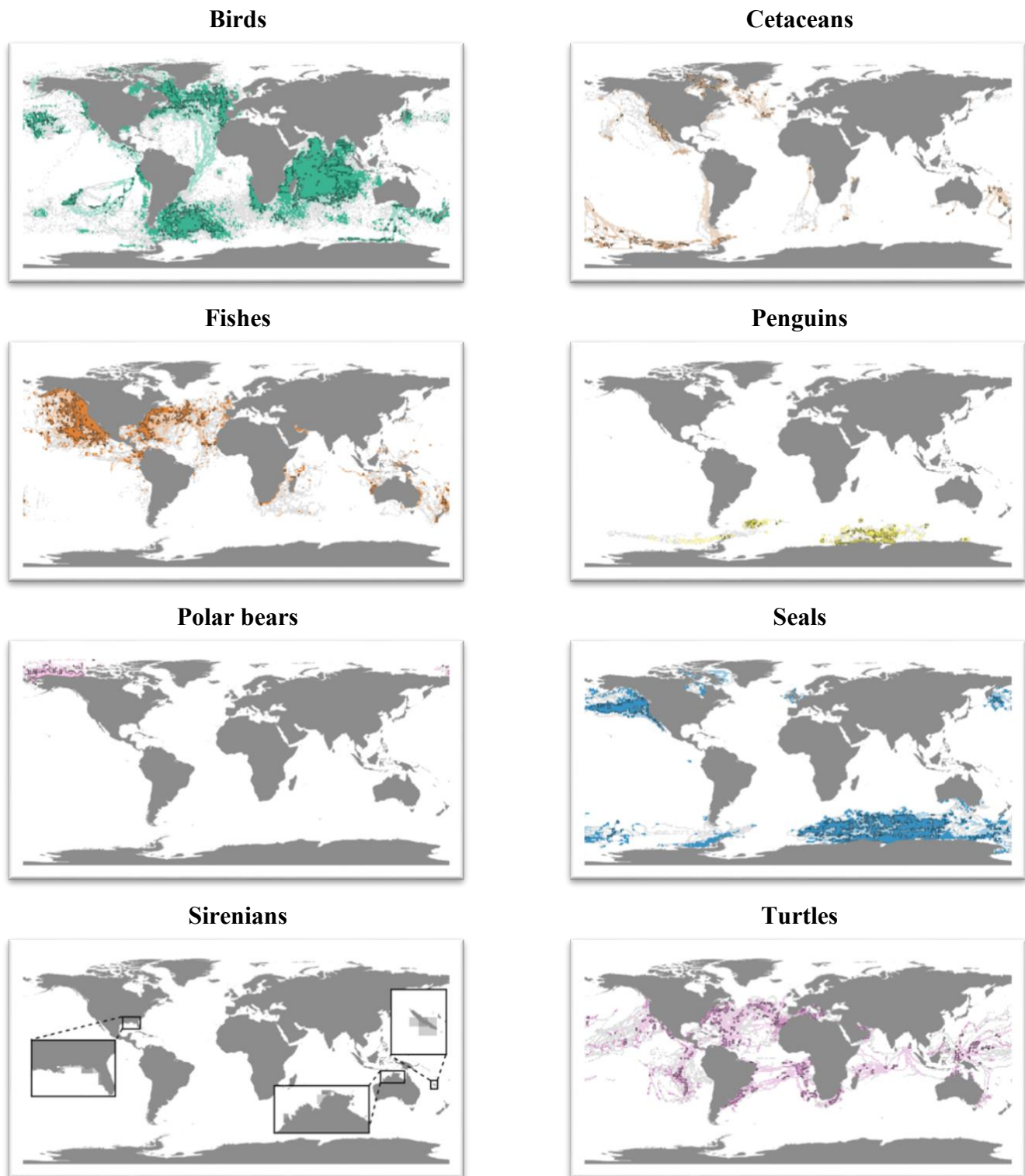


Fig. S9. Detected important migratory corridors and residence areas found by taxa

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

3421 resulted in the maximum number of 1° grid-cells showing coherent direction of movement
3422 within each month for each taxon (fig. S12), and after detection of hotspots of coherence clusters
3423 using on a Lorenz curve approach (fig. S13). Residence areas, indicated by grid-cells shown in
3424 stronger colours, were obtained based on z-scores of one standard deviation below the average
3425 displacement for each taxon. Where both migratory corridors and residence areas were found,
3426 grid cells include a black outline. Grey indicates grid-cells where no specific behaviour was
3427 identified. White areas depict regions without tracking data. Species considered in each taxon
3428 group include flying birds (listed as birds), cetaceans (mostly whales but also dolphins), fishes
3429 (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals, sirenians (i.e., dugongs and
3430 manatees), and turtles.

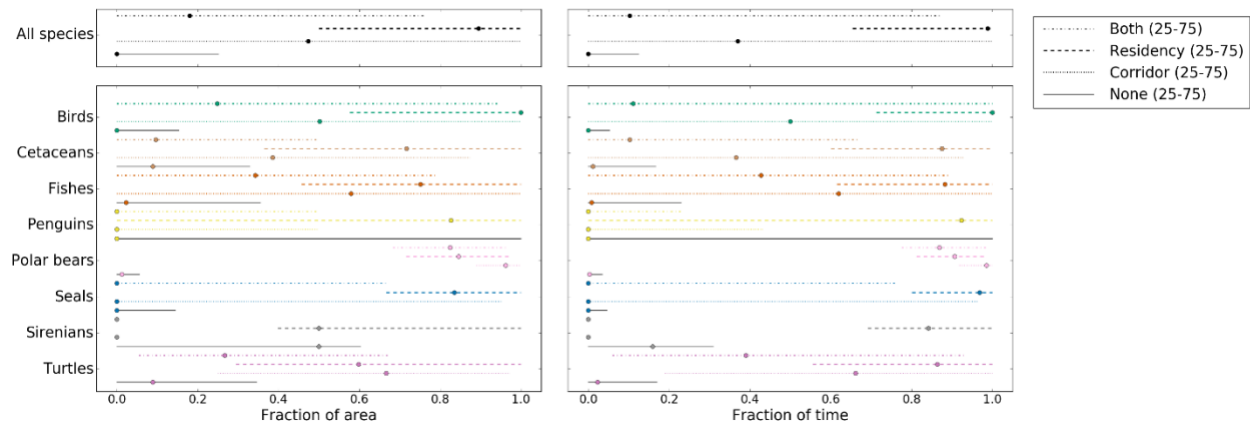


Fig. S10. Statistics of the space and time used for different behaviours per taxa

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.

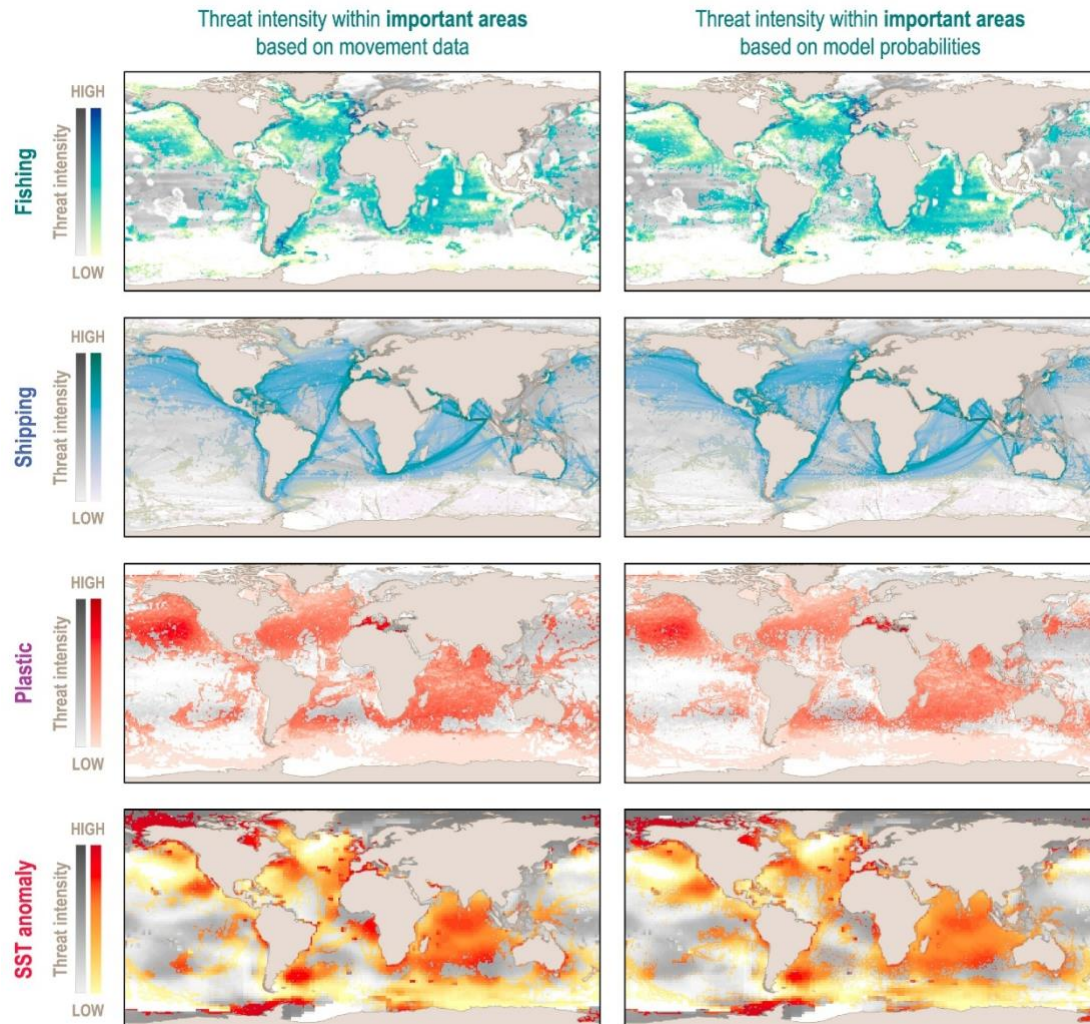
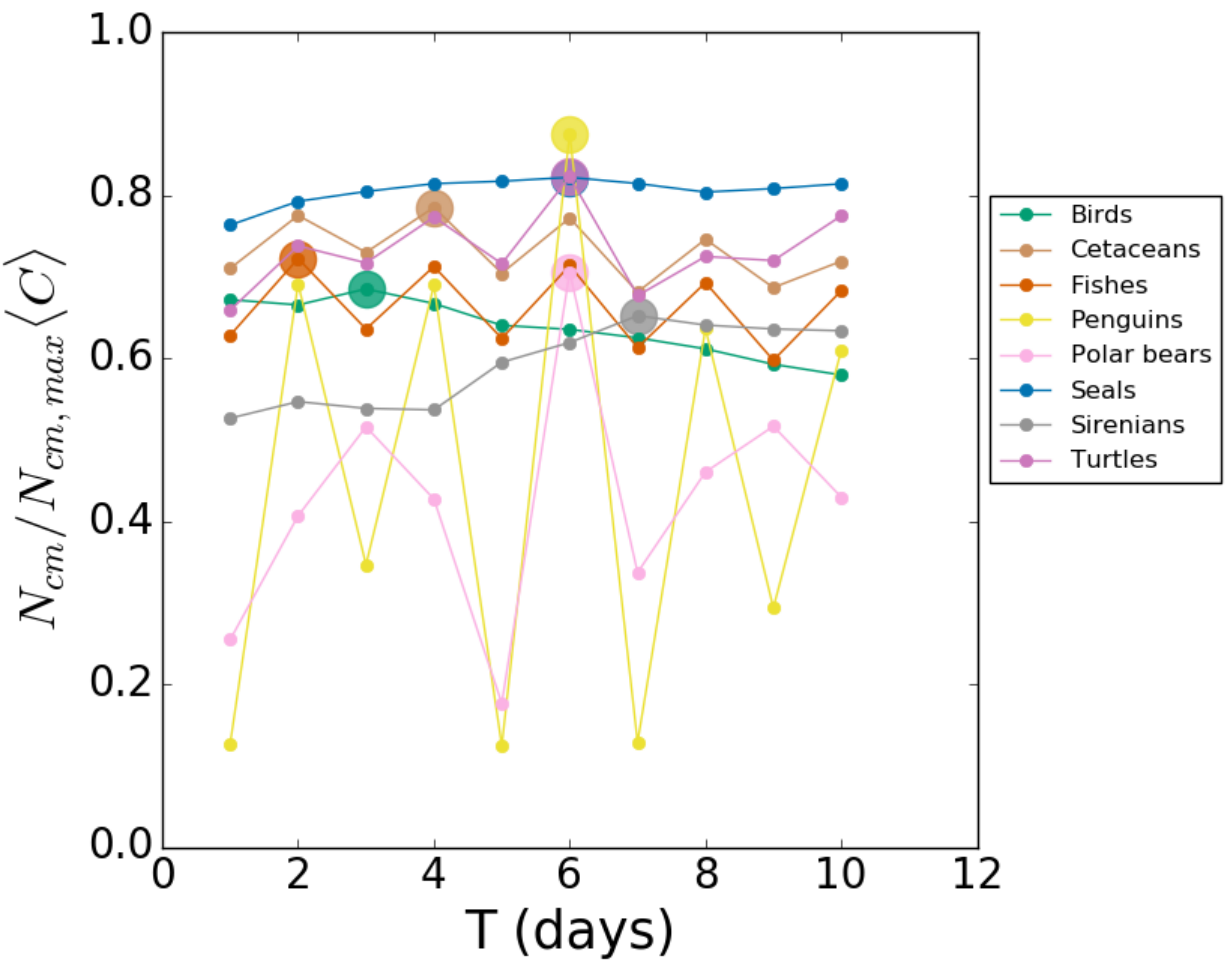


Fig. S11. Global footprint of anthropogenic threats and intensity within important areas for marine megafauna (IMMegAs)

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).

3453



3454

3455 **Fig. S12. Average monthly coherence results at multiple time windows for all taxa**

3456 Our analyses for detection of key movement behaviours indicated by migratory or residency-like
3457 behaviours showed that the maximum number of 1° grid-cells with coherent movement was
3458 obtained for time windows (Tw) < 10 days for all taxa considered: 2 days for fish, 3 days for
3459 birds, 4 days for cetaceans, 6 days for penguins, polar bears, seals, and turtles, and 7 days for
3460 sirenians. Circles indicate the time at which coherence was highest for each taxon. Species
3461 considered in each taxon group include flying birds (listed as birds), cetaceans (mostly whales
3462 but also dolphins), fishes (mostly sharks), penguins, polar bears (*Ursus maritimus*), seals,
3463 sirenians (i.e., dugongs and manatees), and turtles.

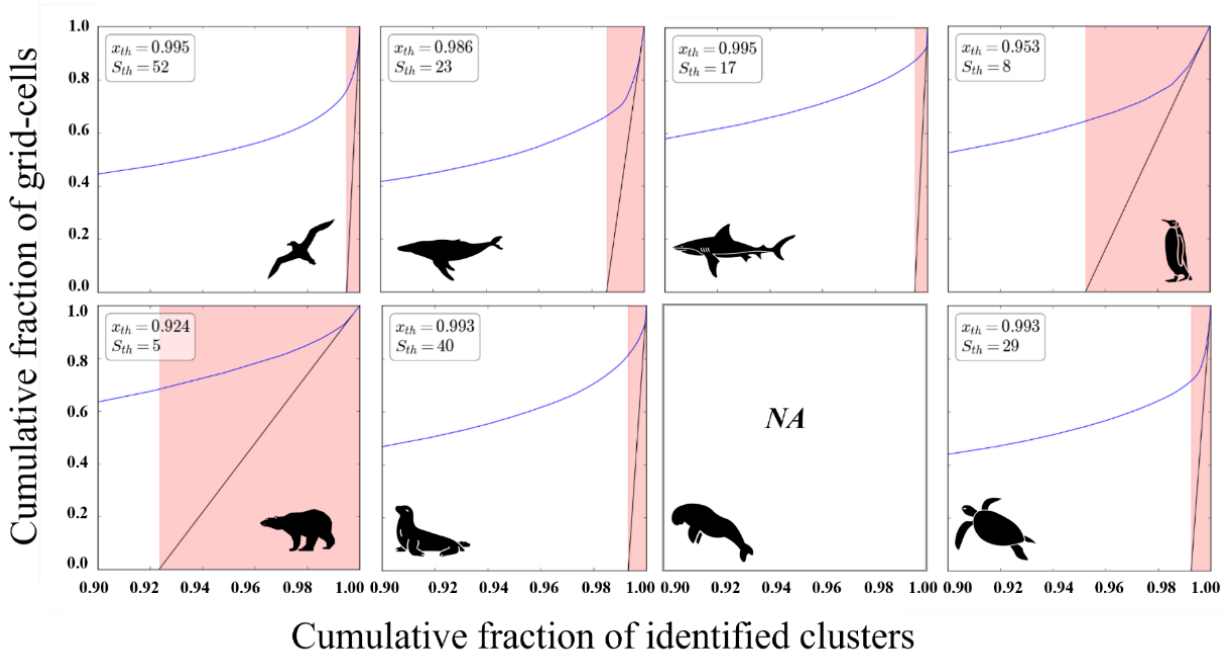


Fig. S13. Detection of cluster hotspots of coherence with the Lorenz curve

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.

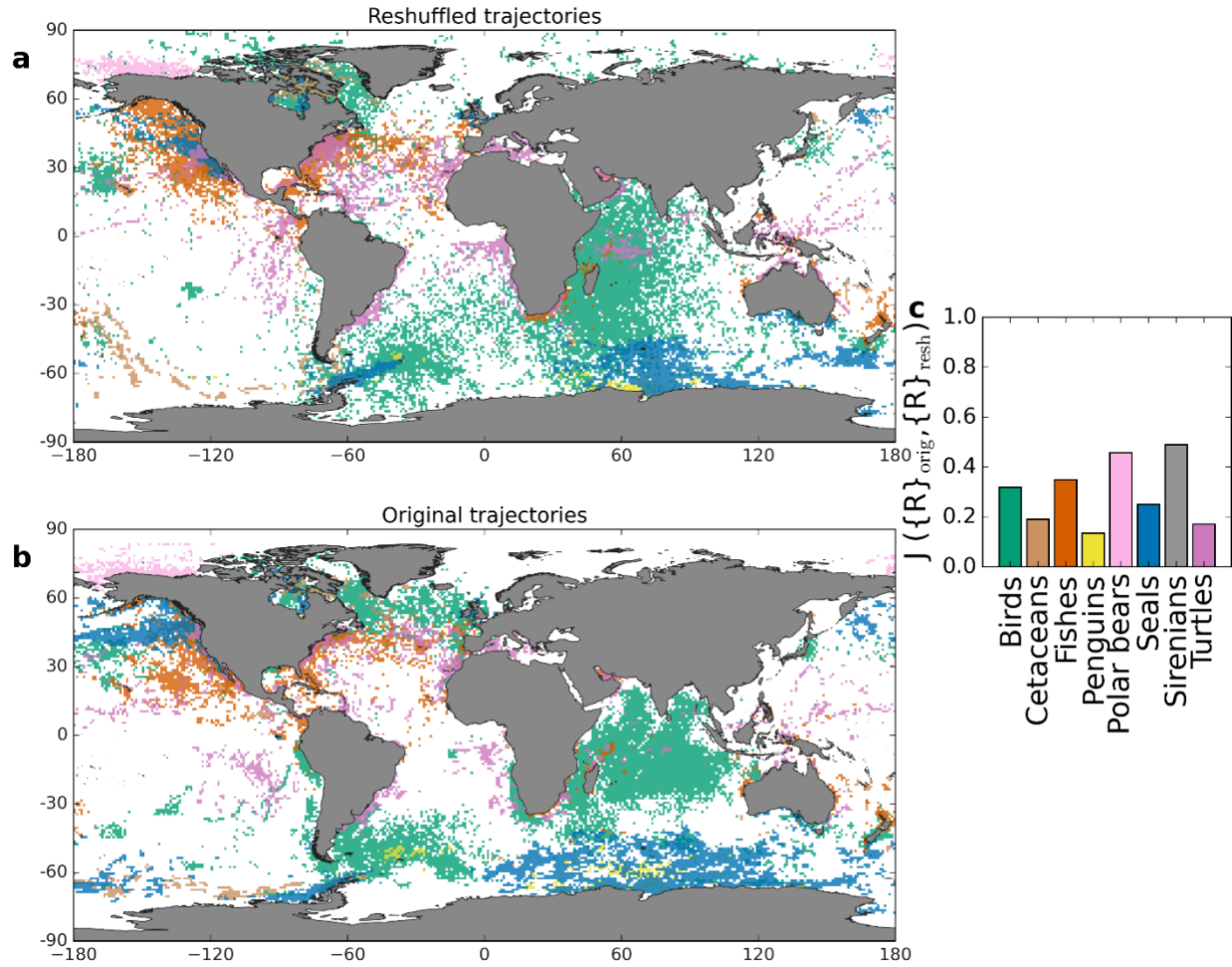


Fig. S14. Comparison of detected residency areas across taxa after randomising tracks

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.

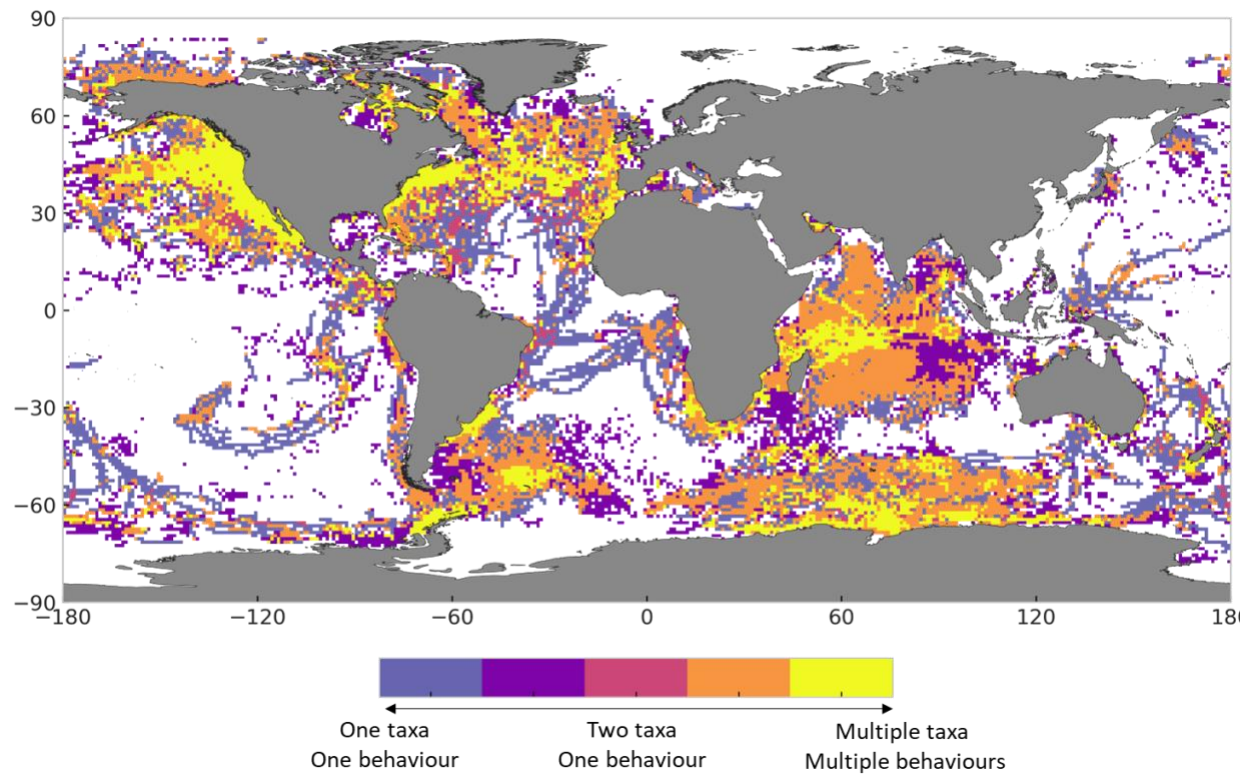
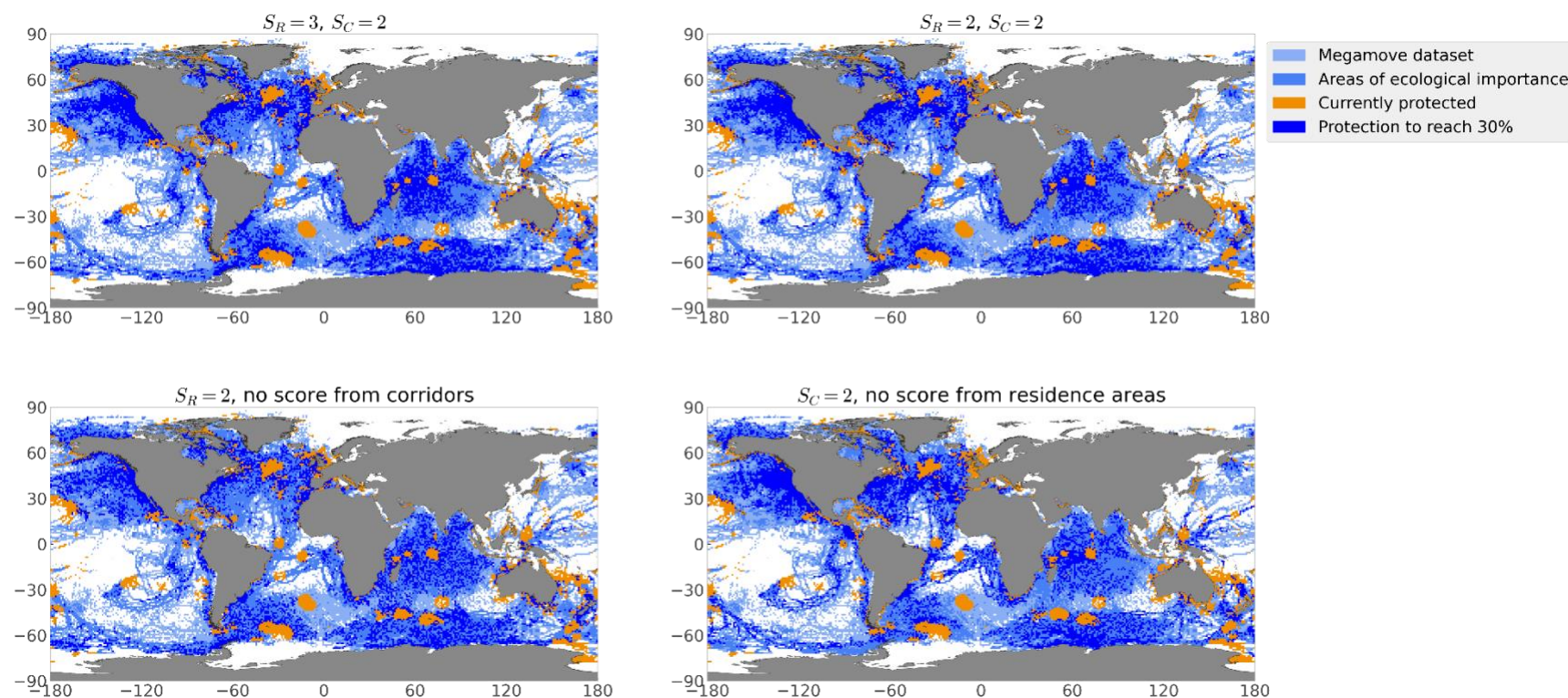


Fig. S15. Depiction of scores computed as part of the optimisation algorithm to select priority areas for global protection of marine megafauna

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).

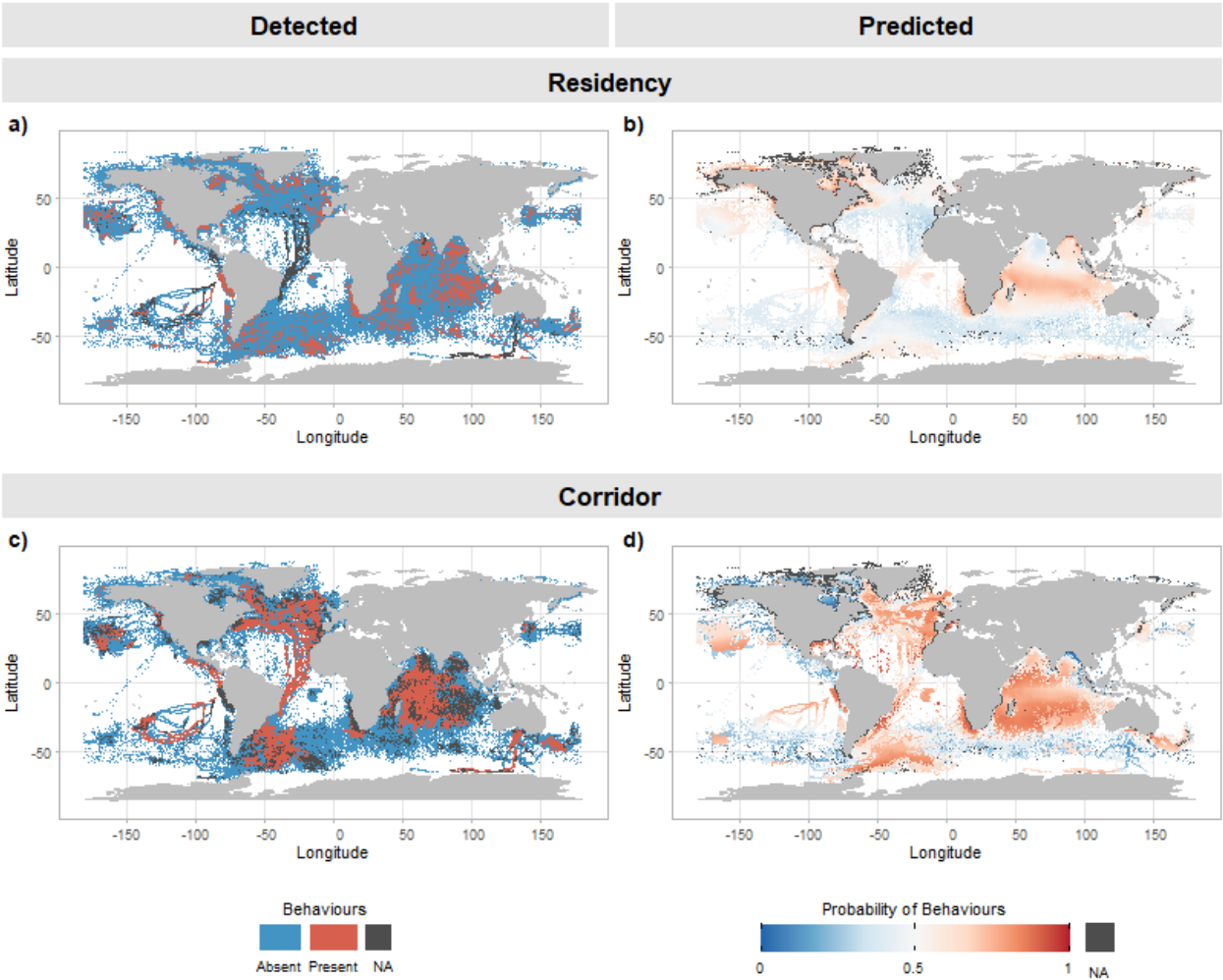
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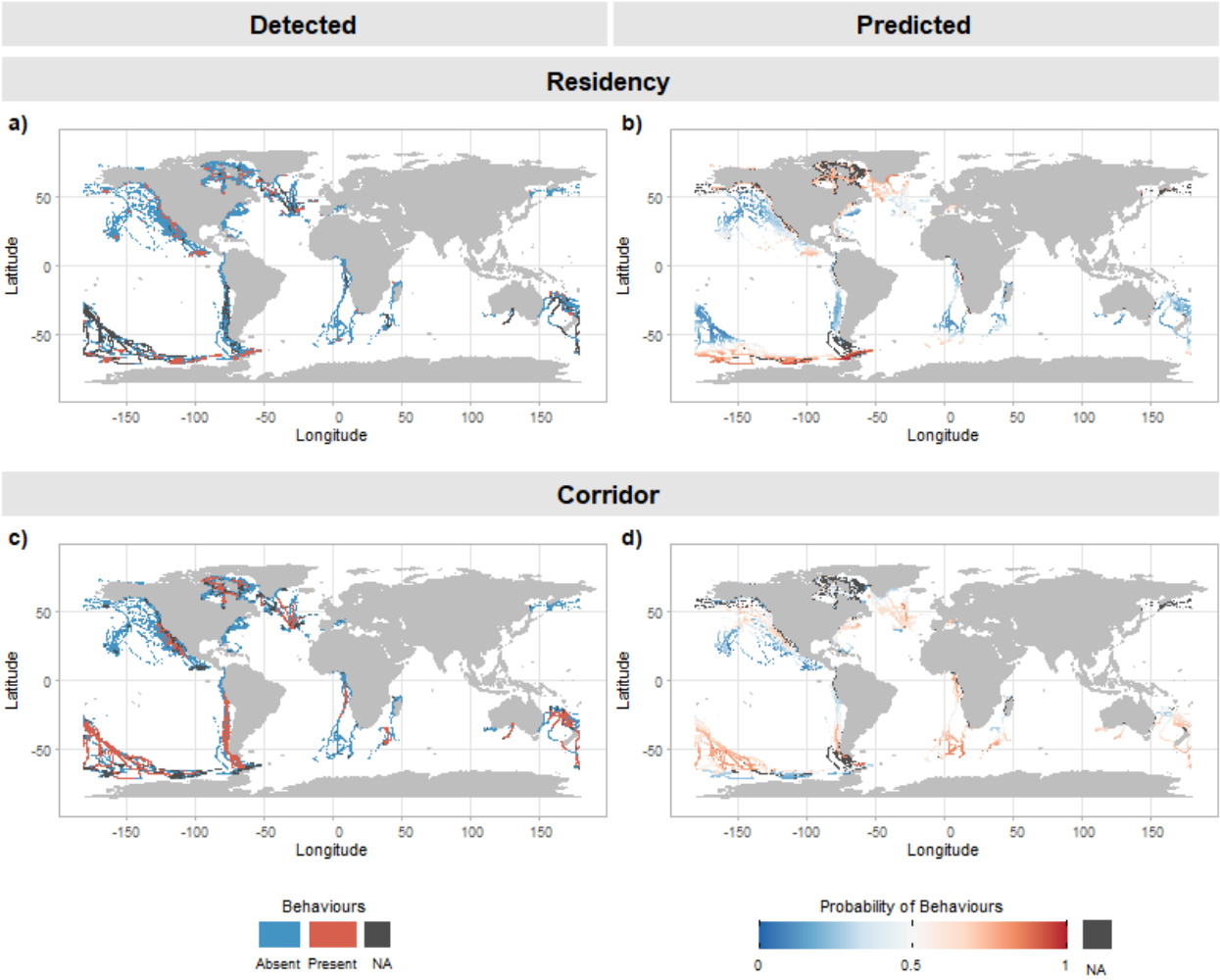


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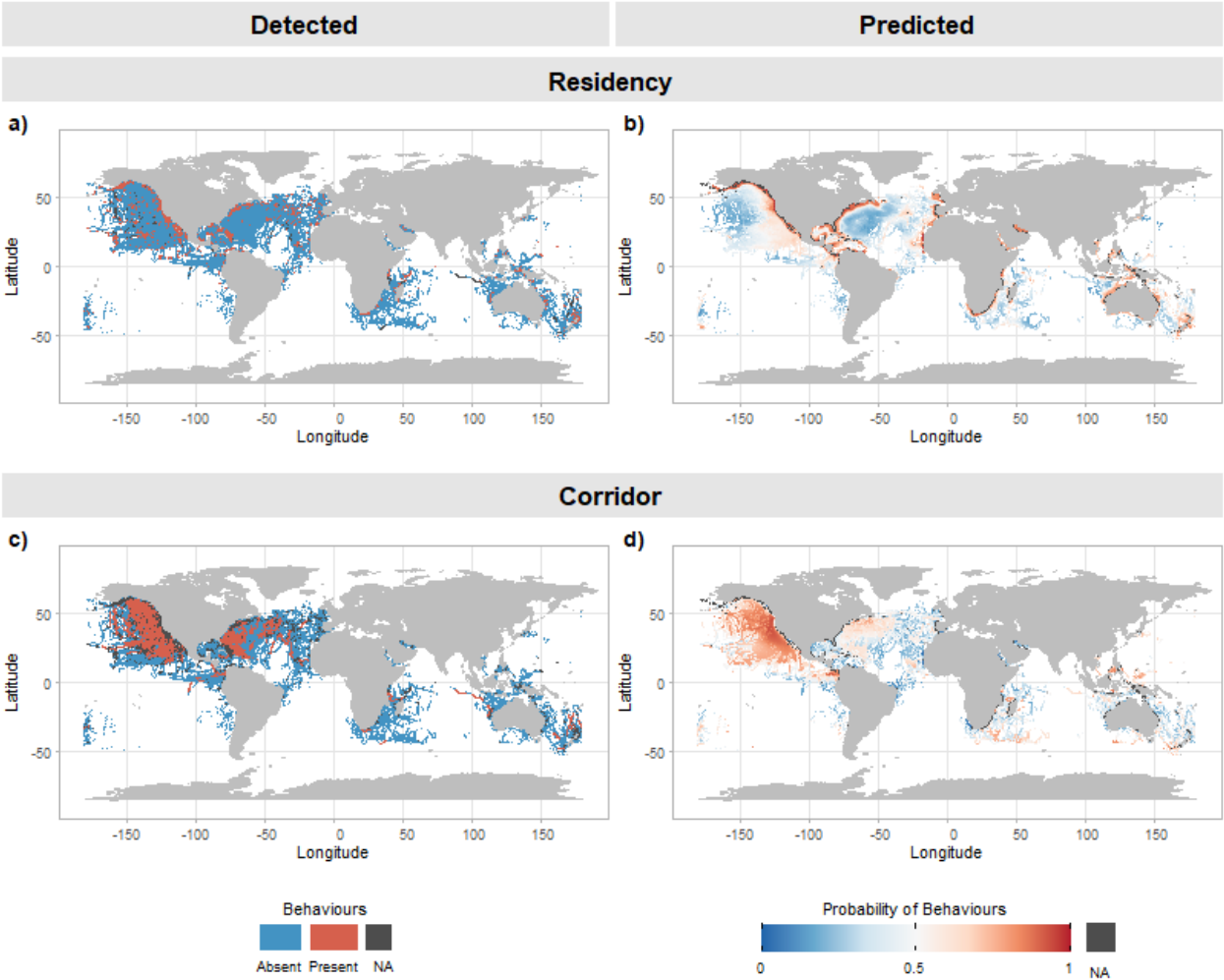
3502 **Fig S16. Sensitivity analyses on the priority areas selected by our optimisation algorithm**

3503 Results obtained when the scores for migratory corridors (S_C) and for residences (S_R) used to run the optimization algorithm were
 3504 changed: (Top left) $S_R=3$ and $S_C=2$ as used throughout the manuscript, (Top right) $S_R=2$ and $S_C=2$, (Bottom left) $S_R=2$ with no score
 3505 for corridors, and (Bottom right) $S_C=2$ with no score for residence areas (and showing the most different results as expected).



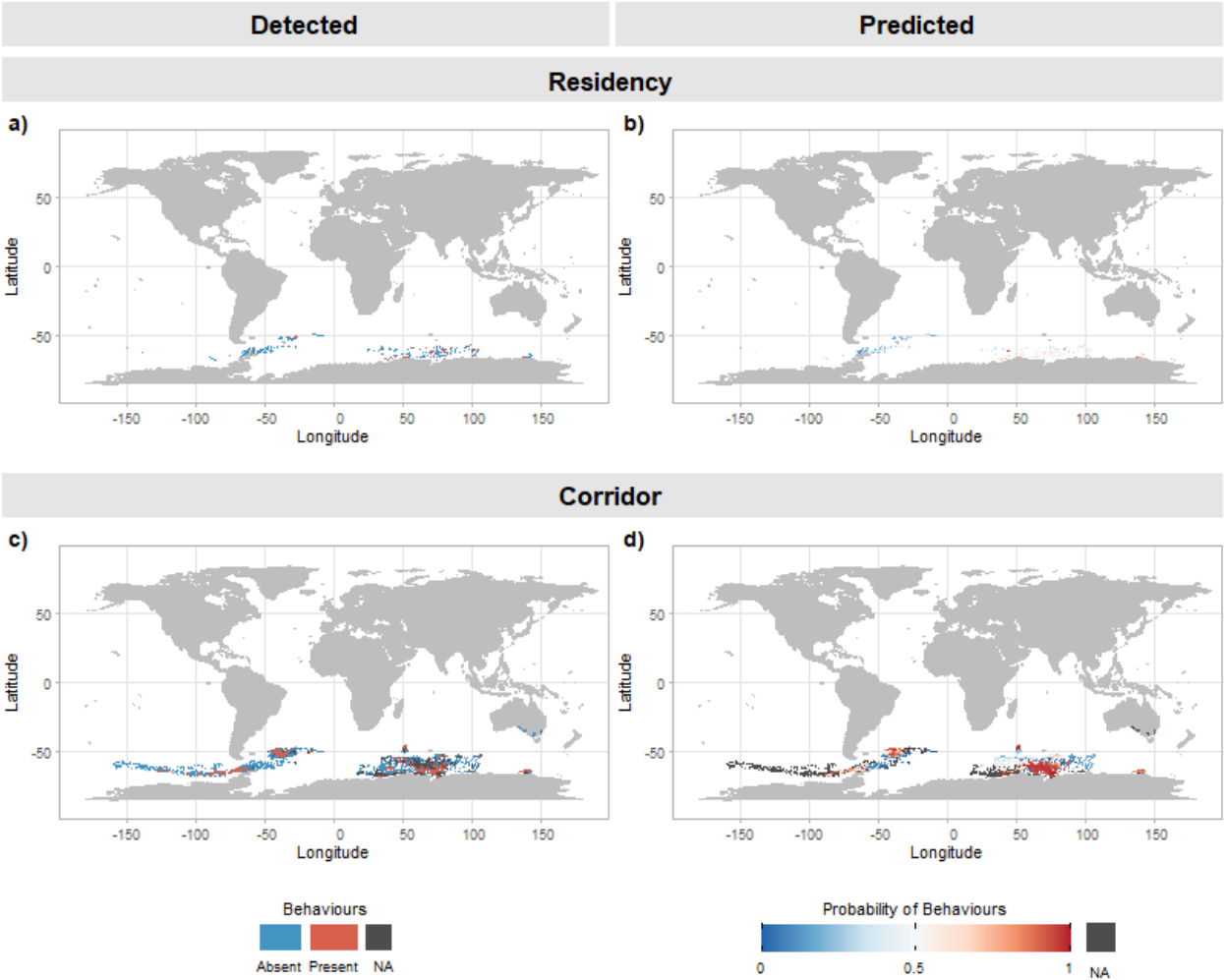


3510 Fishes



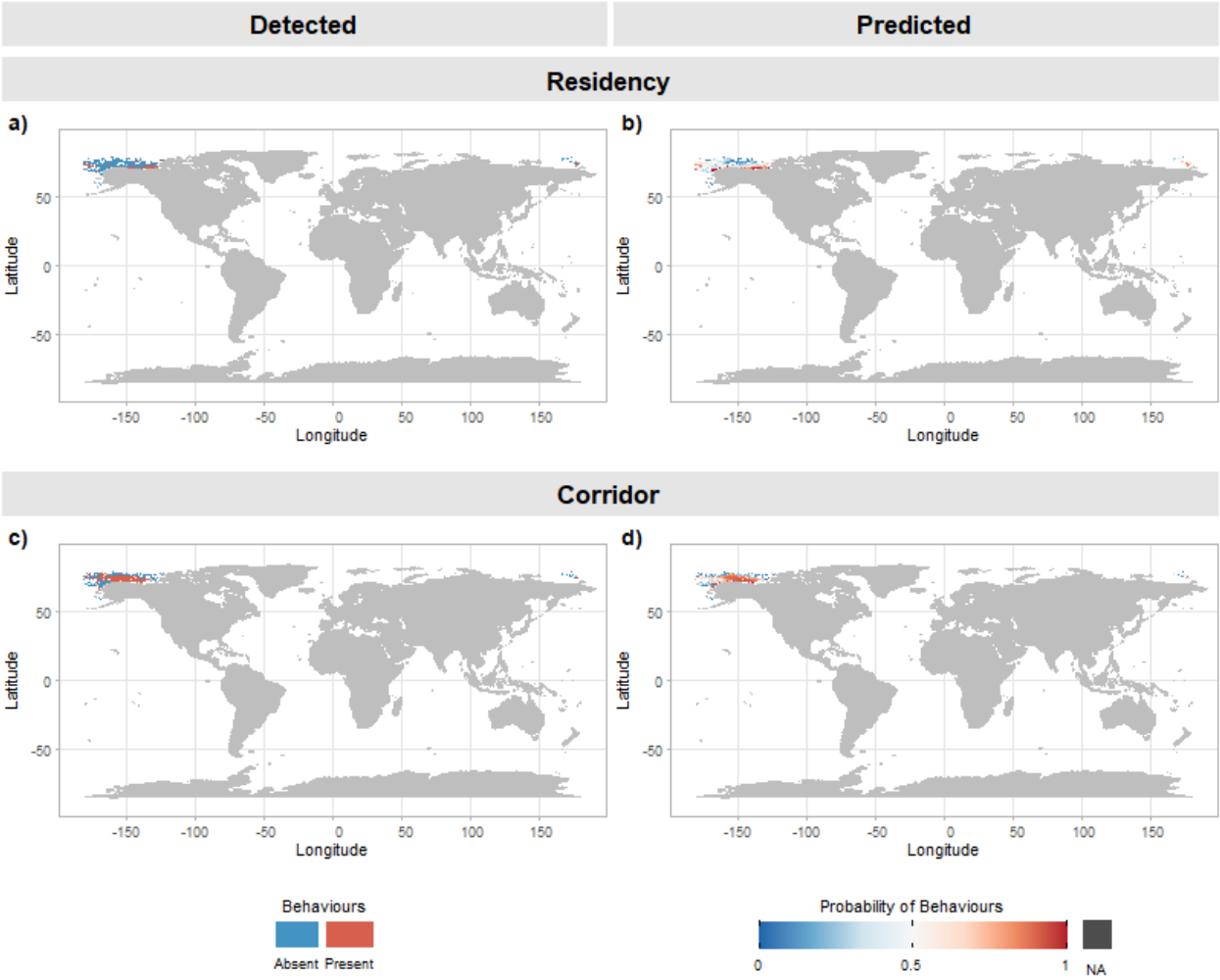
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3512 Penguins



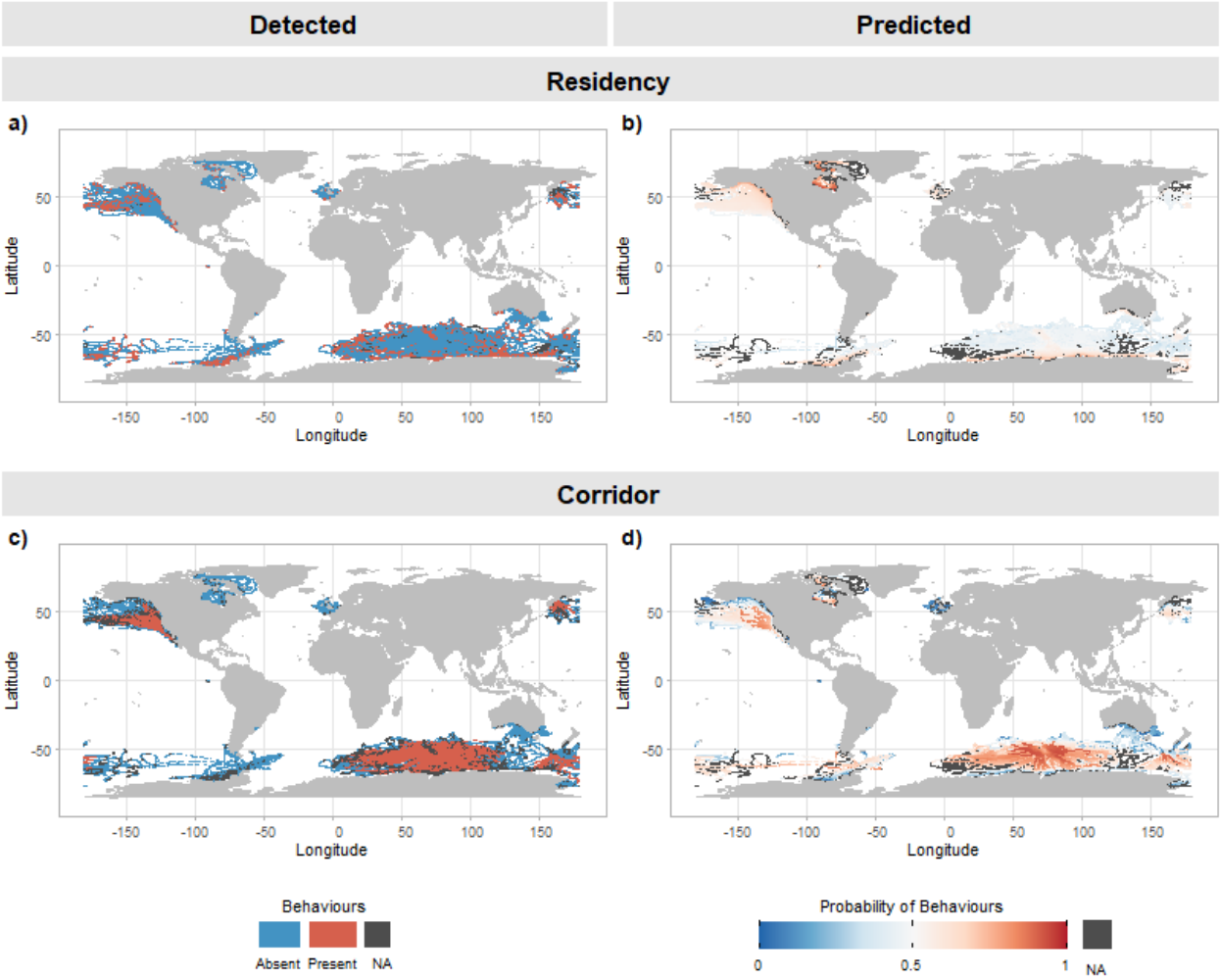
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3514 **Polar bear**



3515

3516 **Seals**



3517

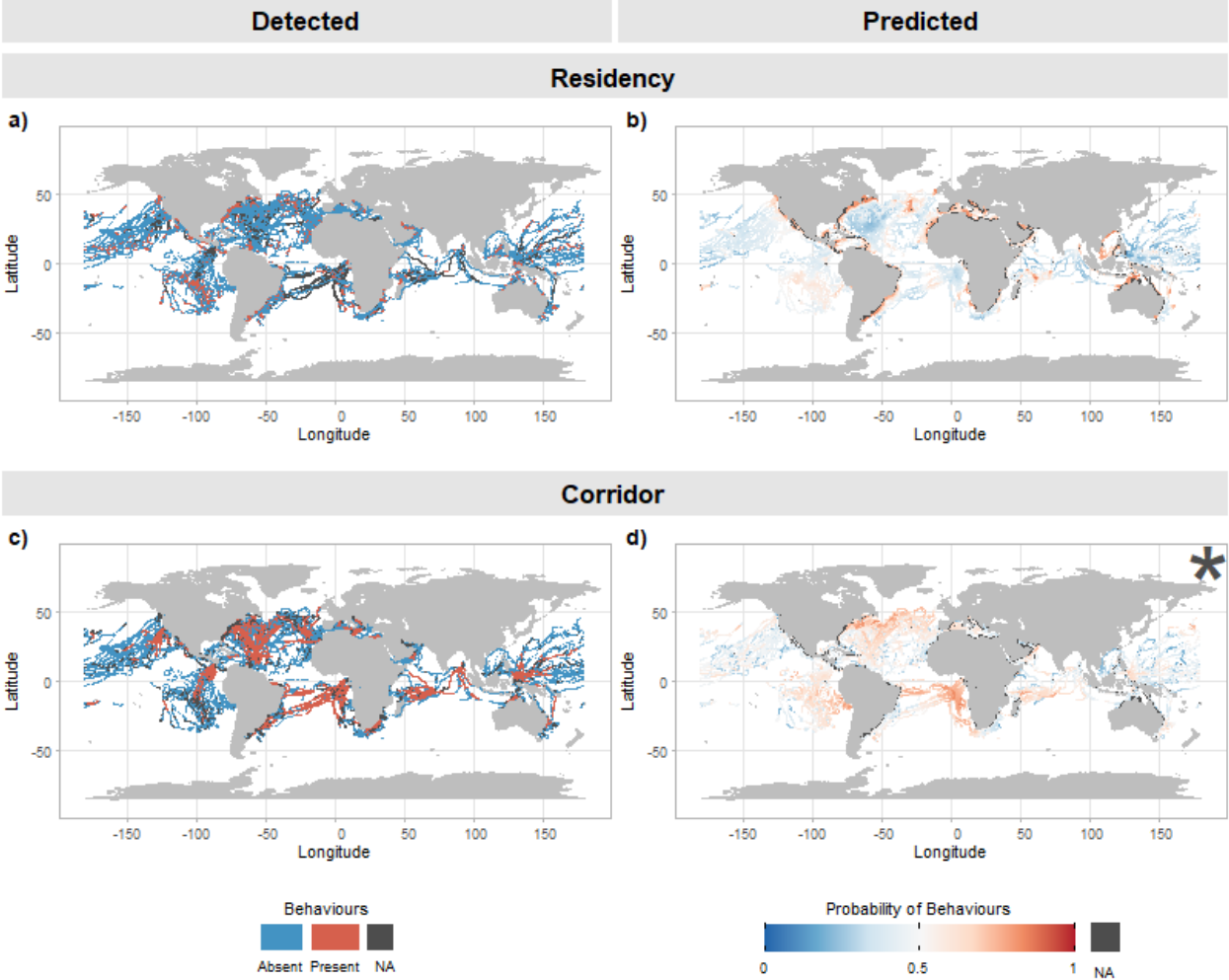


Fig S17. Comparison of detected and predicted areas used for important marine megafauna behaviours

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.