Received: 20 May 2025 | Revised: 3 April 2026 | Accepted: 23 April 2026

DOI: 10.1111/csp2.70314

CONTRIBUTED PAPER

Conservation Science and Practice
A Journal of the Society for Conservation Biology
Open Access
WILEY

Global distribution of aquatic animal telemetry effort reveals geographic biases and opportunities for more inclusive tracking studies

S. T. Kessel[1] | M. Auger-Méthé[2,3] | A. P. Barbosa Martins[4] | S. J. Cooke[5] | A. T. Fisk[6] | A. L. Haley[5] | M. R. Heupel[7] | N. V. Klinard[8] | J. K. Matley[9] | M. L. Piczak[10] | J. A. Robichaud[5] | N. E. Hussey[11]

[1]Conservation Research Department, John G. Shedd Aquarium, Chicago, Illinois, USA

[2]Department of Statistics, University of British Columbia, Vancouver, British Columbia, Canada

[3]Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, British Columbia, Canada

[4]South Australian Research and Development Institute, Adelaide, South Australia, Australia

[5]Fish Ecology and Conservation Physiology Laboratory, Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University of Ottawa, Ontario, Canada

[6]School of Environment, University of Windsor, Windsor, Ontario, Canada

[7]Institute for Marine and Antarctic Studies, University of Tasmania, Battery Point, Tasmania, Australia

[8]Department of Biology, Dalhousie University, Halifax, Nova Scotia, Canada

[9]College of Science and Engineering, Flinders University, Adelaide, South Australia, Australia

[10]Department of Forest and Conservation Sciences, University of British Columbia, Vancouver, British Columbia, Canada

[11]Biological Sciences, University of Windsor, Windsor, Ontario, Canada

Correspondence
S. T. Kessel, Conservation Research Department, John G. Shedd Aquarium, 1200 S. DuSable Lake Shore Drive, Chicago IL 60605, USA.
Email: skessel@sheddaquarium.org

Funding information
Paul M. Angell Family Foundation, Grant/Award Number: PGAFF-02123; Dr. Scholl Foundation, Grant/Award Number: DSF-2023-00029; The Brunswick Foundation Inc, Grant/Award Number: BF-SA-07-23; Kenneth M. Molson Foundation; Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery

Abstract

Aquatic animal telemetry studies (both acoustic and satellite) have been conducted across diverse global ecosystems since their emergence and embrace as a reliable tool in the 1980s. Despite an impressively broad distribution of study sites, important biogeographic regions remain poorly studied. To examine the factors correlated with the global distribution of telemetry studies up to December 31, 2022, we modeled the combined number of acoustic and satellite telemetry studies published in each country using explanatory covariates: mean political stability score, mean total conservation funding, mean population size, total number of citable scientific documents produced, combined length of the freshwater and marine coastlines, number of identified Key Biodiversity Areas (KBA), and whether English was the nation's first language. The most important variables correlated with the distribution of telemetry studies were mean political stability score, conservation funding, number of identified KBAs, and English as a first language. Of 2728 aquatic animal telemetry studies, 75% were conducted in nations with political stability scores from the top three most stable of 11 total categories, increasing to 87% when normalized by number of nations per category group. Only 195 studies (7.2%) fell within the boundaries of areas identified as global priorities for fisheries management and conservation focus, while 543 (19.9%) fell within the boundaries of identified KBAs. Despite the associated difficulties of working in politically unstable regions and the known imbalance in global scientific funding, without focused effort a more complete understanding of global aquatic ecosystems and their connectivity will not be possible. In turn, our ability to effectively counter persistent biodiversity loss will be hindered. Increased efforts to build local capacity in such regions through training, collaboration, accessibility to funding, and fostering awareness of loan schemes for acoustic tracking infrastructure are priorities to ensure electronic tracking tools are accessible to all regions of the globe.

KEYWORDS

acoustic telemetry, ecosystem connectivity, political instability, satellite telemetry, spatial ecology, tracking

1 | INTRODUCTION

In the face of ensuing biodiversity loss associated with the Anthropocene (Steffen et al., 2007), recognition of the need for effective species conservation and management is greater than ever (Johnson et al., 2017). To support evidence-informed conservation and management that benefit species and habitats, there is growing need for ecosystem-level approaches that elucidate large-scale connectivity drivers and patterns (Cooke et al., 2024; Kukkala & Moilanen, 2017; Matley et al., 2022). As such, describing and understanding movement ecology at multiple scales is a key component for developing effective ecosystem-based conservation management measures (Allen & Singh, 2016; Beltran et al., 2025; Brooks et al., 2006; Cowen et al., 2000; Frisk et al., 2014; Katzner & Arlettaz, 2020; Taylor et al., 1993). At the species level, movements and migrations of animals over the course of their lives define the level of habitat dependence and required connectivity for survival and population growth, and thus must be described through investigation (Allen & Singh, 2016; Brooks et al., 2018).

In the past four decades, technological advancements have greatly increased our ability to document the movement ecology of animals at resolutions relevant to policy and management decisions (Brooks et al., 2018; Fraser et al., 2018; Hays et al., 2019; Klinard et al., 2025; Lennox et al., 2017). An early technique used to document species movement ecology was mark-recapture, which required tagging large numbers of individuals and recapturing a proportion of those tagged over the range of their movements (Lettink & Armstrong, 2003). Often, recapture rates were low, and data resolution was reliant on physical encounters, which could be biased by preconceptions of where to target effort. The evolution of telemetry tags (acoustic, radio, and satellite) revolutionized the field of movement ecology in terrestrial (Kays et al., 2015) and aquatic realms (Hussey et al., 2015). Telemetry tags now enable researchers to record movements of individuals at spatial (from sub-meter detailed positioning to trans-oceanic movements) and temporal (from fine scale to longevity now exceeding 10 years for some tag types) resolutions that were previously unattainable or unimaginable, and relevant to long-term and adaptive management decisions (Brooks et al., 2018; Hays et al., 2019; Lowerre-Barbieri et al., 2019). The two most used telemetry modalities in aquatic environments are acoustic and satellite, with a global proliferation of their employment over the past few decades (Hart & Hyrenbach, 2009; Hussey et al., 2015; Matley et al., 2022; Robichaud et al., 2025). Satellite telemetry tags are attached to animals with locational information relayed to satellites from the surface either when an archival tag detaches or an animal with a real-time locational tag breaches the surface, while acoustic tags are most commonly inserted internally and transmit signals to archival receiving stations that are downloaded periodically.

With the proliferation of the use of aquatic telemetry tags, government agencies are increasingly incorporating the resulting data into the development of conservation and management measures (Brooks et al., 2018; Brownscombe et al., 2019; Klinard et al., 2025; Matley-et al., 2022). Despite wide geographical use of satellite and acoustic telemetry, a review by Hussey et al. (2015) indicated gaps in the global distribution of studies, often in developing nations and remote regions (e.g., West Africa, the Indo Pacific and the Polar Regions). This past effort left large areas un-investigated, which may have biased our broader geographical understanding of aquatic animals and their ecosystems (Hughes et al., 2021; Hussey et al., 2015). The past distribution of telemetry effort may also have neglected areas of greatest need for spatial data (Renema et al., 2008). For example, most effort may fall outside of areas identified as global priorities for fisheries management and conservation focus, including the Baja Peninsula/Sea of Cortez, Northwest Africa, Southeast Africa, The Red Sea, and the Indo Pacific (as identified by Worm & Branch, 2012) and identified global Key Biodiversity Areas (KBA; BirdLife International, 2025), where data are urgently needed. Thus, understanding which factors have influenced the distribution of global telemetry studies could identify barriers to its application and help direct future telemetry efforts.

Recent global reviews have assessed elements of study focus relative to the distribution of acoustic (Matley et al., 2022) and satellite (Robichaud et al., 2025) telemetry research. These reviews have highlighted that increasing effort in developing nations and remote regions is a priority for optimizing the application of telemetry to understand aquatic ecosystems and to support effective global conservation. Here, our assessment builds upon the global telemetry database compiled in Hussey et al. (2015) to: (i) define the global distribution of aquatic acoustic and satellite telemetry studies up to December 31, 2022; and (ii) determine the number of studies conducted in areas identified as global priorities for fisheries management and conservation focus, and within KBAs; we then (iii) identify which factors have been the most important in shaping the observed distribution of telemetry effort; and (iv) identify geographical regions of greatest need for future focus.

2 | METHODS

2.1 | Identification of studies and extraction of study locations

Although other telemetric tools are available, such as very high frequency radio telemetry (freshwater only) and passive integrated transponders, consistent with Hussey et al. (2015), here we focus on the two most widely used methods in aquatic ecosystems: acoustic and satellite telemetry. Data for the past global distribution of telemetry studies were obtained from Hussey et al. (2015) and then updated. In brief, the original literature search in Hussey et al. (2015) was conducted to identify existing peer-reviewed acoustic and satellite telemetry studies published up to December 31, 2013. For acoustic telemetry, the search terms "acoustic." "ultrasonic," and "sonic" followed by each of the words: "telemetry," "tracking," and "tag" were used in an ISI Web of Science® search. For pop-off and positional satellite telemetry, the search terms "satellite," "PSAT," and "SPOT" followed by each of the words: "telemetry," "tracking," and "tag," were used. A second literature search was conducted in February 2023 to identify acoustic and satellite telemetry studies from 2014 to 2022. For acoustic telemetry, TrackdAT (www.trackdat.org), an open-source metadata repository of peer-reviewed acoustic telemetry research was used (Matley et al., 2024). TrackdAT used the following search term in ISI Web of Science®: ALL = ("Acoustic telemetry" OR "Acoustic tracking" OR "Passive telemetry" OR "Acoustic transmit*" OR "Acoustic receiver*" OR "Acoustic tag*" OR "Ultrasonic tracking" OR "Ultrasonic telemetry" OR "Fish track*"). For satellite telemetry, the following search string: "satellite telemetry" OR "PSAT" OR "SPOT" AND "telemetry" OR "tracking" AND ("aquatic" OR "marine") NOT "acoustic" was used. For both searches, study locations (latitude and longitude) were extracted directly from the text. Locations associated with acoustic telemetry studies represent the center point of the receiver array, and release location of animals were used for satellite telemetry papers. Where multiple release locations were presented per study, within a 100 km radius, an average latitude and longitude were calculated.

2.2 | Visualization and categorization

Study locations extracted from each paper were plotted in ArcGIS Pro®. Polygons were created for the boundaries of the five areas (Baja Peninsula/Sea of Cortez, Northwest Africa, Southeast Africa, The Red Sea, and the Indo Pacific) identified as global priorities for fisheries management and conservation focus, as defined by Worm and Branch (2012). These priority areas were designated due to "low management effectiveness, high species richness, and rapidly increasing catches" (Worm & Branch, 2012). Established boundaries for marine and freshwater KBAs (BirdLife International, 2025), were also imported into ArcGIS Pro® and overlain on telemetry study locations. KBAs were defined by a partnership of multiple conservation focused organizations as "globally significant sites for conservation—crucial places on our planet where unique species and ecosystems occur in important numbers or extent" (BirdLife International, 2025). The number of studies conducted inside the boundary of each important area (priority areas and KBAs), both by each modality (acoustic and satellite) and combined, were identified using the "Select by Location" function and then calculated as a percentage of the total. Additionally, countries were assigned to one of 11 categories based on equal intervals of political score (Foreign Policy, 2023), consistent with the ranking system of the Fragile States Index, with group 1 the most stable and 11 the least. For consistency of display, countries were also assigned to 11 categories based on orders of magnitude of annual conservation funding in US$ (Waldron et al., 2013). For both, the number of telemetry studies in each was normalized by the number of countries in each of the 11 groups. Global study locations of both acoustic and satellite telemetry were plotted against graduated colors for each country based on both their political stability score and mean annual conservation funding. Studies were then assigned to six taxonomic animal groups based on the focus species of each study. These were bird (flightless only), crustacean, elasmobranch, marine mammal, reptile, teleost, and "other" (which included amphibians, bivalves, cephalopods, cnidarians, echinoderms, and gastropods). The decision to only consider flightless birds (penguins) was made as we felt that the study of flighted aquatic-associated birds (e.g., waterfowl) aligns more closely with the broader field of avian telemetry, which has different associated influences and challenges. The study locations for each taxonomic group were then presented for acoustic and satellite modalities to explore variation in geographic trends of investigation between taxa and technology used.

2.3 | Analysis

To examine which factors were important for predicting the past global distribution of telemetry studies, the combined number of acoustic and satellite telemetry studies published per focus country (i.e., country in which the study was based) were modeled with the following explanatory covariates: mean political stability score, mean total conservation funding, mean population size, the number of KBAs designated in each country, total number of citable scientific documents produced, combined length of the freshwater and marine coastlines, and whether English was the nation's first language (see below for sources). Political stability was chosen as less-stable nations can be more challenging to conduct research in, both in terms of logistics and safety (Sluka, 2020). Ease of access to funding in each country is known to be a key factor that influences the ability to conduct research (Waldron et al., 2013). Population size was included as it can directly contribute to scientific output potential (Dolgonosov, 2016). KBAs were chosen to identify the presence of recognized international conservation priorities in each country (i.e., an identified need for focused investigation). The number of citable scientific documents produced by country was included to identify potential disparity between general scientific output and aquatic telemetry publication outputs. Coastline length was included as a proxy for aquatic telemetry study opportunity (i.e., fewer aquatic environments would likely correlate with less studies). Finally, English as a first language was included to account for the bias of the higher proportion of English language journals included in international literature databases such as ISI Web of Science (Ferguson & Carmen Plo, 2011) and the historical dominance of this language in the scientific literature. The modeling process was then repeated for defined taxonomic groups that had >350 combined publications representing >550 unique national study locations (i.e., some publications had multiple study locations in multiple countries)—teleost, elasmobranch, and marine mammal—to determine the influence of the above defined covariates on the geographic distribution of telemetry study effort by taxa.

Mean political stability score was obtained from the Fragile States Index, created by the Fund for Peace and published by Foreign Policy (2023), and data were an average over the period 2006–2022, with 2006 being the earliest year scores were available. Mean total conservation spending by country (in US$) for the period 2001–2008 was obtained from Waldron et al. (2013), and is based on global terrestrial mammal conservation funding. While the timeframe of data available only covers a portion of the assessed period for telemetry studies, and the focus of funding was not for aquatic species, it was deemed the most representative available proxy for conservation funding based on the fact that: (i) it overlapped with our assessed period, (ii) it provides an average value for total conservation funding per year for each country, and (iii) it is representative of a country's overall willingness and ability to invest resources in conservation research, assuming similar investment in terrestrial and aquatic realms. Mean country population size was obtained from the World Bank Archives (2023) for the assessed period 1986–2022. The number of citable scientific documents was obtained from the Scimago Journal & Country Rank (Scimago, 2023). Total marine coastline lengths (km) for each country were obtained from the Central Intelligence Agency (CIA) World Factbook

(CIA, 2016a). Freshwater coastline lengths (km) by country were obtained from the DeLorme 2015 Data Catalogue—Hydro Polygons (DeLorme, 2016), where all water bodies met or exceeded Shuttle Radar Topography Mission (SRTM) water body capture criteria (SRTM Data Editing Rules, v2, March 12, 2003). Hydro polygons of waterbodies were plotted in ArcMap Pro® then isolated by national borders. Marine and freshwater coastlines were then combined to provide one distance (km) measure per country. Countries that use English as a first language were also determined from the CIA World Factbook (CIA, 2016b).

All covariates were non-transformed, with the exception of mean total conservation spending which was log transformed ($\log(x + 0.0001)$) given preliminary analyses indicated that the order of magnitude of conservation spending better explained the number of telemetry papers published when compared with untransformed data. Mean gross domestic product (GDP) per capita was initially included but was highly correlated with mean political stability score ($r = -0.79$), and consequently was excluded. All other covariates demonstrated low correlation values ($r \leq |0.48|$). For the final model runs, only countries with complete data for all covariates were included (see Appendix S1 for a list of excluded countries).

As 36.3% (70/193) of the countries investigated had no peer-reviewed aquatic telemetry publications (Appendix S2), resulting in frequent zeros and overdispersion, we adopted a zero-altered negative binomial (ZANB) model (Zuur et al., 2011). A ZANB is a consecutive two-step model that first considers the presence or absence of a publication per country and then analyses the occurrence data per country with a count model (Zuur et al., 2011). The ZANB model was implemented using the function "hurdle" within the R package "pscl" (Zeileis et al. 2008). The length of coastline was used in step one of the ZANB to model the presence of publications and all possible combinations were used in step two to model the count of publications. We compared the models using Akaike's Information Criteria (AIC) and considered models with ΔAIC <2 of the model with the lowest AIC value to be our top models while considering potential uninformative parameters (Burnham & Anderson, 2004; Sutherland et al., 2023).

3 | RESULTS

The literature searches identified 1636 acoustic and 1092 satellite telemetry peer reviewed publications prior to and including December 31, 2022. The top 10 countries with the most combined telemetry studies were, in descending order, United States, Canada, Australia, United Kingdom, Norway, France, Mexico, Japan, Antarctica, and South Africa (Table 1a). Taxonomically, the animal groups with the most combined studies were, from most to least, teleost, elasmobranch, marine mammal, reptile, bird (flightless), crustacean, and other (Table 1b).

TABLE 1a Top 10 countries with the most combined telemetry studies; and (b) number of telemetry studies by taxonomic animal group and number of countries they were focused in ("Other" includes amphibians, bivalves, cephalopods, cnidarians, echinoderms, and gastropods).

(a)

Rank	Country	Acoustic	Satellite	Total
1	United States	593	366	959
2	Canada	229	135	364
3	Australia	202	88	290
4	United Kingdom	68	79	147
5	Norway	91	22	113
6	France	50	43	93
7	Mexico	15	63	78
8	Japan	49	21	70
9	Antarctica	4	61	65
10	South Africa	34	29	63

(b)

Animal group	Acoustic	Satellite	Total	Countries
Teleost	1230	149	1379	69
Elasmobranch	308	203	511	59
Marine mammal	9	377	386	47
Reptile	30	299	329	83
Bird (flightless)	0	57	57	12
Crustacean	36	0	36	9
Other	23	7	30	11

Only 195 of 2728 identified studies (7.2%) fell within the boundaries of areas identified as global priorities for fisheries management and conservation focus (Baja Peninsula/Sea of Cortez, Northwest Africa, Southeast Africa, The Red Sea, and the Indo Pacific; Figure 1), while 543 (19.9%) fell within the boundaries of identified KBAs. The majority of studies were conducted in countries ranked in the three most politically stable and highest conservation funding categories (87% and 95%, respectively) when normalized by category group size (Figures 2 and 3). Relative to political stability, acoustic telemetry studies were conducted in nations from

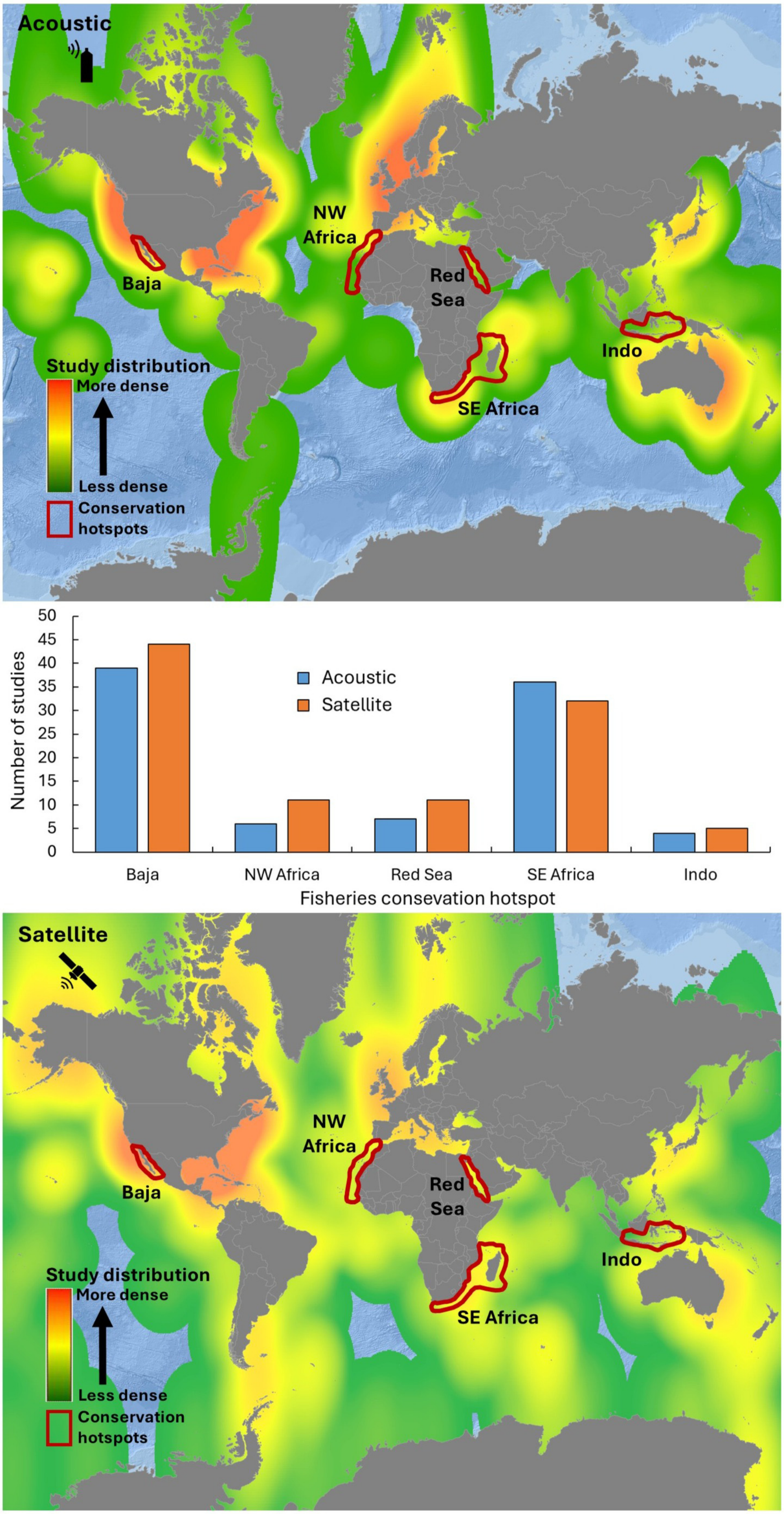

FIGURE 1 Distribution of global aquatic animal telemetry effort (density) relative to the five global priority areas for fisheries management and conservation focus, as identified by Worm and Branch (2012). Priority area boundaries were designated based on low management effectiveness, high species richness and rapidly increasing fisheries catches. Maps show published studies (up to December 31, 2022) as kernel density plots, relative to priority area boundaries, for acoustic (top) and satellite (bottom) animal telemetry. Bar plot (center) shows the number of telemetry studies that fall within the boundaries of each priority area for acoustic (blue) and satellite (orange) telemetry.

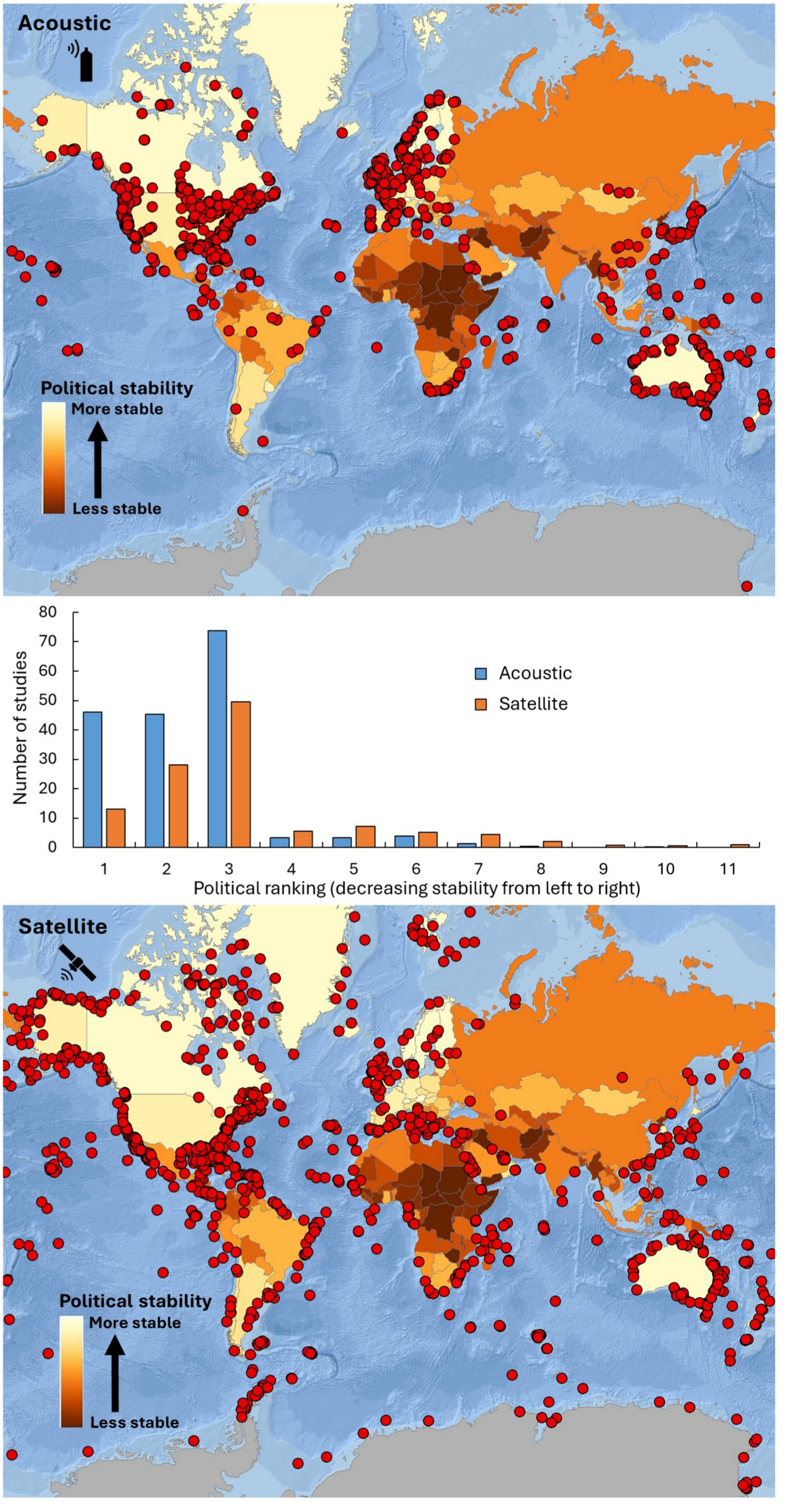

FIGURE 2 Distribution of global aquatic animal telemetry effort (locations) relative to global national political stability defined by the Fragile States Index (foreignpolicy.com). Maps show published telemetry study (up to December 31, 2022) locations (red dots) relative to global national political stability for acoustic (top) and satellite (bottom) animal telemetry. Bar plot (center) shows the number of telemetry studies, normalized by number of countries represented in each political stability category group, that fall within the national boundaries of countries categorized in each stability ranking (1 most stable–11 least stable) for acoustic (blue) and satellite (orange) telemetry studies.

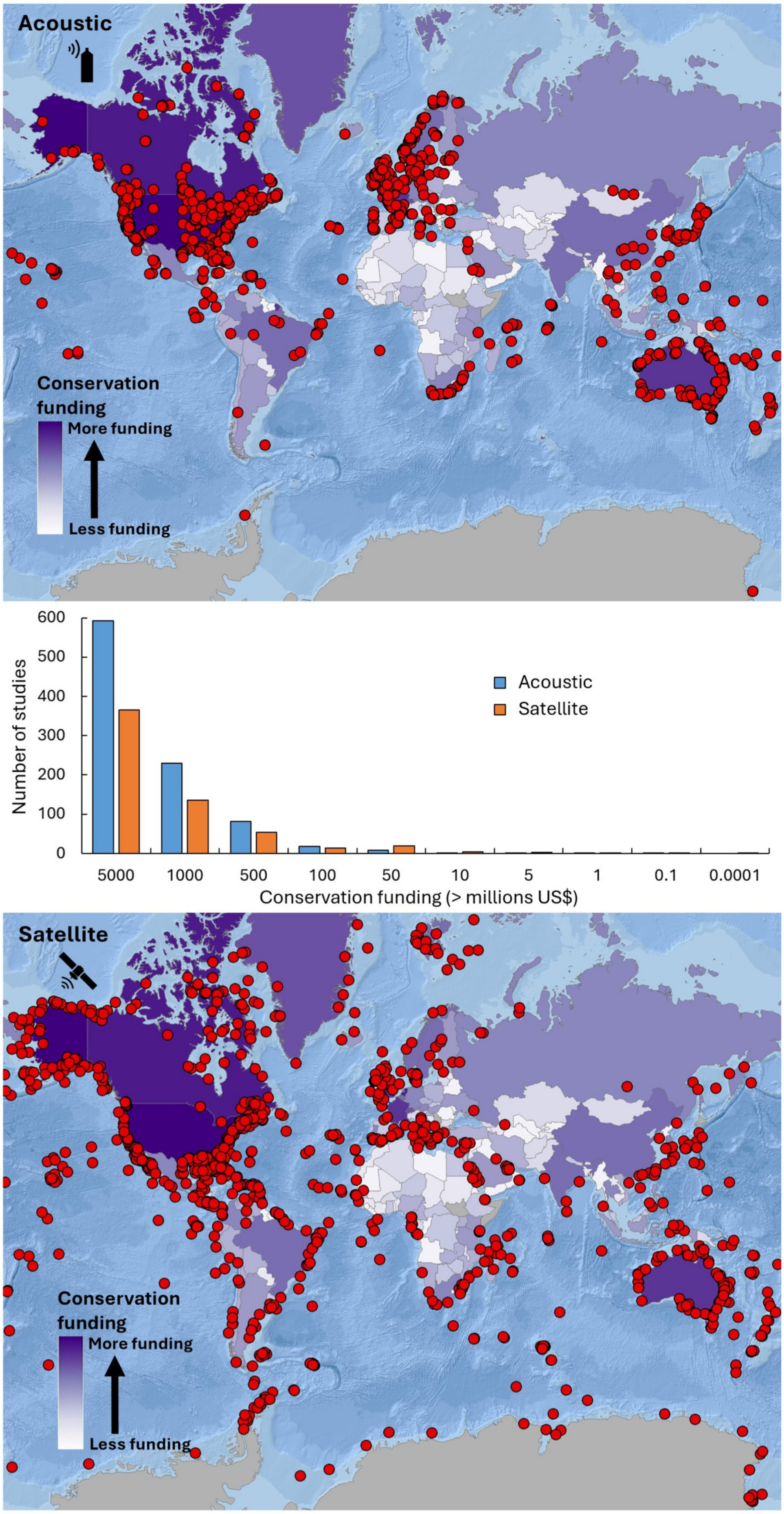

FIGURE 3 Distribution of global aquatic animal telemetry effort (locations) relative to national annual conservation funding as calculated by Waldron et al. (2013). Maps show published telemetry study (up to December 31, 2022) locations (red dots) relative to national annual conservation funding for acoustic (top) and satellite (bottom) animal telemetry. Bar plot (center) shows the number of telemetry studies, normalized by the number of countries represented in each spending category, that fall within the national boundaries of countries categorized in each funding bracket for acoustic (blue) and satellite (orange) telemetry studies.

TABLE 2 ΔAIC and Akaike weights for the 10 best models and for the intercept model (no covariate).

Covariates	Log	*k*	ΔAIC	*w*
PoliticalStability + **KBA** + **ConservationFunding** + **English**	−428.2	8	0	0.34
PoliticalStability + **KBA** + **ConservationFunding** + **English** + Population	−427.9	9	1.36	0.17
PoliticalStability + **KBA** + **ConservationFunding** + **English** + Documents	−428.2	9	1.95	0.13
PoliticalStability + **KBA** + **ConservationFunding**	−430.3	7	2.10	0.12
PoliticalStability + **KBA** + **ConservationFunding** + Population	−429.7	8	2.98	0.08
PoliticalStability + **KBA** + **ConservationFunding** + Population + **English** + Documents	−427.9	10	3.34	0.05
PoliticalStability + **KBA** + **ConservationFunding** + Documents	−430.2	8	4.02	0.03
PoliticalStability + **KBA** + **ConservationFunding** + Population + Documents	−429.7	9	4.91	<0.01
PoliticalStability + **KBA**	−434.5	6	9.03	<0.01
PoliticalStability + **KBA** + **English**	−433.8	7	9.29	<0.01
Intercept	−480.2	4	95.91	<0.01

Note: All models are a zero-altered negative binomial (ZANB) form, with length of coastline included as a hurdle covariate (used to determine the presence of publications). The covariates presented are those explored to explain the count of publications. See online appendix for the full list of models (Appendix S3). The covariates found in the best fit model (Table 3) are bolded throughout.

TABLE 3 Parameters of the best fit zero-altered negative binomial (ZANB) model.

	Estimate	Std. error	*z* value	*p*-value
Zero hurdle model (binomial with logit link)				
Intercept	0.05	0.20	0.28	.78
Coastlines	0.77	0.29	2.61	<.01
Count model (truncated negative binomial with log link)				
Intercept	2.57	0.46	5.55	<.01
PoliticalStability	−0.02	0.01	−3.93	<.01
ConservationFunding	0.20	0.06	3.43	<.01
KBA	<0.01	<0.01	3.23	<.01
English = Y	0.65	0.33	1.99	.05
Log(theta)	−0.12	0.23	−0.49	.63

Note: This model includes length of coastline as a hurdle covariate (used to determine the presence of publications) and three covariates for the count of publications.

categories 1–10 and satellite telemetry studies from categories 1 to 11 (Figure 2).

The top three models according to AIC contained the variables: political stability, conservation funding, number of KBA, and English as a first language. The models with ΔAIC <2 were the only models that had these four covariates and the sum of their Akaike weights was 0.64 (Table 2). Among these models, the best fit model was the most parsimonious, with length of coastline as a hurdle covariate used to determine the presence of non-zero values (i.e., presence of publications). Consequently, the probability of having telemetry studies increased with increasing length of coastline in addition to higher conservation spending, number of KBAs, and English as a first language (Table 3). In contrast, the number of publications decreased with increasing political instability score (and therefore decreasing correlated GDP).

When considering taxonomic groups with publications >350 and >550 locations, the most important variables influencing the past distribution of telemetry studies on elasmobranchs were conservation funding and English as a first language, with the best fit model being the most parsimonious. Identical to the model including all taxonomic groups, length of coastline was included as a hurdle covariate to determine the presence of non-zero values. However, for elasmobranchs, length of coastline did not have a significant effect in the model on the number of telemetry studies, while both an increase in conservation spending and English as a first language had a positive effect (Table 4). For teleosts, the top model included political stability, conservation funding, English as a first language, and the number of KBAs. However, the most parsimonious model was the second model including only political stability and number of KBAs.

TABLE 4 ΔAIC and Akaike weights for the top models out of 65 total (ΔAIC< 2) and the intercept model (no covariate) for animal groups with publications >350 and >550 locations.

Covariates	Log	*k*	ΔAIC	*w*
Elasmobranch				
ConservationFunding + **English**	−225	6	0	0.11
ConservationFunding + **English** + Population	−224.3	7	0.71	0.08
ConservationFunding + **English** + KBA + Population	−223.4	8	0.91	0.07
PoliticalStability + **ConservationFunding** + **English**	−224.6	7	1.13	0.06
ConservationFunding + **English** + KBA	−224.6	7	1.17	0.06
ConservationFunding + **English** + Documents	−224.9	7	1.89	0.04
Intercept	*−238.9*	*4*	*23.77*	*<0.01*
Teleost				
PoliticalStability + ConservationFunding + English + **KBA**	−270.6	8	0	0.13
PoliticalStability + **KBA**	−272.7	6	0.19	0.12
PoliticalStability + English + **KBA**	−271.8	7	0.53	0.1
PoliticalStability + ConservationFunding + **KBA**	−272.1	7	1.05	0.08
PoliticalStability + ConservationFunding + English + Documents	−271.4	8	1.63	0.06
PoliticalStability + ConservationFunding + English + **KBA** + Documents	−224.3	9	1.78	0.05
PoliticalStability + ConservationFunding + English + **KBA** + Population	−223.4	9	1.99	0.05
Intercept	*−296.8*	*4*	*44.45*	*<0.01*
Marine Mammal				
PoliticalStability + **ConservationFunding** + Population + **KBA**	−178.3	8	0	0.12
PoliticalStability + Population + **KBA**	−179.4	7	0.16	0.11
PoliticalStability + **ConservationFunding** + Documents + **KBA**	−178.5	8	0.37	0.1
PoliticalStability + **ConservationFunding** + **KBA**	−179.5	7	0.51	0.09
PoliticalStability + **ConservationFunding** + English + Documents + **KBA**	−178	9	1.37	0.06
ConservationFunding + English + Population + **KBA**	−179	8	1.37	0.06
PoliticalStability + **ConservationFunding** + Population + Documents + **KBA**	−178	9	1.39	0.06
PoliticalStability + **ConservationFunding** + Population + English + **KBA**	−178.1	9	1.64	0.05
ConservationFunding + Population + Documents + **KBA**	−179.2	8	1.76	0.05
PoliticalStability + **ConservationFunding** + English + **KBA**	−179.3	8	1.93	0.05
Intercept	*−203.7*	*4*	*42.87*	*<0.01*

Note: All models are a zero-altered negative binomial (ZANB) form, with length of coastline included as a hurdle covariate (used to determine the presence of publications). The covariates presented are those explored to explain the count of publications. The covariates found in the best fit model (Table 5) are bolded throughout.

Further, both of those covariates were included in all the top models ranked according to AIC and were the only covariates that had a significant effect on the number of telemetry studies. The hurdle covariate of length of coastline was included once again. The number of telemetry studies on teleosts increased with increasing length of coastline in addition to number of KBAs while the number of publications decreased with increasing political instability score (Table 4). Finally, for marine mammals, conservation funding, political stability, and number of KBAs were included in the top model according to AIC, with population size included in the top two models. Once again, the number of telemetry studies increased with increasing length of coastline, along with higher conservation spending and number of KBAs, while the number of publications decreased with increasing political instability score (Table 4).

When considering the global distribution of telemetry studies by taxonomic group, distinct patterns of effort were apparent (Figure 4). Teleost studies were widely distributed across the largest geographic area, both marine and freshwater, with the exception of the Southern

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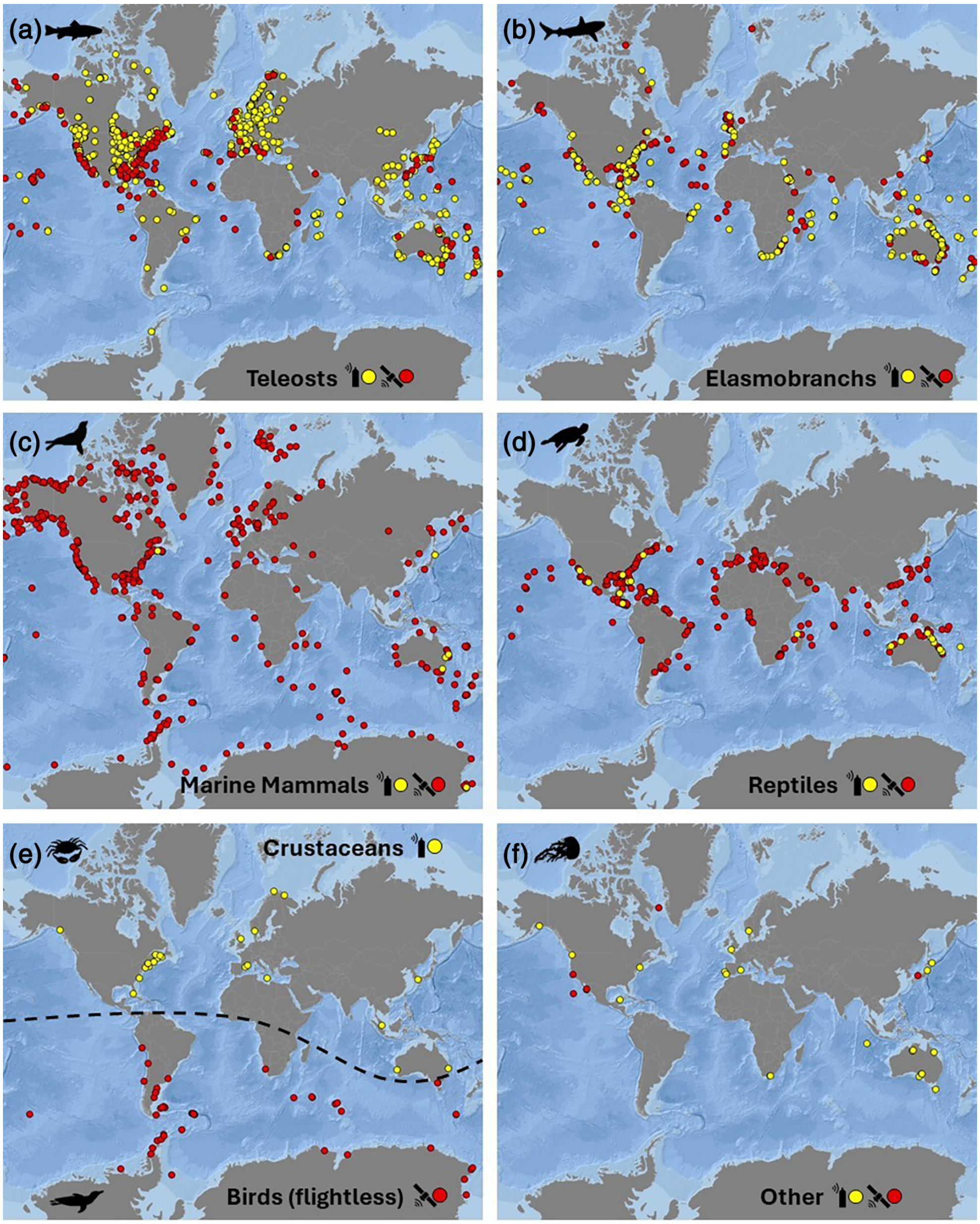

FIGURE 4 Distribution of global aquatic animal telemetry effort (locations) by taxonomic animal group (in order of total number of studies); (a) Teleosts; (b) Elasmobranchs; (c) Marine Mammals; (d) Reptiles; (e) Crustaceans (acoustic only above dashed line) and Birds (flightless; satellite only below dashed line); and (f) Other (amphibians, bivalves, cephalopods, cnidarians, echinoderms, and gastropods). Yellow dots represent acoustic telemetry studies and red dots satellite telemetry studies.

Ocean (Figure 4a). Elasmobranch studies were primarily distributed from temperate to tropical lattitudes, with some representation in the Arctic region (Figure 4b). Similar to teleosts, no studies were undertaken in the Southern Ocean. Marine mammal studies had the widest distribution in the marine environment, particularly from a latitudinal perspective (Figure 4c). Reptile studies were distributed from temperate to tropical latitudes, with notable representation in the Mediterranean (Figure 4d). Flightless bird studies were restricted to southern latitudes, including the Southern Ocean, while crustacean studies were predominantly focused in North America and Europe, with only a few conducted in Asia and Australasia (Figure 4e). Other taxa, which were varied, were sparsely distributed across multiple continents (Figure 4f).

4 | DISCUSSION

Over the past four decades, aquatic animal telemetry studies have been conducted across an impressive global distribution, focused on diverse taxa and ecosystems. While this extensive effort is commendable, the distribution of aquatic telemetry studies has been biased towards politically stable countries, with high GDP and annual conservation funding, and English as a first language. Overall, satellite telemetry studies were more widely

TABLE 5 Parameters of the best fit zero-altered negative binomial (ZANB) model for each animal group.

	Estimate	Std. error	*z* value	*p*-value
Elasmobranch				
Zero hurdle model (binomial with logit link)				
Intercept	−0.95	0.17	−5.48	<.01
Coastlines	<0.01	<0.01	1.25	.21
Count model (truncated negative binomial with log link)				
Intercept	−0.40	0.74	−0.54	.59
ConservationFunding	0.29	0.09	3.36	<.01
English = Y	1.83	0.61	3.02	<.01
Log(theta)	−1.38	0.97	−1.43	.15
Teleost				
Zero hurdle model (binomial with logit link)				
Intercept	−0.89	0.18	−4.86	<.01
Coastlines	0.16	0.07	2.36	.02
Count model (truncated negative binomial with log link)				
Intercept	1.96	0.66	2.95	<.01
PoliticalStability	−0.03	0.01	−3.44	<.01
ConservationFunding	0.17	0.11	1.64	.10
KBA	<0.01	<0.01	2.11	.04
English = Y	0.85	0.43	1.75	.08
Log(theta)	−0.52	0.44	−1.18	.24
Marine mammal				
Zero hurdle model (binomial with logit link)				
Intercept	−1.61	0.22	−7.21	<.01
Coastlines	0.28	0.10	2.92	<.01
Count model (truncated negative binomial with log link)				
Intercept	−0.43	0.64	−0.68	.50
PoliticalStability	−0.01	0.01	−1.46	.14
ConservationFunding	0.52	0.12	4.79	<.01
Population	−0.002	< 0.01	−1.52	.13
KBA	<0.01	<0.01	3.02	<.01
Log(theta)	0.82	0.44	1.85	.06

Note: This model includes length of coastline as a hurdle covariate (used to determine the presence of publications) and covariates for the count of publications.

distributed than acoustic telemetry studies both in remote regions and politically less stable nations, but limited overall effort has been conducted in areas identified as global priorities for fisheries management and conservation focus. Here, we discuss potential factors influencing the distribution of telemetry, areas of greatest need for future investigation, and approaches required to effectively facilitate the expansion of research efforts moving forward.

We determined that politically stable countries with high annual conservation funding had the greatest number of studies using telemetry; for example, USA, Canada, Australia, and the UK together accounted for 64.5% of all telemetry effort. This is consistent with Hughes et al.'s (2021) investigation of how sampling biases shape our view of the natural world, which revealed that 79% of all global biodiversity information is produced from only 10 countries, and 37% from the USA alone. Moreover, here, the top 10 countries account for 82.2% of telemetry effort, leaving only 17.8% of effort distributed among the remaining 183 or 94.8% of countries. This bias towards stable countries with high funding, however, is to be expected given they are most likely to prioritize research focused on their own resources, studies are dependent on the availability of funding (Waldron et al., 2013), and studies are more easily facilitated in politically stable regions. Facilitation refers to the ease of permitting (related to extant and transparent governance structures), transfer/import of field equipment, the relative safety of researchers in the field, and a period of prolonged political stability to allow a study to be completed (Sluka, 2020). Specific to facilitation, politically stable regions are more desirable destinations for research studies and associated funding agencies, which has likely led to a globally disproportionate number of studies conducted in these countries.

Challenges associated with working in logistically difficult regions can be mitigated through partnering with local scientists and prioritizing capacity sharing (Adame, 2021). Research groups with interest and capability of extending telemetry research beyond their jurisdictions should seek reciprocal partnerships with institutions in data-poor regions, including academic, government, and non-profit sectors whenever possible. Capacity sharing can include the exchange of scientific skills, bolstering availability of scientific equipment/infrastructure, and establishment of long-lasting sustainable partnerships with defined short- and long-term goals. This approach has been shown not only to facilitate the successful execution of studies, but also to establish lasting self-perpetuating research legacy in data poor regions (Chin et al., 2019; Wagner et al., 2001). It is also an important approach to avoid the increasingly recognized ethical inappropriateness of "parachute/helicopter science" (Adame, 2021; Stefanoudis et al., 2021) by ensuring that projects involve the appropriate actors from initiation, apply suitable methods and approaches, attentively consider local contexts and ethics, and provide fair and equitable benefit sharing, thus creating opportunities to have agency over the conservation and management of local resources (Asase et al., 2022; Chin et al., 2019; de Vos & Schwartz, 2022). Grant applications for such regions will need to set aside funding to increase in-country capacity through allocations such as equipment and workshops with local stakeholders, possibly subsidized through relevant equipment manufacturers and through existing networks (e.g., Ocean Tracking Network) that facilitate equipment loans (Iverson et al., 2019).

Defining the global distribution of aquatic animal telemetry studies revealed an impressive spread that encompasses all continents and oceans; however, important areas remain largely overlooked. All five areas identified as global priorities for fisheries management and conservation focus (Worm & Branch, 2012) have received limited telemetry-focused research. Despite relatively close proximity to inhabited landmasses, the reason for a lack of focus in these five regions is likely political instability. Factors including challenges in obtaining research permits, logistical difficulties including embargos, and personnel safety (Casadevall & Fang, 2024; Hussey, 2014) can contribute to an active avoidance of these areas of conservation priority. It can be argued, however, that these neglected regions are in greatest need of focused research efforts. This is particularly true for the Indo-Pacific priority area, a global aquatic species richness hotspot (Rabosky et al., 2018), where only nine of the identified studies (0.3% of total) have occurred. True to all highly diverse ecosystems such as this, collecting data relevant to conservation, including movement behavior from telemetry studies, should be considered a priority (Moussy et al. 2022). In addition to the aforementioned priority areas, South America, Eastern Africa, the Northern Indian Ocean (including Arabia), and the Russian Arctic Ocean have received minimal attention, likely due to a combination of political instability, limited conservation funding, and, in some cases, location remoteness. The number of combined freshwater and marine KBAs identified in each country was correlated with the number of telemetry studies, and a higher proportion of total studies were conducted within the boundaries of KBAs relative to fisheries and management hotspots. This indicates that national conservation priorities have been a driver of telemetry effort in some countries. However, conversely, this correlation may be in part the result of relevant available data to identify and designate KBAs (Hughes et al., 2021), including spatial ecology data generated by telemetry studies. A higher correlation with KBAs relative to global priority for fisheries management and conservation focus may be in part attributed to the latter being mainly identified based on marine fisheries data largely focused on teleosts and elasmobranchs (Worm & Branch, 2012). Whereas KBAs were identified based on a greater number of taxa and species (BirdLife International, 2025), potentially providing more opportunities for focused studies. Regardless, both identified global priority areas for fisheries management and conservation focus and KBAs can be considered priority areas for future telemetry efforts.

Comparing the two modalities of telemetry considered in this study, satellite telemetry has been more widely distributed across global aquatic ecosystems than acoustic telemetry. This is particularly true for politically and logistically difficult to access regions. This wider distribution has been facilitated by the contained "fire-and-forget" nature of satellite telemetry whereby satellite tags are more easily transported and deployed on animals, in contrast to acoustic telemetry that requires both tags and larger receivers, in addition to often bulky mooring equipment. For example, following the deployment of satellite tags on animals, whether pop-off archival or positional, the data are relayed to the research team via satellites, negating the need to re-enter the region (Hussey et al., 2015). Limited need to be present in country for satellite telemetry studies has likely not always promoted collaborative partnerships with local researchers. In contrast, for acoustic telemetry, receiver arrays consist of a large number of units that must be deployed, serviced, and downloaded, requiring repeated access to the study site, which is more easily facilitated with local partners (Hussey et al., 2015). Specific to acoustic telemetry, fully submerged aquatic species (i.e., fishes) in difficult-to-access areas such as the Polar Regions are poorly investigated, as a result of increased time commitment, challenging conditions for deploying equipment moorings, infrastructure investment, and operating costs relative to satellite telemetry (Hussey et al., 2015). However, polar regions are a priority research focus due to the disproportionate impacts of climate change on these ecosystems (Hussey et al., 2016).

The fact that acoustic telemetry studies are often conducted over multi-year time scales (Hussey et al., 2015) also introduces an inherent risk that political situations in unstable nations could worsen over the course of the study. Such destabilization can lead to a change in government/personnel, and the validity of permits/permissions can be altered or reversed. In extreme cases, this can make it difficult to complete the study and recover the acoustic telemetry equipment/archived data relative to satellite telemetry. Satellite telemetry is not a direct replacement for acoustic telemetry, as it is restricted to larger animals and is unable to provide accurate location data when the animal is below the surface. However, for satellite tags, the detection of unexpected movements of important spatial conservation relevance (Lennox et al., 2024) is not limited to areas with telemetry infrastructure, but only by satellite coverage that is much more comprehensive and continually improving. Consequently, approaches to collecting adequate data to meet study objectives must be considered relative to the size of the focus species, conditions in the study region, and level of data required. Both techniques have strengths and weaknesses, and ideally should be used in tandem to provide a more complete picture of species and ecosystem dynamics (Hussey et al., 2015).

When our analysis considered taxonomic group, correlated covariates for teleost and marine mammals mirrored those for all studies combined, while elasmobranch focused studies were less correlated with political stability and the number of KBAs of each focus country. Given that satellite and acoustic telemetry studies for elasmobranchs were more evenly distributed, it is possible that the relative benefits and challenges of deployment (Hussey et al., 2015; Matley et al., 2022; Robichaud et al., 2025) counteracted each other to provide a less biased geographic distribution. The latitudinal distribution of marine mammal telemetry effort reflects a combination of their broad distribution and the dominant use of satellite telemetry, which is more suited to remote inaccessible locations such as polar regions and larger body size (Robichaud et al., 2025). In contrast, the broad distribution of teleost studies reflects high biodiversity and morphological variation within this group, requiring the deployment of both acoustic and satellite telemetry (Fisher et al., 2010; Lévêque et al., 2008). High representation of teleost acoustic telemetry studies in freshwater ecosystems likely relates to ease of receiver array maintenance in landlocked water bodies. Moreover, freshwater fish are often smaller in size (Lévêque et al., 2008), requiring the use of smaller acoustic tags and restricting the use of larger satellite tags, which have historically had functionality challenges in freshwater (Hussey et al., 2015; Robichaud et al., 2025). Flightless bird studies were all based on satellite telemetry and limited to the southern hemisphere, consistent with the primary distribution of flightless aquatic birds (Hickcox et al., 2019). Conversely, crustacean studies were based entirely on acoustic telemetry and focused primarily in the northern hemisphere, likely dictated by the location of important fisheries resources and demand for related data (Matley et al., 2022). A lack of studies for several taxonomic groups in the Southern Ocean is most likely driven by a combination of relatively lower aquatic biodiversity and the remoteness of the region.

In this study, limited information was available for current conservation funding for aquatic sciences by nation; consequently, assumptions were necessary regarding data available for terrestrial research. Nevertheless, the availability of conservation funding is a major factor that has limited the effectiveness of conservation research on a global scale (Waldron et al., 2013). Many areas of high global biodiversity and conservation priorities occur in developing and often less politically stable nations that frequently rely on external conservation agencies to provide funding. The availability of this external funding, however, can be negated in politically unstable areas due to international sanctions (Hussey, 2014), which can lead to regional shortfalls in both assigned funding (Waldron et al., 2013) and conservation citation rates (Meijaard et al., 2015). Conversely, instability drives disproportionately higher rates of research in politically stable countries that may not harbor global conservation priority hotspots, but have available funding, easier fieldwork logistics, and well-established scientific infrastructure. Consistent with our findings, the developed countries such as the USA and UK have disproportionately higher levels of research (Lawler et al., 2006) and citation rates (Meijaard et al., 2015) when compared to other countries. Though studies in politically unstable countries are probably considered higher risk for funding organizations, equitable distribution of monetary resources must be geared towards priority areas to maximize global conservation potential and ensure that focus is given to areas of high ecological importance. In addition to scientific and management gains, conservation funding can also contribute to poverty alleviation (through the expansion of livelihood opportunities and management of local resources), highlighting the opportunity to equitably allocate funding to understudied regions (Adams et al., 2004).

English as a first language was a major predictor of the number of telemetry studies published by country. We acknowledge that only papers published in English were considered and that all contributing authors for this study speak English and are based in more politically stable and wealthy nations, introducing a potential bias in interpreting this finding (Nuñez & Amano, 2021). We therefore acknowledge that investigation into the distribution of non-English language studies is required. Moreover, future assessments should include contributors from low- and middle-income countries as well as less politically stable nations to provide additional perspectives. Many nations with a low number of published telemetry studies, such as Brazil and those in Asia and the Indo-Pacific, have extensive and high-quality native language literary outlets (Lawler et al., 2006). Globally, however, the accepted international language of published science is English, and for studies to influence conservation on a broader geographic level they typically need to be published in English to reach a global audience (Ferguson & Carmen Plo, 2011). In reality, scientists from most nations may not be proficient with the English language, which could lead to difficulties compiling manuscripts, or lower motivation to publish research in the English language (Ferguson & Carmen Plo, 2011). As such, a wealth of telemetry data not considered here could exist in different languages and formats (i.e., government reports). Making these existing data accessible for conservation and management at a global scale presents substantial challenges, but could be achieved through long-lasting support of self-perpetuating research legacy and capacity sharing across nations and research communities.

It is evident that research capacity must be enhanced in data poor areas (Lennox et al., 2017; Rodríguez et al., 2022). Efforts to expand capacity sharing, such as pilot workshops to transfer telemetry skills sponsored by The United Nations Food and Agriculture Organization are needed. There are also organizations that facilitate, and bring recognition to efforts to increase research capacity in developing and politically difficult regions, such as 'Ecologists without Borders' (ecowb.org). At the level of the researcher and research groups, the global distribution of study effort shown here can be used to guide future research, considering global data gaps and regions of high global aquatic conservation importance. At the funding agency level, greater consideration of the proposed study location is required when assessing proposals. Studies proposed in data poor areas, despite political or logistical difficulties, should be embraced rather than avoided, given the priority need for data. This could be facilitated through establishment of funds dedicated specifically to these regions (e.g., the Darwin Initiative; gov.uk/government/groups/the-darwin-initiative) and that encourage reciprocal partnerships with local researchers and institutions. Once grants are awarded, flexibility over deliverables (i.e., annual reports and fixed project timelines) should be built into the assessment process to account for the unpredictability of working in such regions. Post-securing of funds, indicators could also be used to assess researcher's commitment and determination to complete the study, accepting that challenges may occur or all aspects of the study are not achievable. Once studies are completed, journal editors and referees should consider the difficulty in obtaining data from certain locations when evaluating a study's merit and scientific contribution.

The distributional bias of aquatic telemetry research effort presented here has been documented across multiple disciplines of conservation research, both aquatic and terrestrial (Martin et al., 2012; Culumber et al., 2019; Hughes et al., 2021; Moussy et al., 2022; Shaw et al., 2024), suggesting that identified challenges are not limited to this field or these technologies. This results in a limited understanding of important conservation and fisheries regions (at the global scale) where comprehensive knowledge is needed for holistic ecosystem level conservation interventions (Kukkala & Moilanen, 2017). Similar shortcomings have been identified for global species monitoring associated with the Convention on Biological Diversity (Moussy et al., 2022). In addition, international agreements, such as the Convention on Migratory Species (Hensz & Soberón, 2018), include species which can move or migrate large distances, including cross-jurisdictional movements with implications for conservation and management planning (Barkley et al., 2019; Daly et al., 2023). Considering the importance of global connectivity of ecosystems (Brooks et al., 2006; Cowen et al., 2000; Frisk et al., 2014), a lack of focus in politically unstable and remote regions will only hinder our understanding of large-scale ecosystem processes (Österblom et al., 2017), including those influenced by the threats of global climate change.

5 | CONCLUSION

To address identified gaps in the distribution of global aquatic animal telemetry (acoustic and satellite) effort, a modified approach will be necessary at all levels of the scientific and funding-agency process. Multiple investigations, including this one, have now identified that focused scientific research (here aquatic animal telemetry) is disproportionately low in many regions designated as global priority areas for biodiversity, fisheries management, and conservation focus. Despite the potential challenges of working in such areas, ongoing telemetry research will require a focus on inclusive partnerships, capacity sharing, and equitable appropriation of funding within these data-poor regions for improved understanding of global aquatic ecosystems and their connectivity. Only through effective and efficient distribution of scientific resources, both human and financial, can we begin to meet current aquatic conservation priorities on a global scale.

AUTHOR CONTRIBUTIONS

S.T.K., M.A.M., S.J.C., A.T.F., M.R.H., and N.E.H., conceived and guided this study; S.T.K., A.B.M., A.L.H., N.V.K., J.K.M., M.L.P., J.A.R. conducted literature searches and extracted data; S.T.K., M.A.M. and A.L.H. conducted data analysis; S.T.K drafted manuscript; S.T.K., N.V.K. and J.K.M. produced the figures. All authors critically reviewed the manuscript and approved the final version.

ACKNOWLEDGMENTS

Financial and logistical support for the first half of this study (assessment of effort up to 2013) was provided to the Ocean Tracking Network's International Scientific Advisory Committee through funding from the Canada Foundation for Innovation and the Natural Sciences and Engineering Research Council of Canada. Financial support for the second part of this study (assessment of effort 2014–2022) was provided by the Paul M. Angell Family Foundation, The Brunswick Foundation, the Dr. Scholl Foundation, Kenneth Molson Foundation, University of Windsor, and NSERC Discovery to NEH.

DATA AVAILABILITY STATEMENT

Available upon request.

ORCID

S. T. Kessel https://orcid.org/0000-0001-7729-7701
A. P. Barbosa Martins https://orcid.org/0000-0003-3691-9644
A. L. Haley https://orcid.org/0000-0002-3582-9850
J. A. Robichaud https://orcid.org/0000-0002-9721-6873

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SUPPORTING INFORMATION

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How to cite this article: Kessel, S. T., Auger-Méthé, M., Barbosa Martins, A. P., Cooke, S. J., Fisk, A. T., Haley, A. L., Heupel, M. R., Klinard, N. V., Matley, J. K., Piczak, M. L., Robichaud, J. A., & Hussey, N. E. (2026). Global distribution of aquatic animal telemetry effort reveals geographic biases and opportunities for more inclusive tracking studies. *Conservation Science and Practice*, *8*(7), e70314. https://doi.org/10.1111/csp2.70314