Environmental Reviews

Review

Global trends in aquatic animal satellite telemetry studies

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Abstract

Satellite telemetry has revolutionized the study of aquatic animal movement by enabling high-resolution tracking across vast spatial and temporal scales. Here we undertake a global systematic review of studies since 1982 to summarise state of knowledge by taxonomic group, sample size, life history stage studied, and tracking mode (i.e., archival vs. near real-time). We then classify studies according to defined research and management themes, highlight geographic trends aligned with FAO major fishing areas, and examine how these themes are distributed globally. Of a total of 1137 studies, encompassing over 30 000 tagged individuals across diverse aquatic taxa, mammals, fish, and reptiles were the most studied. Research has largely focused on marine systems, particularly in the northern Atlantic and Pacific, but freshwater ecosystems remain underrepresented. Most studies explored general movement patterns, with fewer addressing applied conservation topics such as movement barriers or protected area effectiveness. Overall, integration with complementary methods (e.g., genetic or physiological sampling) was limited. Addressing identified gaps in underrepresented taxa (e.g., invertebrates), regions (e.g., the Indian Ocean), and emerging topics (e.g., climate change responses) will be critical to fully realize the potential of satellite telemetry for conservation and management of aquatic biodiversity.

Key words: biotelemetry, migration, animal movement, spatial ecology, conservation, movement ecology

Introduction

Electronic tagging, including biotelemetry, collects information about the locations of aquatic animals to document where, when, why, and how they move (Hussey et al. 2015; Chung et al. 2021). These rapidly evolving technologies have been used to answer diverse questions across both fundamental and applied topics (Hussey et al. 2015; Crossin et al. 2017). For example, animal tracking can examine fundamental questions pertaining to life history, survival, morphology, habitat associations, environmental drivers, fitness, and energetics to elucidate ecological and evolutionary patterns and processes (Jacoby and Piper 2023; Trappes 2023). Animal tracking can also be used to address applied conservation and management questions from local to global scales such as the spatial and seasonal use and efficacy of protected areas, non-native species control/management, stock assessments, marine spatial planning, and defining management units (Cooke et al. 2016; Crossin et al. 2017; Lowerre-Barbieri et al. 2019; Whitlock et al. 2022).

Satellite telemetry is the remote acquisition of animal location data through tags that transmit information to satellites. This technology represents a revolutionary development in aquatic animal tracking given its pivotal role in tracking species across broad spatial and temporal scales in the last several decades (e.g., Block et al. 2005, 2011; Goodyear et al. 2008; Braun et al. 2019; Queiroz et al. 2019). Satellite telemetry works by transmitting data from a tag at the water's surface to low-orbiting satellites, often including both location and tag-recorded environmental information. Animals are typically tracked using two broad categories of satellite tags. Satellite-linked radio transmitters (SLRTs) track animals that spend time near the surface (e.g., to bask, respire, or forage) in real time, whereas pop-up satellite archival transmitters (PSATs) are used for fully submerged animals that remain at depth, with the tags transmitting data once they disengage and float to the surface. Among SLRT tags, SPOT and SPLASH tags (both of which are units developed by Wildlife Computers, Remond, WA, USA) are commonly used. SPOT tags provide location data only, while SPLASH tags can also transmit environmental data about the animal's surroundings, including depth, temperature, acceleration, salinity, and dissolved oxygen. Satellite telemetry enables tracking of mobile species at broad spatial and temporal scales in aquatic ecosystems with minimal maintenance. Since tags only need to be deployed once, researchers can passively monitor animals for extended periods without the need to return and service equipment. With long battery lives (e.g., up to a decade) and global satellite coverage, this method allows tracking even in remote or logistically challenging locations (Dagorn et al. 2007). We acknowledge that our focus on satellite telemetry excludes important biologging technologies such as heart-rate or time-depth recorders, which have yielded foundational insights (e.g., Weimerskirch et al. 2000; Costa et al. 2003). While these approaches are integral to the broader field of electronic tagging, our review is intentionally limited to studies involving remote locational data transmission rather than archival methods requiring tag recovery.

Previous reviews have examined the use of satellite telemetry to study aquatic animal movements, with most focusing on specific taxa (e.g., Hart and Hyrenbach 2009; Hammerschlag et al. 2011; Renshaw et al. 2023) or geographical regions (e.g., Javed et al. 2003; Abecasis et al. 2018). Notably, Hussey et al. (2015) conducted a global review of aquatic telemetry, encompassing both satellite and acoustic methods, and synthesized studies related to four-dimensional movement (i.e., horizontal, vertical, and over time), integration with other biological metrics, and the use of animals as oceanographers. Despite the growing use of satellite telemetry to study aquatic species, few reviews have investigated how this technology has been used to examine questions relevant to conservation and management. Despite this gap, reviews like Sequeira et al. (2025) have recently emerged. These data assessed the global space use patterns of marine megafauna with the goal of commenting on how to achieve conservation targets. Managing aquatic organisms is inherently complex, requiring policies that navigate both ecological and socio-economic dimensions (Anderson et al. 2015; Hare 2020). However, management efforts are often hindered by insufficient data due to logistical constraints and limited resources, thereby warranting the review of these topics to identify and address gaps in our knowledge.

Satellite telemetry remains an important tool for studying the movements of aquatic animals in the wild and given its widespread use, a contemporary understanding of how it is applied across taxa and geographic locations, as well as examining the application of this technology to management-related objectives. Following the approach of Matley et al. (2022), we synthesise trends across space and time, as well as taxa in satellite telemetry research, and highlight knowledge gaps associated with management themes. Our overlying goal is to evaluate contemporary trends in satellite telemetry research to direct future studies to enhance global conservation and management efforts.

Approach

We used Web of Science Core Collection (Clarivate Analytics) to collect primary literature that used satellite telemetry throughout the world in English only. We assessed multiple search string options and cross-referenced with key publications to ensure the chosen search string was as effective as possible. We conducted the search in two phases: prior to 2013, and from 2013 to 2022. The first phase of the review (<2013) included a literature search on 31 December 2013 using the search terms: "satellite", "PSAT", and "SPOT", followed by the terms "telemetry", "tracking", and "tag". For the second phase (>2013), the search was performed on 14 February 2023 using the same search string. Our study was completed in two phases as it was analysed in a first review (i.e., Hussey et al. 2015) and then brought up to date, with additional data collected for this article. We only included primary publications that used satellite telemetry on wild aquatic animals. Further, only flightless aquatic birds (e.g., penguin species such as Adelie penguins, *Pygoscelis adeliae*) were included in the review because they spend a large proportion of their life in the water (compared to other flighted aquatic birds, e.g., terns). We conducted data extraction following Matley et al. (2022), which consisted of collecting information on study duration, ecosystem type, taxa, number of tagged animals, tag type (SLRT vs. PSAT), and other complementary methods used (if any, such as traditional fisheries sampling, biological sampling, visual observations, hydroacoustics, experimental approaches, or other telemetry technologies, as per Matley et al. (2023). The geographic location was categorised by the Food and Agriculture Organization (FAO) Major Fishing Areas, and if tracked animals were found in more than one, each FAO area was recorded (e.g., a tuna that moved from the Northeast to Northwest Atlantic).

We assigned management-related objectives for each study, focussing on 14 management-related objectives (see Table 1 for definitions), as in Matley et al. (2022), to determine how satellite telemetry research is linked to global management themes. Examples include studies on migration, fisheries, climate change, spawning, and protected areas. Here, we highlight how satellite telemetry supports current and future management programs and simultaneously assess the gaps in management objectives that may be answered with satellite telemetry and/or complementary methods (Table 2). It may also serve to highlight future research avenues to move past baseline, though crucial, fundamental information toward applicable conservation solutions and identify where research priorities and infrastructure differ. To ensure consistency, one author performed the management-related categorization for all studies based on management objectives explicitly presented in the abstract. If a management

Table 1. Definitions of management objectives, modified from Matley et al. (2022).

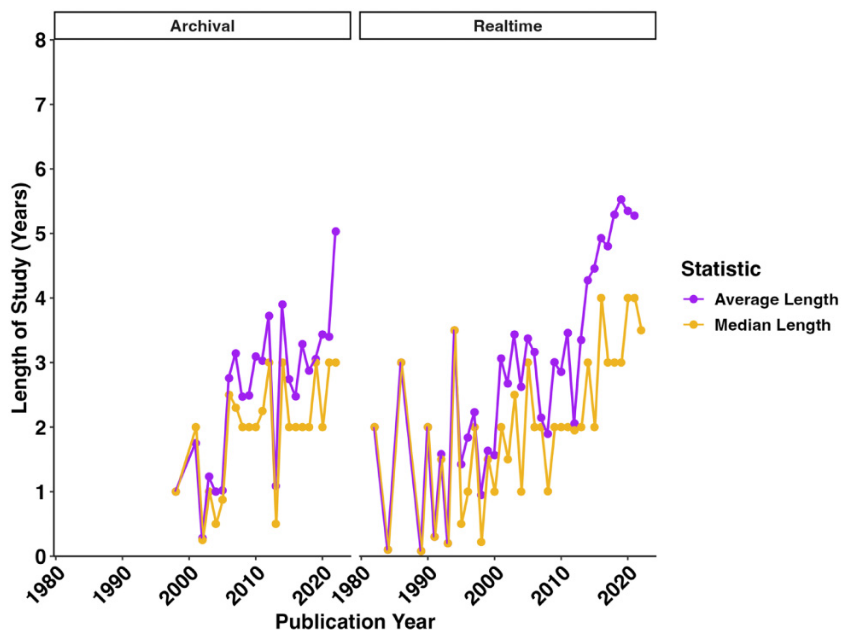
Management objective	Description
Aquaculture	Must be related to direct application of aquaculture (e.g., escaped fish from pen, pathogens, predators).
Climate change	Must relate to explicitly stated climate change events (e.g., irregular weather patterns, drastic increases in water temperature or pH, hypoxia). They do not need to be long-term studies if they are specifically rationalized in relation to climate change. Nevertheless, just because a study may be informative due to climate related trends, it may still not be sufficient. For example, if a study simply explores space use of animals under normal conditions and then states baseline knowledge is important for climate change scenarios, it is not sufficient.
Fisheries-specific (non-aquaculture)	Must be directly related to a fishery component of interest (e.g., integrates fishery specific tools, attributes, or goals) and not simply that this fish is important to fisheries/management or part of a stock assessment. This can include natural mortality and mortality estimates for catch and release.
General movement	This category incorporates general movement patterns (including diving) or space use not defined elsewhere and is not necessarily related directly to management. Studies that examined habitat, environmental, and diel/seasonal/lunar drivers of space use were designated as general movement.
Impediments/passage/ construction	One or more objectives of the study were related to the behaviour, physiology, or survival of tagged individuals as they encounter or interact with human-built impediments or structures. Can include dams, weirs, land reclamation (ports, airports), power stations, hydropower production, fish passage structures, as well as artificial reefs and fish aggregating devices (FADs).
Invasive species	The purpose of the study was to examine an invasive species or one acting in direct conflict with one, as opposed to a study that was done for another purpose on an invasive species—the fact that the species is invasive has to be what drives the study objective(s).
Migration	The purpose of the study was to identify or examine migration-related movements of individuals or species. If the species is known to exhibit these behaviours but none of the objectives were related to it, the study did not qualify. Furthermore, unless specifically stated in regard to migratory processes, the study of “long-distance” movements was not sufficient because it is scale-dependent and not a biological dimension.
Protected area	The purpose of the study was directly related to the designation of a protected area/MPA/fishery closure or evaluating the role or effectiveness of an existing protected area/fishery closure. Simply because a study took place in a protected area or area that is closed to fishing does not mean it qualifies.
Spawning/mating/nesting	Must directly relate to reproductive activities or behaviours corresponding with the act of spawning or nesting or mating (e.g., fish aggregating to spawn). If the animal is making “long-distance” movements for the purpose of reproduction, the “spawning/mating” and “migration” categories were both selected.
Stocking	All or part of the study’s purpose was to examine a species that is in decline or the subject of stocking and must incorporate individuals in an area directly being affected by these issues, otherwise must directly link them.
Restoration	Must be directly related to ecological restoration, examples could include the assessment of efficacy of ecological restoration efforts.
Tourism	Must directly relate to tourism such that satellite telemetry is used to investigate the effects of animal behaviour on tourism or effects of tourism on animal behaviour. Examples may include cage-diving or feeding activities. Studies that indirectly relate to tourism (e.g., study was conducted on Great Barrier Reef where tourism happens) do not apply.
Water quality/pollution/pathogens/disease	Incorporates external cues or factors (although not environmental) that can affect the health or behaviour of tagged animals. Required study to investigate individuals as they interact with these issues or must directly link to that occurrence in the species or the area. Simply because water quality/pollution/pathogens/disease is a generic concern is not sufficient. A study designed to incorporate parasites or infections such as sea lice are valid in this category if directly investigated.
Population	Related to population estimates using ST.

objective could not be assigned from the abstract, the full text was then examined to ensure that an objective was properly assigned from the listed study aims. In cases where management aims were not considered by the authors, or when a category could not be identified, studies were assigned to the “general movement” category, following the methods of Matley et al. (2022). Finally, in cases where authors belatedly linked their work with a management goal in the final paragraphs of the discussion or conclusion, the management objective was assigned based on the actual work that was executed and outlined a priori (e.g., a study set out to track migration; authors then mention in the discussion that it is a beneficial study for climate change because the study was carried out in a region that will experience extreme weather events. The study would be assigned to migration and not to climate change; Table 1). We categorized each study into one management-related objective, except in the cases where a study explicitly investigated more than one objective. For each category, we examined the number of studies for each FAO area, taxa, and each species’ family. Results have been reported as either proportions of studies or total values, based on whether or not said result is referring to number of occurrences (i.e., to account for studies where multiple values applied).

Table 2. Complementary approaches used in combination with satellite telemetry, modified from Matley et al. (2023).

Broad complementary method	Sub-category	Description	Examples
Traditional fisheries sampling	Direct capture	Capture method that forms dedicated part of study.	Fishing, netting, by hand
	Recapture	Repeated capture of individuals as distinct part of study.	Mark-recapture
	Benthic sampling	Collection or quantification of organisms within substrate associated with tracked animals.	Direct observation, survey, netting
	Egg collection	Collection of eggs as distinct part of study.	Netting, by hand, survey
Biological sampling	Genetics	Application of genetic (or genomic) analysis.	Fin, gill, feces sampling
	Microchemistry	Measurement of elemental or isotopic composition.	Otolith, scale, vertebrae sampling
	Stable isotopes	Quantification of stable isotopes.	Muscle, liver, blood sampling
	Gut contents	Identification and quantification of prey in gastrointestinal tract.	Stomach sampling
	Morphometrics	Measurements of body shape and size as distinct part of study.	Photo, direct measurement
	Tissue sampling	Direct sampling of tissues (not stated above).	Biopsy, blood collection, ultrasound
Visual observations	Underwater	Observations made under the surface of the water.	Scuba, snorkel, video, survey
Hydroacoustics	Hydroacoustics	Use of underwater acoustic equipment distinct from acoustic tracking.	Boat survey, audio recording
Experimental approaches	Respirometry	Measured output from respirometry experiment.	Swim tunnel

Fig. 1. Average study length and median study length per year for both archival and real-time transmitter types.



Findings

Study metrics

Our global literature review yielded 1137 satellite telemetry articles that were published between 1982 and 2022. The highest number of satellite telemetry studies were published in 2020 ($n = 87$, 7.7%), followed by 2021 ($n = 85$, 7.5%) and 2017 ($n = 80$, 7.0%). The mean study length in years overall was 3.8, while the average length of study time when real-time tags were used was 4.1 years and 2.9 years for archival (Fig. 1). The median study length for both tag types was 2. The number of individuals tagged was reported in 99% of all studies ($n = 1135$). Across all studies, we estimate that over 34 000 individual animals have been tagged for satellite telemetry tracking, although not every study identified how many produced valid data. Some studies were also unclear about the exact breakdown of tags when multiple species or taxa were tracked in a single study. Based on the information we extracted, the median number of individuals tagged per study was 16, while the average was 27. The total number of indi-

Fig. 2. Total number of individuals tagged for satellite telemetry each year.

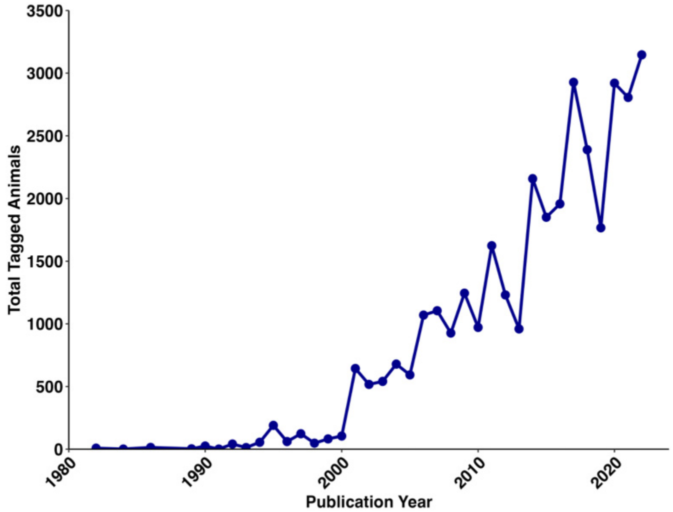
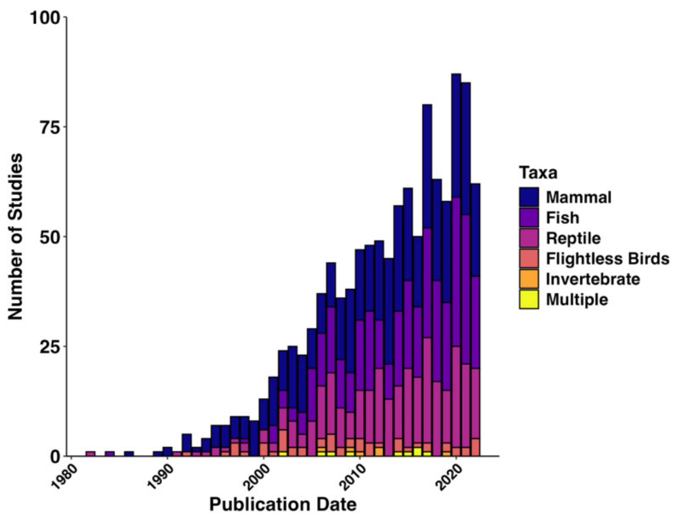


Fig. 3. Total number of satellite telemetry studies over time as proportion of taxa.



viduals tagged per year increased over time, consistent with the increase in total studies published over time (Fig. 2).

Taxa

Of the 1137 studies found in our search, 1128 tracked a single animal taxon, while nine tracked multiple taxa (Fig. 3). Studies were published on 187 different species from 57 families across five taxa. Mammals were studied the most often at 448 occurrences, accounting for 39.1% of all publications, followed by fish (n = 344, 30.0%), reptiles (n = 293, 25.6%), flightless birds (n = 55, 4.7%), and invertebrates (n = 7, 0.6%). The first published satellite telemetry study for each taxon was in 1982 for reptiles (Stoneburner 1982), 1984 for fish (Priede 1984), 1987 for mammals (Tanaka 1987), and 1992 for flightless birds (Davis and Miller 1992) (Fig. 3). Satellite telemetry was not used on invertebrates until 2006 (Gilly et al. 2006).

Mammals

Studies involving mammals occurred from 1986 to 2022, with the most studies occurring in 2021 (n = 30, 6.7%), followed by 2017 (n = 29, 6.5%) and 2020 (n = 28, 6.3%) (Fig. 4A). Of all studies involving mammals (n = 448), 440 focused solely on mammals (98.2%) while 8 (1.8%) tracked mammals alongside flightless birds, fish, invertebrates, and reptiles. We identified 15 families and 72 species of mammals that have been studied with ST. The most studied mammal families were: Phocidae (earless seals; n = 166, 33.5%), Otariidae (eared seals; n = 73, 14.7%), Balaenopteridae (baleen whales; n = 64, 12.9%), Delphinidae (oceanic dolphins; n = 49, 9.9%), and Monodontidae (cetaceans; n = 35, 7.1%). At the species level, the most tracked mammals were humpback whales (*Megaptera novaeangliae*; n = 33, 6.7%), polar bears (*Ursus maritimus*; n = 27, 5.5%), southern elephant seals (*Mirounga leonina*; n = 27, 5.5%), harbour seals (*Phoca vitulina*; n = 23, 4.6%), and gray seals (*Halichoerus grypus*; n = 22, 4.4%).

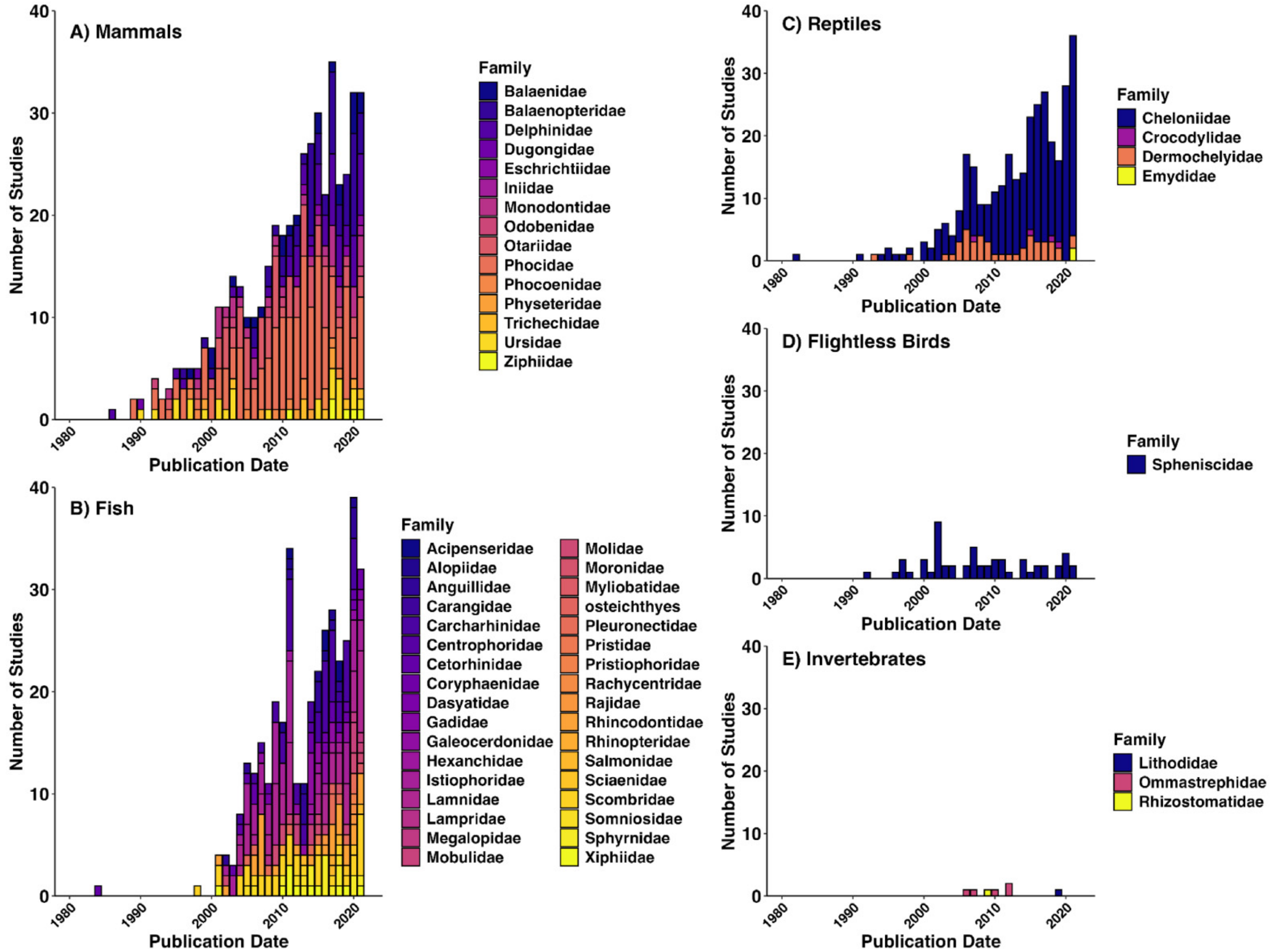
Fish

Fish have been studied using satellite telemetry 344 times from 1984 to 2022, with most studies published in 2020 and 2021 (each n = 34, 9.9%; Fig. 4B). Most studies involving fish (n = 340 98.8%) focused on fish alone; however, a small proportion of tracking studies (n = 4, 1.2%) also evaluated mammals or reptiles. Thirty-four families and 89 species of fish have been studied with ST. The most notable families included: Carcharhinidae (requiem sharks; n = 66, 15.8%), Lamnidae (mackerel sharks; n = 57, 13.7%), Istiophoridae (billfishes; n = 55, 13.2%), Scombridae (mackerels and tunas; n = 36, 8.6%), and Rhinocondontidae (whale sharks; n = 30, 7.2%). The most studied species included white shark (*Carcharodon carcharias*; n = 30, 7.2%), whale shark (*Rhincodon typus*; n = 30, 7.2%), blue shark (*Prionace glauca*; n = 23, 5.5%), tiger shark (*Galeocerdo cuvier*; n = 23, 5.5%), and Atlantic bluefin tuna (*Thunnus thynnus*; n = 17, 4.1%).

Reptiles

Studies using satellite telemetry on reptiles occurred from 1982 to 2022, with the most published in 2017 (n = 24; Fig. 4C). Of the 293 studies involving reptiles, most studies (n = 287, 98.0%) did not include other taxa; however, a handful were published with tracking information on flightless birds, fish, or mammals as well (n = 6, 2.0%). Only 11 species across four families of reptiles have been tracked using ST, with most studies on Cheloniidae (sea turtles; n = 301, 85.5%). The remaining families included Dermochelyidae (leatherback turtles, *Dermochelys coriace;* n = 45, 12.8%), Crocodylidae (crocodiles; n = 4, 1.1%), and Emydidae (pond turtles; n = 2, 0.6%). The most tracked sea turtle species included loggerhead (*Caretta caretta*; n = 137, 38.9%), green (*Chelonia mydas*; n = 89, 25.3%), hawksbill (*Eretmochelys imbricata*; n = 28, 7.9%), and Kemp's ridley (*Lepidochelys Kempii*;

Fig. 4. Number of satellite telemetry studies over time for each taxon, as proportions of families.



$n = 21$, 6.0%), and olive ridley (*Lepidochelys olivacea*; $n = 21$, 6.0%). Among crocodiles, tracking studies focused on the saltwater crocodile (*Crocodylus porosus*; $n = 2$, 0.6%), American crocodile (*Crocodylus acutus*; $n = 1$, 0.3%), and Nile crocodile (*Crocodylus niloticus*; $n = 1$, 0.3%). Finally, the Emydidae studies were specifically done on diamondback terrapin (*Malaclemys terrapin*; $n = 2$, 0.6%).

Flightless aquatic birds

Considerably fewer studies used satellite telemetry to track flightless aquatic birds compared to mammals, fish, and reptiles ($n = 55$). The most studies published in a year occurred in 2002 ($n = 6$, 10.1%), 2022 ($n = 4$, 7.3%), and 2007 ($n = 4$, 7.3%; Fig. 4D). Most satellite telemetry studies on flightless birds did not simultaneously track other taxa ($n = 54$, 98.1%). One study looked at penguins alongside Antarctic fur seals (*Arctocephalus gazella*; Barlow et al. 2002). Because of our restriction to flightless birds, the only family included in our study was Spheniscidae (penguins; $n = 61$, 100%). A total of 12 penguin species were studied using satellite telemetry, including Magellanic penguin (*Spheniscus magellanicus*; $n = 13$, 21.3%), Adelie penguin (*Pygoscelis adeliae*; $n = 11$, 18.0%), king penguin (*Aptenodytes patagonicus*; $n = 10$, 16.4%), and gentoo penguin (*Pygoscelis papua*; $n = 5$, 8.2%).

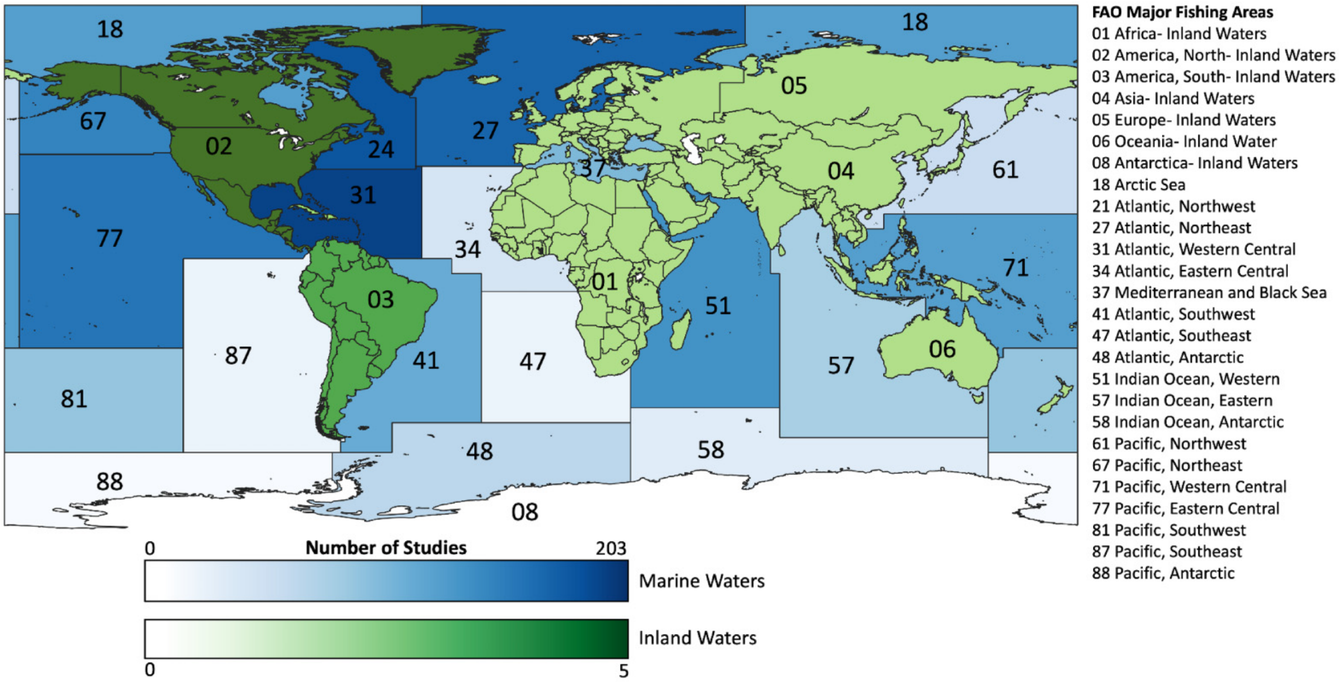
Invertebrates

Satellite telemetry has rarely been used to track invertebrates ($n = 7$); however, we identified seven studies that occurred between 2006 and 2019 (Fig. 5E). Of the seven studies, six focused solely on invertebrates (85.7%), except for Davis et al. (2007) who explored jumbo squid (*Dosidicus gigas*) behaviour in relation to sperm whale behaviour. Only three invertebrate species from three families were studied using satellite telemetry: Humboldt squid (Ommastrephidae; $n = 5$, 71.4%), Antarctic king crab (*Lithodes antarcticus*, Lithodidae; $n = 1$, 14.2%), and Nomura's jellyfish (*Stomolophus nomurai*, Rhizostomatidae; $n = 1$, 14.2%).

Biological information

Sex was reported in only 64% of studies ($n = 731$, 64.3%) and most studies reported life stage ($n = 879$, 77.3%). Similarly to total tag number, the sex of the individuals tagged was not always made clear, and we found that authors did not always clearly identify the sex of each species or taxa when

Fig. 5. Global distribution of studies using satellite telemetry by the Food and Agriculture Organization (FAO) Major Fishing Areas across marine and inland waters, represented by colour gradient (blue and green, respectively). The corresponding number for each FAO area is labelled within each polygon.



multiple were tagged. Reported life stages included adults ($n = 573$, 50.4%), juveniles ($n = 110$, 9.7%), or both ($n = 196$, 17.2%). The other 22.7% ($n = 258$) either did not report life stage or were unable to identify it. At the taxa level, most tagged mammals were reported to be adults ($n = 223$, 45.1%), followed by both age classes ($n = 112$, 22.6%), and juveniles ($n = 41$, 8.3%). An age class was not reported for the remaining 24.0% ($n = 119$) of tagged mammals. The greatest proportion of tagged fish ($n = 164$, 39.3%) did not have a reported age class. The remaining 60.7% were classified as adults ($n = 155$, 37.2%), both juveniles and adults ($n = 67$, 16.1%), or juveniles ($n = 31$, 7.4%). In reptiles, most tagging was done on adults ($n = 217$, 61.6%), followed by both ($n = 51$, 14.5%), and juveniles ($n = 40$, 11.4). There was no age class reported for the remaining reptiles tagged ($n = 44$, 12.5%). For tagged flightless bird species, age class was unknown 24.6% of the time ($n = 15$). Adult birds were mostly tagged ($n = 37$, 60.7%), followed by both ($n = 5$, 8.2%) and juveniles ($n = 4$, 6.6%). Limited information on age class for invertebrate species was available (57% were unknown); however, from those reported 28.6% ($n = 2$) were adults, and one study (14.3%) tagged both adults and juveniles.

Tag type

All but two studies ($n = 1135$, 99.8%) reported the model of satellite tag used in their study. The specific model of satellite tags used varied greatly, but most studies ($n = 885$, 74.2%) used real-time transmitters while the remaining used archival ($n = 291$, 25.6%). At the taxa level, mammals were predominantly tracked with real-time tags ($n = 440$, 99.5%), however there was one instance where archival tags were used ($n = 1$, 0.25%) and another where it was not reported ($n = 1$, 0.25%). For fish tracking, archival was the dominant transmitter choice ($n = 271$, 79.7%), with the remaining using real-time ($n = 69$, 20.3%). All studies done on flightless birds used real-time tags ($n = 53$, 100%), whereas all studies on invertebrates used archival ($n = 6$, 100%). For reptiles, real-time tags were used 95.5% of the time ($n = 274$), archival 4.2% ($n = 12$), and one study did not report the tag type (0.3%). Finally, in studies where multiple taxa were tracked, most used real-time transmitters ($n = 8$, 88.9%), while archival was used only once (11.1%).

Complementary approaches

Although most studies focused on satellite telemetry alone ($n = 1000$, 87.6%), some studies also incorporated acoustic telemetry tags ($n = 73$, 6.4%), radio tags ($n = 49$, 4.3%), or PIT tags ($n = 19$, 1.7%; Table 3) to track animal movements. At the taxa level, the importance of secondary tag types varied. Acoustic telemetry tags were most used in fish ($n = 48$, 65.8%), radio tags were most frequent in mammals ($n = 36$, 73.8%), and PIT tags were predominantly used in reptiles ($n = 17$, 89.5%).

Most ($n = 881$, 76%) studies did not use a complimentary methodology alongside satellite telemetry (Table 4). The remaining studies reported using biological sampling ($n = 145$, 12.5%), visual observations ($n = 66$, 5.7%), traditional sampling ($n = 53$, 4.6%), other experimental approaches ($n = 10$,

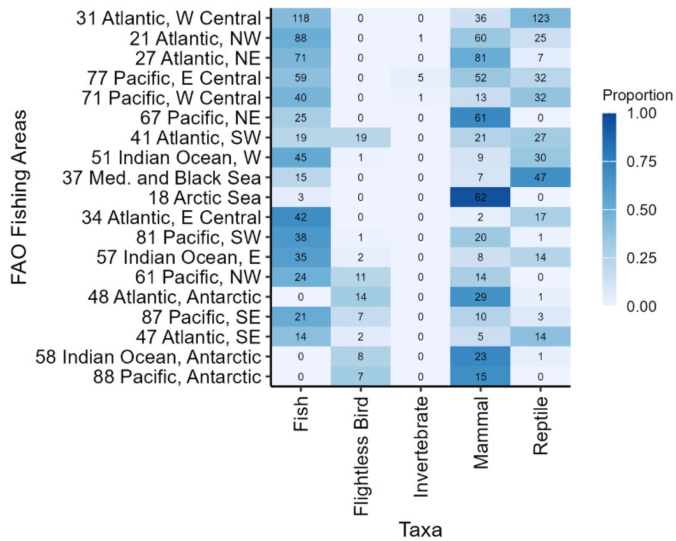
Table 3. Summary of occurrences using satellite telemetry alone, and then in combination with other telemetry tag types across all studies in our review ($n = 1137$).

Tag type	Number of occurrences	% of all studies
Satellite Telemetry	1000	87.6
Acoustic	73	6.4
Radio	49	4.3
PIT	19	1.7

Table 4. Summary of occurrences of complementary approaches (see Table 1 for full definitions) and respective proportions from all studies ($n = 1137$).

Complementary approach	Number of occurrences	% of all studies
None	881	76.0
Biological Sampling	145	12.5
Visual Observations	66	5.7
Traditional Sampling	53	4.6
Experimental Approaches	10	0.9
Hydroacoustics	4	0.3

Fig. 6. Proportional total number of studies using satellite telemetry across Food and Agriculture Organization (FAO) Major Fishing Areas and taxa, ordered from highest to lowest total number of studies from top to bottom. Colour indicates the proportion of each taxon calculated within each row.



0.9%), and hydroacoustics ($n = 4$, 0.3%). Again, the importance of these experimental approaches varied across taxa. Biological sampling was most common in mammals ($n = 73$, 50.3%), followed by reptiles ($n = 43$, 29.7%), and fish ($n = 26$, 17.9%). Visual observations were performed on mammals ($n = 38$, 57.6%), fish ($n = 17$, 25.8%), reptiles ($n = 6$, 9.1%), flightless birds ($n = 4$, 6.1%), and invertebrates ($n = 1.5\%$). Traditional sampling was most common in fish ($n = 24$, 45.3%), mammals ($n = 15$, 28.3%), and reptiles ($n = 13$, 24.5%) but was also used in invertebrates on one occasion (1.9%). Experimental approaches were only used in mammals ($n = 9$, 90%) and fish ($n = 1$, 10%). Finally, hydroacoustics was used in mammals ($n = 2$, 50%), fish ($n = 1$, 25%), and flightless birds ($n = 1$, 25%). We would like to reiterate that the categories presented here follow those outlined in Matley et al. (2022). As such, we may not have highlighted every distinct instance of complementary methods used alongside satellite telemetry but instead grouped them under broader categories (Table 2).

FAO major fishing areas

Satellite telemetry studies occurred in 25 of the 27 designated FAO Major Fishing Areas. The only two that were not represented were FAO Former USSR area—Inland Waters and Antarctica—Inland Waters (Fig. 5). Most studies occurred in only one FAO Major Fishing Area ($n = 1045$, 91.9%), but several had tagged animals that moved across multiple ($n = 92$, 8.1%), and two were deemed "global studies" where animals were tagged and tracked ocean-wide (see Dale et al. 2022; Womersley et al. 2022). Taking into consideration that several studies included multiple FAO areas, the below values are summarized from a total of 1260 FAO occurrences across the 1137 total studies.

Most satellite telemetry tracking was conducted in marine systems (99.1%, $n = 1250$), with fewer studies in freshwater ecosystems and inland waters ($n = 11$; 0.9%). The Atlantic FAO areas were the most represented across all groups: Atlantic, Western Central ($n = 203$, 16.1%), Atlantic, Northwest ($n = 144$, 11.4%), and Atlantic, Northeast ($n = 125$, 9.9%; Fig. 5). These were followed by two Pacific regions: Pacific, Eastern Central ($n = 116$, 9.2%), and Pacific, Northeast ($n = 73$, 5.8%; see Supplemental Information A for more details).

The average number of taxa studied per FAO and the median number studied was 3. Across all FAO Major Fishing Areas, none included studies on all five taxa (Fig. 6). Mammals were studied in the greatest proportion of all FAOs ($n = 22$, 28.9%), followed by fish ($n = 18$, 23.7%), reptiles ($n = 17$, 22.4%), flightless birds ($n = 9$, 11.8%), and invertebrates ($n = 3$, 3.9%). Multi-taxa studies also occurred in seven different FAOs (9.2%). Several FAOs had studies from four out of five taxa and studies that covered multiple taxa. This includes the Indian Ocean, Western (fish ($n = 28$, 43.8%), reptiles ($n = 25$, 39.1%), mammals ($n = 9$, 14.1%), flightless birds ($n = 1$, 1.6%), multi-taxa ($n = 1$, 1.6%)), the Pacific, Western Central (fish ($n = 24$, 39.3%), reptiles ($n = 24$, 39.3%), mammals ($n = 10$, 16.4%), multi-taxa ($n = 2$, 3.2%), invertebrates ($n = 1$, 1.6%)), the Atlantic, Southwest (flightless birds ($n = 16$, 27.1%), mammals ($n = 16$, 27.1%), reptiles ($n = 16$, 27.1%), fish ($n = 9$, 15.3%), multi-taxa ($n = 2$, 3.38%)), and the Pacific, Southwest (fish ($n = 24$, 54.5%), mammals ($n = 17$, 38.6%), flightless birds ($n = 1$, 2.3%), reptiles ($n = 1$, 2.3%), multi-taxa ($n = 1$, 2.3%)). Notably, four FAOs also contained studies from four out the five taxa, including Atlantic, Southwest (reptiles ($n = 13$, 52.0%), fish ($n = 5$, 20.0%), mammals ($n = 5$, 20.0%), flightless birds ($n = 2$, 8.0%)), Indian Ocean, Eastern (fish ($n = 21$, 48.8%), reptile ($n = 13$, 30.2%), mammal ($n = 7$, 16.3%), flightless bird

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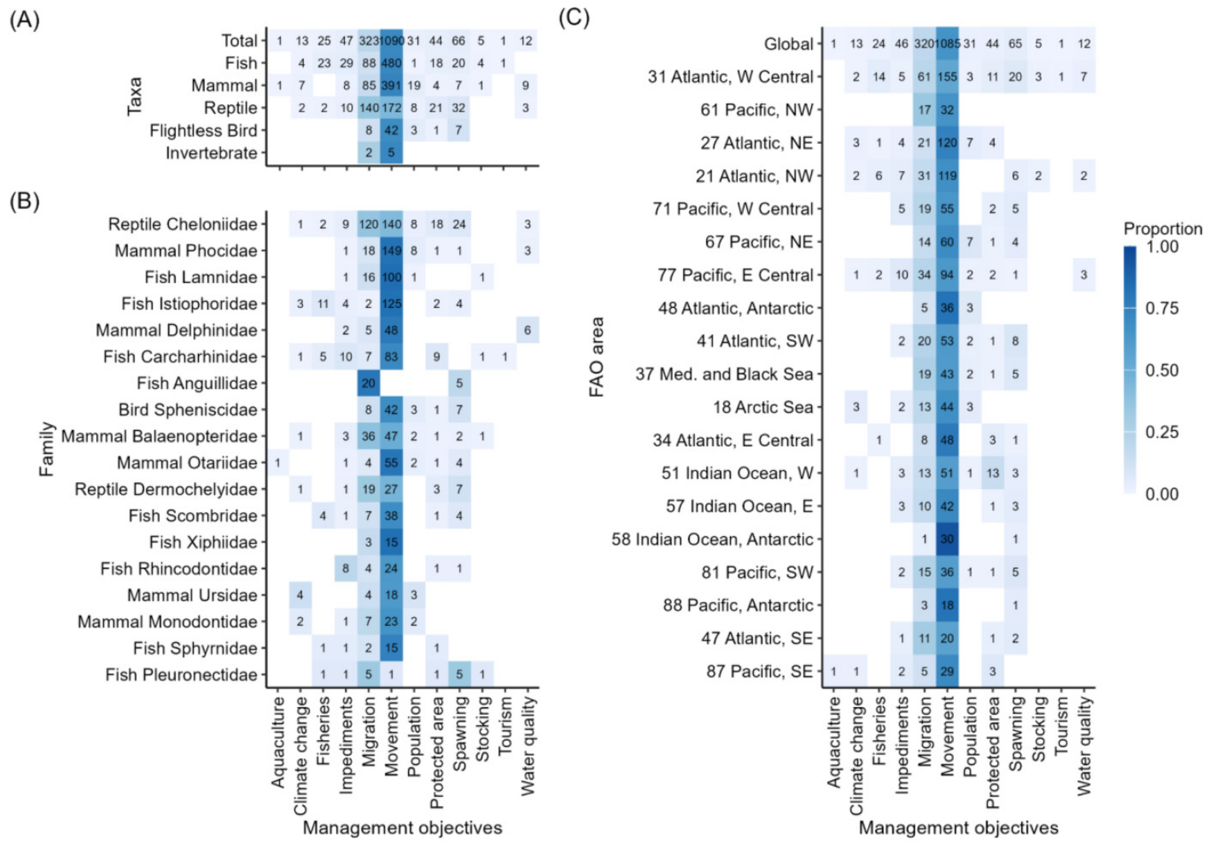
Fig. 7. Proportional total of management objectives using satellite telemetry targeted for (A) taxa, (B) families with >15 studies, and (C) Food and Agriculture Organization (FAO) Major Fishing Areas with >20 studies. Taxa, fish family, and FAO area are ordered from highest to lowest total number of studies from top to bottom. Colour indicates the proportion of each objective calculated within each row.



(n = 2, 4.7%)), Atlantic, Northwest (fish (n = 67, 46.5%), mammals (n = 56, 38.9%), reptiles (n = 20, 13.9%), invertebrates (n = 1, 0.7%)), and Pacific, Southeast (mammals (n = 10, 40.0%), fish (n = 8, 32.0%), flightless birds (n = 5, 20.0%), reptiles (n = 2, 8.0%)).

Management-related objectives

We identified 1658 occurrences of 12 of 14 management-related objectives (aquaculture, climate change, fisheries, impediments, migration, movement, population, protected areas, spawning, stocking, tourism, water quality; Table 1) across all studies (Fig. 7). Most studies considered one management-related objective (98.53%), with the remaining 1.47% addressing two objectives. Overall, general movement accounted for the highest proportion of management-related objectives identified (n = 1090, 66%), followed by migration (n = 323, 19.5%), spawning (n = 66, 4%), impediments (e.g., tagged individuals encountering dams, weirs, artificial reefs; n = 47, 2.84%), protected areas (n = 44, 2.7%), population estimates (n = 31, 1.94%) estimates and fishing (n = 25, 1.5%; see Table 5 for an example of each category). The remaining five management-related objectives (i.e., climate change, water quality, stocking, aquaculture, fisheries, tourism) each accounted for less than 1% of objectives identified, while invasive species and restoration were not addressed in any study.

Management-related objectives across taxa

Across taxa, the management-related objective general movement accounted for over 70% of all objectives for satellite telemetry studies on mammals (73.5%, n = 391), fish (n = 480, 72.7%), and invertebrates (71.4%, n = 5; Fig. 7B). This is unsurprising, as general movement studies are often needed to acquire baseline information to form concrete applied questions. In flightless aquatic birds, general movement was the primary objective 68.85% (n = 42) of the time, and in reptiles, the top two objectives were general movement (n = 172, 44.3%), followed closely by migration (n = 140, 36.0%). The greatest diversity of management-related objectives addressed within a taxon occurred for fish and mammals (n = 10 each), followed by reptiles (n = 8), flightless birds (n = 6), and invertebrates (n = 2). Across all families, general movement was the most studied management-related objective, examined in 57 different families (Fig. 7B). For 20 of those families, general movement was the only management-related objective studied (i.e., in fish: Aetobatidae, Alopiidae, Centrophoridae, Dasyatidae, Hexanchidae, Lampridae, Laridae, Myliobatidae, Pristidae, Pristiophoridae, Sciaenidae, Somniosidae, Squalidae; in mammals: Dugongidae, Iniidae,

Table 5. Case studies of publications applying satellite telemetry to management objectives, there were no studies found that examined either invasive species, stocking, or restoration, so these categories were excluded from this table.

Management objective category	Species	Taxa	FAO area	Study context	Management application	Reference
Aquaculture	South American sea lion	Mammal	87 Pacific, Southeast	Satellite telemetry and stable isotope analysis were used to assess the spatial overlap between sea lions and salmon farms and to quantify their diet. Tracking showed foraging near salmon farms, with farmed salmonids being a significant dietary component. A shift from farmed salmonids to native prey occurred when salmon production declined due to an outbreak of infectious salmon anemia virus.	Findings highlight the potential impact of aquaculture on predator foraging behaviour. Management practices could incorporate telemetry and dietary analyses to better understand and mitigate the effects of farmed fish on marine predators, ensuring sustainable aquaculture operations while preserving wildlife foraging ecology.	Sepúlveda et al. (2015)
Climate change	Narwhal	Mammal	18 Arctic Sea	Satellite telemetry was combined with 25 years of sea surface temperatures and abundance estimates to assess thermal exposure and found that climate change restricted habitat range.	Warming ocean temperatures are likely to restrict narwhal habitat, potentially forcing migrations or leading to local extinctions. These findings highlight the need for conservation strategies that account for shifting habitats, emphasizing the importance of protecting northern refugia and mitigating climate change impacts on Arctic marine ecosystems.	Chambault et al. (2020)
Fisheries-specific (non-aquaculture)	Dolphinfish	Fish	31 Atlantic, Western Central	Satellite telemetry revealed cross-boundary movements and migration pathways across different economic zones throughout the northern Caribbean Islands and the US.	Coordinated international management is essential to ensure consistent policies across jurisdictions, as regional connectivity influences fishing mortality, spawning biomass, and stock health. Understanding these movements is critical for accurate stock assessments and sustainable fisheries management across the U.S. and Caribbean nations.	Merten et al. (2016)
General movement	Nomura's jellyfish	Invertebrate	71 Pacific, Western Central	Satellite telemetry and ultrasonic pingers were used to study the swimming depths and vertical movement of jellyfish. The results showed that these jellyfish predominantly swam at depths less than 40 m, with deeper movements observed in winter and at night. This depth variability suggests that swimming behaviour is influenced by ocean vertical structure.	These findings are crucial for developing targeted jellyfish control measures, such as selective trawl gears and timing of fishing operations based on jellyfish depth patterns. The information can be used to predict jellyfish movements, reduce the economic damage to fisheries, and improve the efficiency of removal strategies based on depth-specific distribution.	Honda et al. (2009)
Impediments/ passage/ construction	Flatback turtle	Reptile	57 Indian Ocean, Eastern	Satellite telemetry was used to track turtles before, during, and after a major dredging operation to assess movement and dive behaviour. Results showed that turtles increased their use of dredging areas and took longer, deeper resting dives, but no injury or mortality events were recorded.	Findings suggest that mitigation measures, such as Marine Fauna Observers on board, may reduce injury and mortality risks. Tracking data can improve Environmental Impact Assessments by refining impact predictions and informing more effective dredging management strategies to minimize disturbance to marine turtles.	Whittock et al. 2017

Table 5. (*continued*).

Management objective category	Species	Taxa	FAO area	Study context	Management application	Reference
Migration	Chinstrap penguin	Flightless Bird	48 Atlantic, Antarctic	Satellite telemetry tracked the winter movements of penguins from two colonies in the South Shetland Islands. Results showed distinct foraging behaviours in 2000 and 2004, with penguins foraging inshore in 2000 but offshore in 2004. Additionally, some penguins migrated up to 1,300 km, suggesting varying migratory strategies based on ancestral population ties.	The study highlights the importance of understanding individual migratory patterns for effective conservation management, particularly in the face of changing oceanographic conditions. Satellite telemetry can inform migration management strategies by identifying critical foraging areas, migration corridors, and the impact of environmental changes on penguin movement, guiding protection efforts for breeding and foraging habitats.	Trivelpiece et al. (2007)
Protected area	Bull, great hammer-head, and tiger sharks	Fish	31 Atlantic, Western Central	The effectiveness of marine protected areas (MPAs) in conserving highly mobile shark species remains unclear, necessitating an assessment of their overlap with core habitat use areas via ST.	Expanding MPAs to include U.S. territorial waters could enhance protection for sharks, particularly the overfished great hammerhead, and support regional conservation efforts.	Graham et al. (2016)
Spawning/ mating/ nesting	South Pacific eels	Fish	81 Pacific, Southwest	Spawning locations of tropical South Pacific eels remain uncertain, with possibilities ranging from centralized spawning sites to multiple local spawning areas. Satellite telemetry tags were used in combination with other methods, including larval sampling, morphological and genetic analyses, and virtual larval drift modelling, to identify potential spawning sites and better understand eel movements within the Pacific Ocean.	Tags surfaced prematurely after 11 to 25 days, 91 to 345 km from release, with some eels approaching known larval catch locations near American Samoa, suggesting local spawning. Silver eels exhibited diel vertical migrations and moved toward increasing salinity and eddies, indicating potential habitat preferences. These findings highlight the importance of identifying and protecting critical spawning habitats and migration corridors to ensure the sustainability of South Pacific eel populations.	Schabetsberger et al. (2021)
Stocking	Bowhead whale	Mammal	21 Atlantic, Northwest	Satellite telemetry was used to whales revealing their migratory routes and seasonal habitat use. Novel findings regarding migrations challenge assumptions about stock discreteness and suggest that current abundance estimates may be underestimated.	Satellite telemetry can refine population assessments and management strategies by providing more accurate migration and habitat-use data. The study highlights the need to reconsider stock structure and improve abundance estimates, which can inform conservation policies and ensure effective protection of critical habitats.	Heide-JØrgensen et al. (2006)
Tourism	Tiger shark	Fish	31 Atlantic, Western Central	This study used Satellite telemetry to examine the long-range migrations and habitat use across areas with differing levels of ecotourism. The data rejected the idea of behaviourally mediated effects of provisioning at large scales and revealed new insights into the sharks' long-distance migrations and use of productive feeding areas in the Gulf Stream and subtropical Atlantic.	Satellite telemetry can inform management strategies for shark ecotourism by providing evidence that challenges assumptions about negative impacts on predator behaviour. The study suggests that while provisioning ecotourism may have some benefits for public awareness and conservation, its effects on shark behaviour are minimal. This can guide ecotourism policies that aim to balance conservation goals with sustainable tourism practices.	Hammerschalg et al. (2012)

Table 5. (*concluded*).

Management objective category	Species	Taxa	FAO area	Study context	Management application	Reference
Water quality/ pollution/ pathogens/ disease	Kemp's ridley sea turtle	Reptile	31 Atlantic, Western Central	The 2010 Deepwater Horizon oil spill released millions of barrels of crude oil into key foraging areas. Stable isotope analysis, combined with Satellite telemetry provided evidence of oil exposure.	Understanding oil exposure is critical for assessing long-term population trends, including impacts on growth and recovery. Consistent monitoring using C isotope signatures in scutes as biomarkers can inform conservation strategies and guide mitigation efforts in affected habitats.	Reich et al. (2017)
Population	White Shark	Fish	77 Pacific, Eastern Central	Satellite telemetry was used to estimate survival rates and cause-specific mortality for sharks in the northeastern Pacific, examining the effects of intrinsic and environmental factors on mortality risk.	The findings highlight bycatch as the main mortality source for sharks, emphasizing the need for quick release practices, while accounting for environmental factors that influence survival.	Benson et al. (2018)

Note: FAO, Food and Agriculture Organization.

Ziphiidae; in invertebrates: Rhizostomatidae; and in reptiles: Emydidae). Similarly, migration was a common management-related objective studied across 37 families. There were 140 migration studies on reptiles primarily conducted on Cheloniidae and a limited number on Dermochelyidae and Crocodylidae. There were a similar number of fish and mammal migration studies ($n = 87$) and ($n = 85$), respectively, with a greater diversity of families within fish ($n = 21$) than in mammals ($n = 10$), which consisted mainly of cetaceans and seals. There were seven migration studies on flightless birds for the Spheniscidae family, and only two invertebrate migration studies on Ommastrephidae. After movement and migration, the greatest diversity of families was observed in studies related to impediments ($n = 17$), protected areas ($n = 16$), spawning ($n = 13$), and climate change ($n = 8$). The remaining management-related objectives had three or fewer families studied per objective.

Management objectives across FAO areas

General movement was the most studied management-related objective across all FAO areas and was investigated in 23 of the 26 areas (all except for Oceania—Inland, Europe—Inland, and Antarctica; Fig. 7C). Migration was the next most studied objective across all FAOs and was examined in 22 different fishing areas. Like overall trends in the occurrence of management-related objectives, there were minimal contributions from the remaining 10 objective categories. The greatest diversity of management-related objectives was studied in the Atlantic Western Central ($n = 11$), followed by Pacific Eastern Central ($n = 8$). The Atlantic Northwest and Southwest and Indian Ocean Western each had studies on seven different management-related objectives, and the Atlantic Northeast, and Pacific Southwest and Southeast each had studies on six different management-related objectives. All other FAOs had studies on five or fewer management-related objectives. There were 92 studies that incorporated two or more FAO areas in their tagging efforts.

Discussion

Here, we synthesized current trends in satellite telemetry research on aquatic animals as they relate to taxa, location, and management-related objectives from 1137 primary journal articles published between 1982 and 2022. We found that research has spanned diverse taxa and mammals have been a common focus of these studies. However, substantial efforts have increasingly included fish and reptiles. Recently, invertebrates, such as squids, jellyfish, and crabs have also been tagged with satellite telemetry. Most satellite telemetry studies did not incorporate complementary methods, leaving plenty of opportunity to bolster these data; however, some studies made use of approaches such as biological sampling (e.g., genetics or diet). The greatest number of studies occurred in the oceans surrounding North America and Europe (i.e., North Atlantic and Pacific) and very few studies occurred inland in freshwaters. Most studies included in our review focused on evaluating general movements and did not identify objectives related to specific management themes, highlighting that satellite telemetry may be used more often to address fundamental questions. Here, we discuss our results related to trends in diversity of taxa, complementary methods, FAO areas (i.e., geographic locations), management-related objectives, applications for protected areas, limitations for further adoption of this technology, and, finally, study limitations.

Most satellite telemetry articles studied the movement of taxa including mammals, fish, and reptiles. Flightless aquatic birds and invertebrates were also studied, although to a much lesser extent. It is worth noting that because we focused on satellite telemetry specifically, we have not covered all instances where satellite technology was used to track these taxa. For example, Fosette et al. (2015) used satellite tracking and accelerometers to assess jellyfish swimming responses to current drift, however this study was not included in our review as it did not incorporate satellite telemetry (i.e., remote relay) specifically. The patterns that lead to certain taxa being tracked with satellite telemetry more than others are likely largely reflective of animal size and associated tag burden, as well as the logistics of satellite telemetry for tracking the species. More recently, there has been the development of the microPAT (Wildlife Computers), which currently is the smallest pop-up archival satellite tag available, at 46 g (see Lennox et al. 2025). Although these smaller tags represent substantial technological advancements, they are still relatively large compared to other tracking technologies (e.g., acoustic and PIT) for use on many aquatic animals. As miniaturisation of satellite tags continues, there will be opportunities to study smaller organisms, as well as younger life stages (e.g., juveniles), which has been observed with acoustic telemetry miniaturisation (Lennox et al. 2025).

Aquatic mammals are often considered strong candidates for satellite telemetry tracking, as their large body size typically allows for tag attachment without hindering regular movements or behaviours. However, it is important to recognize that all studies reviewed should, in principle, only deploy tags on individuals large enough to avoid tag burden—related impacts, regardless of taxon (see Matley et al. 2024, for a review on fishes). In addition to size, logistical factors influence study design: many marine mammals cannot be easily captured, requiring specialized attachment techniques that may limit tag retention and study duration—particularly for delphinids and large whales. In contrast, fish and some polar marine mammals (e.g., seals), which are more easily captured, often allow for more secure tag attachment and longer deployments. Differences in taxa behaviour also explain the trends seen in real-time versus archival tag usage. Real-time data acquisition requires the tag to be at the surface during deployment on the study species, and therefore able to communicate with the satellite system overhead (e.g., ARGOS, Iridium, GPS). For species that surface more regularly (e.g., air breathing species like whales, pinnipeds, flightless birds, sea turtles), this is not a problem, but for those that spend all their time below the surface, archival are more realistic. Some of the tendencies toward studying certain taxa are also driven by accessibility, researcher familiarity, and the charismatic nature of particular groups. Much of this is ultimately related to human biases projected onto research (Rosenthal et al. 2017). In ecological research, the availability of funding to work with certain taxa over others creates a bias in research topics and fundamental knowledge of a species (Jenner and Wills 2007; Donaldson et al. 2016). Species with a well-known, previously studied natural history are easier to locate and tag, thereby influencing when and where satellite telemetry studies can be conducted (Hart and Hyrenbach 2009). Researchers may inherently direct our focus to charismatic megafauna (Ward et al. 2008; Borgi and Cirulli 2016) and/or economically or culturally important species (e.g., Comte et al. 2013), which can lead to research funds and efforts being concentrated on species such as turtles, sharks, whales, and seals (Clark and May 2002), as was also seen here.

Satellite telemetry studies occurred in nearly all FAO areas, but some regions received more focus. FAO areas encompassing the Atlantic, Pacific, and Arctic oceans bordering North America were the most studied, which was similar to the global distribution of acoustic telemetry studies (Matley et al. 2022). The European and South American Atlantic Ocean FAO areas, Western Indian Ocean, and the Pacific side of Australia and Oceania were also highly studied. Geographic underrepresentation in ecological research has been attributed to factors such as access to funding and more broadly, the geographic distribution of academic researchers (Culumber et al. 2019). The cost of the tags themselves, access to the study species, data retrieval (i.e., ARGOS satellite uplink) and expert analysis can be prohibitive to underfunded FAOs or research programs (Linberg and Walker 2010). To a lesser extent, a bias toward temperate zones has also been suggested in ecological literature, although there is limited empirical evidence to support this claim (Clarke et al. 2017; Stroud and Feely 2017). Other factors include the feasibility, political stability, and general preference for certain locations (Reeves and Gimpel 2012). Geographic bias has also been historically overlooked in ecological research. In a study conducted on biases in ecology, less than 60% of respondents reported that they had considered geographic or funding biases in research (Zvereva and Kozlov 2021). Ultimately, a robust understanding of species movement should take a global approach to tracking. Satellite telemetry is particularly relevant here given its ability to track across FAO boundaries.

One of the well-established benefits of satellite telemetry is the global coverage and indeed some studies have reported animals moving huge distances across oceans (e.g., Dale et al. 2022; Womersley et al. 2022). Yet less than 10% of studies reviewed here included data from multiple FAOs. This finding was surprising, as we expected more animals to undertake movements across FAOs. While FAO regions are large and several span multiple ecological zones (e.g., FAO 24, 27, 31), the lack of movement across FAO boundaries is ecologically reasonable when considering environmental factors such as water temperature. Many species remain within a single FAO region where their preferred habitat conditions are already met. For instance, highly mobile species like beluga whales (*Delphinapterus leucas*; Castellote et al. 2021) and loggerhead turtles may have the capacity to traverse great distances, but their specific environmental requirements (i.e., subarctic and tropical waters, respectively) limit their need to cross into different FAO zones. Finally, we found that there were relatively few studies undertaken in areas such as the South American Pacific Ocean and the Indian Ocean. Addressing these gaps should in turn create a more robust understanding of the movement of species and can also help determine the broader health and productivity of all FAO areas.

Satellite telemetry studies were far less common in inland FAO areas compared to marine regions. This differs from acoustic telemetry studies, which have been widely applied in inland waters, particularly in North America and Europe (Matley et al. 2022). The limited use of satellite telemetry in freshwater systems is likely due to a combination of practical and ecological constraints that make its application less suitable in these environments. For instance, satellite tags are often too large for many freshwater species, and their use could impair natural behaviours, raise ethical concerns, and produce data that are not representative of untagged individuals. While the development and widespread adoption of acoustic telemetry has helped mitigate some of these limitations over the past several decades (Matley et al. 2022), satellite telemetry still presents challenges in freshwater contexts. Light-based geolocation, for example, has relatively large errors (Teo et al. 2004), making satellite telemetry more appropriate for tracking broad-scale oceanic movements than the finer-scale movements typical in freshwater systems. PSATs also commonly rely on saltwater to corrode a metal component for tag release (Block et al. 1998), which does not function in freshwater. Thus, the lower frequency of satellite telemetry use in inland waters is not a reflection of bias, but rather an expected outcome based on the constraints of the technology and the spatial and biological characteristics of freshwater systems. Moreover, marine ecosystems cover a vastly larger area globally, and the broad-scale movements of many marine species are better aligned with the strengths of satellite telemetry, contributing to its greater prevalence in oceanic studies.

Several studies reviewed here demonstrated how satellite telemetry has been used alongside other complementary data collected from biological sampling (e.g., Luo et al. 2012), traditional sampling (e.g., Van Bonn et al. 2011), visual observations (e.g., Smith et al. 2012), experimental approaches (e.g., Richardson et al. 2009), and hydroacoustics (e.g., Schaber et al. 2022). Biological and traditional sampling methods were not commonly used alongside satellite telemetry, which may be a consequence of the logistics associated with undertaking field studies on aquatic animals. For example, it is difficult to repeatedly collect biopsies (i.e., biological sampling) from cetacean species that are often inaccessible beneath the water's surface (Noren and Mocklin 2012). Complementary data may also be collected at the time of tagging, but then subsequently published in other studies. Studies that made use of visual observations relied on animals that surfaced to breathe (e.g., sea turtles or marine mammals), which limits the application to non-air breathing animals such as fishes and invertebrates. Next, satellite telemetry transmitters are mostly fixed to aquatic animals externally, which can limit the ability to undertake experimental approaches commonly used in acoustic telemetry (e.g., locomotor activity; Hellstrom et al. 2016). Finally, hydroacoustics could have been used infrequently due to the inherent mismatch of spatial scale with satellite telemetry, where hydroacoustics are typically used to study biomass in fine-scale areas. There also remains opportunity to incorporate additional sensors (e.g., dissolved oxygen, temperature, depth etc., e.g., Vedor et al. 2021) into satellite tag packages specifically. These metrics have been recorded in the past using biologgers but the incorporation of sensors into satellite tag packages directly may further improve our ability to synchronize data collection and improve our analytical capabilities, similarly to what has been observed in acoustic telemetry work (Hussey et al. 2015). Despite the logistical challenges associated with complementary methods, there remains great opportunity to bolster satellite telemetry studies to expand our understanding of factors (e.g., diet or cardiac activity) influencing movement (Matley et al. 2022).

Across all management-related objectives, general movement was the most frequently studied category using satellite telemetry. This likely reflects the technology's strength in addressing fundamental ecological questions, particularly for species that move long distances and spend extended periods below the surface, where direct observation is difficult. In such cases, satellite telemetry enables researchers to gain new insights into the movement ecology of elusive or wide-ranging species—insights that may not be accessible through other methods. As such, much of the research using satellite telemetry may be inherently more exploratory in nature, especially for taxa with limited baseline data. Understanding these general movement patterns is a crucial first step, particularly for populations of conservation concern (e.g., elasmobranchs; Renshaw et al. 2023) and in the context of rapidly changing aquatic ecosystems. We reiterate the message of others that while this foundational knowledge is essential, future studies should strive to delineate clear research questions aligned with explicit management objectives early in the research design phase (Hays et al. 2019). Doing so can help ensure that even exploratory studies contribute actionable insights to conservation and management efforts, particularly as our understanding of species ecology continues to grow.

Among the studies that focused on answering research questions related to management-related objectives, common themes included migration (e.g., Werry et al. 2014), spawning (e.g., Perry et al. 2020), impediments (e.g., Aschettino et al. 2020), protected areas (e.g., Doherty et al. 2017), and population estimates (e.g., Citta et al. 2017). After general movement, migration was the next most frequently studied management-related objective. Identifying migration corridors is critical for protecting animals both during transit and upon reaching their destinations (Alerstam and Backman 2018), particularly given the significant energetic investment required for migration (Braithwaite et al. 2015). Reptiles and mammals were the most frequently studied taxa from a migratory context. For many species, migration patterns and destinations remain unknown or understudied, warranting further investigation (e.g., Herr et al. 2022). Identifying patterns related to spawning and mating is essential for the long-term and sustainable protection of aquatic animals. Satellite telemetry is particularly useful for identifying spawning areas in remote locations where acoustic receiver arrays may be difficult to install (Schlenker et al. 2021). Some animals, such as whales and turtles, undergo obligate long-distance migrations to reach spawning grounds, making it crucial to map and protect their routes and key habitats (Shimada et al. 2021). Promisingly, satellite telemetry has been valuable for pinpointing previously unidentified spawning habitats, such as those used by Anguillidae (Koster et al. 2021). Management-related objectives related to impediments in aquatic environments were also relatively underrepresented. The development of urban infrastructure and offshore renewable energy sources can impose significant barriers to movement (Halpern 2008; Womersley et al. 2022; reviewed in Lennox et al. 2025). Carcharhinids and Istiophorids were the most frequently studied fish families in relation to marine impediments, potentially due to their frequent encounters with human activities in coastal zones—for example, blue marlin interactions with fishing gear (Kerstetter et al. 2003). However, the broad spatial scale of satellite telemetry, combined with a lack of data from inland FAO areas, may help explain its limited application in studying fish passage and the movement constraints imposed by in-water infrastructure within freshwaters such as hydropower dams (see Arthington et al. 2023). To address this gap, integrating multiple telemetry methods that operate at different spatial and temporal resolutions may provide a more comprehensive understanding of movement restrictions across species and environments.

Satellite telemetry has shown to be useful to evaluate the efficacy of protected areas, given that it can track long-distance movements, leading to the identification of transboundary movement patterns (e.g., Peñaherrera-Palma et al. 2020). Protected areas were most studied in the West Indian Ocean, which could be a result of the fact that the area is a biodiversity hotspot (see Gaither et al. 2013) or strong regional conservation efforts within the region (e.g., locally managed marine areas; LLMAs; Rocliffe et al. 2014). The use of protected areas by fishes and reptiles were studied most, with Carcharhinids encompassing the most tracked fish family. Satellite telemetry can support specific management-related objectives to ensure protected areas are functioning to effectively protect highly mobile species with large home ranges, such as tiger sharks (*Galeocerdo cuvier*) which may need larger protected areas to fully encompass their movements in and around critical habitats (Smukall et al. 2022). Thus, satellite telemetry can be a valuable tool to assess the effectiveness of spatial protection measures (Hays et al. 2021).

Certain management-related objectives—such as those related to fisheries, aquaculture, tourism, and water quality—were rarely studied using ST. This is likely due to the broad spatial scale of ST, which may not align well with the finer spatiotemporal scales required for these applications. Surprisingly, management-related objectives related to fisheries and fisheries-related impediments were understudied, despite the potential to use satellite telemetry to examine movements in relation to this anthropogenic stressor. Specifically, satellite telemetry is well suited to studying interactions with large-scale open ocean fishing gear, including fish aggregating devices (FADs) (Kerstetter et al. 2003; Eddy et al. 2016Sulikowski et al. 2020; Queiroz et al. 2019). Given the increasing global reliance on fisheries and the importance of sustainable management, more research is needed to assess how aquatic animals navigate and interact with fishing activities (e.g., Quieroz et al. 2016). Interestingly, mammals were the most studied taxa in water quality research, likely due to their prevalence in urbanized habitats (e.g., Balmer et al. 2018). Finally, few studies examined movements in relation to climate change (e.g., Hammerschlag et al. 2022), potentially due to a temporal mismatch between climate change trends and the relatively short duration of satellite telemetry studies. The average study duration across the 1137 publications was 3.8 years, which may be insufficient to detect long-term responses to climate change. Additionally, the scarcity of baseline or historical satellite telemetry data may limit the ability to draw comparisons over time. Confounding effects from other anthropogenic stressors may also obscure climate-driven movement patterns. Addressing these gaps will require long-term monitoring efforts that combine satellite telemetry with other data sources to better understand how climate change is altering movement patterns.

Despite the increasing use of satellite telemetry over time, there are still limitations associated with its application. While many aspects of satellite telemetry have improved since the first generations of tags, satellite telemetry tags tend to be larger than alternative tag types (e.g., acoustic tags), restricting their use for species with small body sizes and early life history stages (Jepsen et al. 2015). There are also challenges with tag retention and performance on aquatic species that vary depending on the tagging method and species. For example, while premature release or malfunction can occur with PSATs or tow-style SLRTs (Musyl et al. 2011), most SLRTs are securely affixed—such as through the dorsal fin in sharks—where retention is generally high. In these cases, biofouling or gradual tissue growth around the tag can interfere with transmission or reduce data quality over time. Improvements in transmitter technology (i.e., miniaturisation and higher accuracy) and increases in satellite coverage have been made to address tag burden and transmission concerns across tag types (Gould et al. 2024) Additionally, geolocation estimates from archival tags often have complex spatial error structures that can obscure specific movement patterns and require cautious interpretation of the data. However, progress continues to improve the accuracy and usability of these data, including geolocation models that can provide location estimates for species that spend time in the aphotic zone (Braun et al. 2018; Horton et al. 2024). A barrier to the use of satellite telemetry technology is that it is a relatively high-cost tracking method. Among all transmitter types (e.g., acoustic, radio, PIT), satellite transmitters are the most expensive, with additional costs arising from satellite time and operational expenses associated with the deployment (Sequeira et al. 2019) and then eventual collection of the tag via recovery surveys (Gatti et al. 2020). Licensing fees for accessing satellite networks to retrieve collected data further compound the financial burden (Hardin et al. 2024). These costs often limit sample sizes and restrict the adoption of satellite telemetry for many research programs. Despite these challenges, satellite telemetry is part of the standard toolkit for studying aquatic animals, and promises to become even more prominent, particularly with the ongoing miniaturization of tags. There remains opportunity to create more collaborative networks to connect researchers across the globe, such as the Spatial Ecological Analysis of Mega-vertebrate Population (OBIS-SEAMAP), Migratory Connectivity, Marine Megafauna Movement Analytical Program, and the Global Shark Movement Project, which could increase transparency, data sharing, and collaboration (Renshaw et al. 2023). Additionally, there have been increasing calls for movement data to be made readily available online in a standardized format to support basic science, conservation, and public engagement (Wikelski et al. 2024).

Limitations

Our global literature review likely did not encompass the full range of relevant publications, and it is inevitable that we will have missed some literature due to any number of reasons. We focused on peer-reviewed papers, which may have excluded campaigns or studies reported in grey literature. This includes work by governments and NGOs, which publish primarily in grey literature (Lawrence 2017). Consequently, our analysis may have overlooked valuable insights from such sources. Additionally, our review was limited to English-language articles, potentially excluding important non-English literature (see Konno et al. 2020; Amano et al. 2023), which could have further narrowed the scope of our findings. To address these limitations, future research should aim to incorporate grey literature, including reports from government and NGO agencies, and expand literature searches to include non-English publications. It is also likely that the broad categories used here do not fully capture some of the nuanced applications and supporting information related to satellite telemetry. Nonetheless, given our focus on patterns and large number of relevant studies we discovered during our review, we believe our findings provide a comprehensive and reliable overview of the state of aquatic satellite telemetry studies to date.

Conclusion

Our global literature review provides a comprehensive assessment of the use of satellite telemetry to study aquatic animal movement across taxa, complementary methods, geographic regions, and management-related objectives. Over the past four decades, satellite telemetry has been widely applied, particularly to mammals, fish, and reptiles, with increasing efforts to track invertebrates in recent years. However, our findings reveal significant biases in the taxa studied, geographic distribution, and research focus, likely driven by technological limitations, accessibility, and funding availability. Most studies focused on fundamental questions regarding general movement rather than applied management questions, highlighting an opportunity to better integrate satellite telemetry data into conservation and management efforts. Despite its broad applications, satellite telemetry remains underutilized in freshwater environments, where adoption may increase as tags decrease in size and improvements in geolocation algorithms reduce location uncertainty. Expanding the use of satellite telemetry to address emerging conservation challenges (e.g., offshore wind), particularly in underrepresented regions and taxa, will be critical in the coming years. Future research should focus on improving satellite telemetry technology, increasing collaboration across research networks, and integrating complementary tracking methods to enhance the ecological and management relevance of findings. Addressing gaps in geographic coverage and management applications will strengthen our understanding of aquatic animal movement and inform effective conservation strategies. As satellite telemetry continues to evolve, it holds great promise for advancing movement ecology and supporting global efforts to protect aquatic biodiversity.

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