

The use of acoustic and satellite telemetry to study elasmobranchs in Latin America: past efforts and future directions

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ABSTRACT. The study of marine animal movements is crucial for understanding the diversity of oceanic ecosystems and the fundamental role of each species. Today, acoustic and satellite telemetry are non-invasive methods that is widely used to track marine animals, including elasmobranchs (sharks and rays). Despite its importance, there is no systematic review assessing the use of telemetry in elasmobranch studies in Latin America. We conducted a literature review and analyzed 106 publications, of which the majority pertained to elasmobranch studies in Mexico ($n = 60$), Brazil ($n = 16$), and Ecuador ($n = 13$). The predominant focus among studies was habitat use ($n = 94$). Pop-off satellite archival transmitting (PAT or PSAT) tags and smart position and temperature (SPOT) tags were primarily used for large spatial scale studies (i.e., migration). Acoustic telemetry was better suited for tracking long-term behavior over comparatively smaller spatial scales (e.g., regional movements). While successful cases exist in the literature, challenges remain due to the high financial costs, effort to maintain collaborative equipment, and limited research output in Latin America. Our findings highlight the need to enhance the application of telemetry data for effective elasmobranch management and conservation and reflect the importance of connecting research outcomes to practical actions amid ongoing management and conservation challenges.

Key words: telemetry, habitat use, movement ecology, shark, ray, elasmobranch, management, conservation.

INTRODUCTION

The study of animal movement and habitat use arises from the need to understand the vast biodiversity within marine ecosystems and the fundamental role each species plays in these complex systems. Telemetry is a key tool for this purpose, as it enables detailed tracking of the movements and behaviors of animals in their natural habitats via satellite tags, depth sensors, and radio frequency systems (Hussey et al. 2015). This tool provides precise data on migration, habitat use, intra- and interspecific interactions (Lahoz-Monfort and Magrath 2021). Additionally, telemetry offers valuable information to support fisheries management, conservation, and assessments of human impacts on marine ecosystems, thereby contributing to efforts to protect animals and preserve their habitats (Crossin et al. 2017, Brownscombe et al. 2022).

The history of telemetry in aquatic animal studies dates to 1653, when Izaak Walton first reported attaching ribbon tags to the tails of juvenile Atlantic Salmon (*Salmo salar*) to track their migration following the marine phase of development. While the exact materials Walton used are unknown, it is presumed that these ribbon tags were simple and flexible labels made from paper or cloth that were designed to be visible above the water to aid in identification when the fish were recaptured (McFarlane et al. 1990, Walton and Cotton 1898). The first underwater telemetry study was conducted by Trefethen (1956), who also focused on salmonids, specifically Pacific salmon (*Oncorhynchus* spp.), and aimed to study their migration patterns and behaviors (Hockersmith and Beeman 2012). Since then, tagging methods have evolved from natural marks to spaghetti tags (McFarlane et al. 1990, Kohler and Turner 2001) and from passive synthetic tags to electronic

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tags that rely on radio telemetry, which involves recording and transmitting instrument readings (Rodgers 2001). Satellite tags have been developed to suit the unique morphological and behavioral traits of animal carriers, including fish, marine mammals, birds, and reptiles (Hussey et al. 2015).

Chondrichthyes is a class of cartilaginous fish that includes sharks, skates, and rays (96%), as well as chimeras (4%) (Bigelow 1953, Hamlet 1999). These species typically exhibit low population growth rates due to their longevity, late sexual maturity, long gestation periods, and low fecundity, making them highly susceptible to anthropogenic impacts (Hamlet 1999, Barria and Colmenero 2019). Elasmobranchs encompass a large number of predatory species, from the small rocky-reef dwelling Horn Shark (*Heterodontus francisci*) to the large-bodied, wide-ranging, migratory White Shark (*Carcharodon carcharias*). As meso- or top predators of the ecosystems they inhabit, they are natural regulators of trophic dynamics (Young et al. 2015) and important indicators of the health and productivity of marine ecosystems (Graham and Largier 1997, Croll et al. 2005, Wingfield et al. 2011). However, elasmobranchs are difficult to study given their broad habitat ranges, life cycles, and mobility that can span oceanic basins (Llopiz and Cowen 2008, Llopiz et al. 2010, Catalán et al. 2011, Llopiz and Hobday 2015).

Elasmobranch telemetry studies, which began in 1965, have provided basic information on diel patterns of movement and space utilization, depth distributions, body temperatures, swimming speeds, and physiological parameters, offering valuable insights into population status, distribution patterns, habitat use, and behavior (Stevens 1999, Hammerschlag 2011, Matley 2022, Renshaw 2023). Satellite telemetry tools, such as smart position and temperature transmitting (SPOT) tags and pop-off satellite-linked archival transmitting (PAT or PSAT) tags, have since been developed to track elasmobranch movements over large spatial scales (Weng et al. 2005, Rigby et al. 2019, Hart et al. 2021, Hicks and Lobel 2024). Smart position and temperature transmitting and PSAT tags, which are attached externally (Weng et al. 2005, Hart et al. 2021, Hicks and Lobel 2024), can provide unique and valuable information about the migratory behavior of elasmobranchs (Bonfil and O'Brien 2015) (Table 1).

Smart position and temperature transmitting tags track movement by sending a geographic message to a satellite every time a tagged fin breaks the surface of the water, along with depth and temperature data (Welch and Eveson 1999, Jewell et al. 2011, Rigby et al. 2019). However, they do not archive or transmit data when the animal is submerged, which may result in data gaps depending on surfacing behavior. Smart position and temperature transmitting tags provide relatively accurate position data (<250 m to 5 km), depending on the number of satellite connections, with a lower number of connections resulting in higher position error.

Pop-off satellite-linked archival transmitting tags are programmed to automatically release from an animal on a predetermined date or when exposed to specific depth (pressure)

conditions; once released, the tags float to the surface. At the surface, the exposed antenna transmits summary data to a satellite. A full, detailed data archive can be downloaded if a tag is physically recovered. Pop-off satellite-linked archival transmitting tags record light (Welch and Eveson 1999), depth, and temperature data. Geolocation information can be estimated using the recorded light levels (dawn and dusk) based on the latitudinal position of the individual carrying the tag. However, geolocation estimates can carry errors of 60–80 km (Seitz et al. 2003). Therefore, PSAT tags are mainly used to study large-scale movements and temperature and depth preferences (Jewell et al. 2011, Rigby et al. 2019).

In recent years, acoustic telemetry has become essential to conservation efforts for endangered aquatic species (Cooke et al. 2008). It represents a useful alternative in deep, vertically stratified aquatic habitats, as acoustic telemetry allows signals to be transmitted and received even when the tagged animals are submerged (Hartog et al. 2009, Strickland et al. 2020). Acoustic telemetry, which employs tags from companies like InnoSea (formerly VEMCO; Boston, USA), Wildlife Computers (Redmond, USA), or Lotek Wireless (Newmarket, Canada), is used mainly in elasmobranch studies to examine detailed behavior and movement patterns in specific areas. Acoustic tags are especially effective for long-term research, given that some tags (e.g., V16) can last up to 10 years, whereas most satellite tags have lifespans of <1 year. Acoustic telemetry has also been widely used to study elasmobranchs since the early 1980s (Klimley and Nelson 1984, Bessudo et al. 2011, Rodríguez-Arana-Favela 2018, Acosta-Pinzón 2023). This type of telemetry is considered a powerful tool for studying elasmobranch behavior and spatial ecology without disturbing natural activities. Once animals adapt to acoustic tags, stress is minimized (Zanella 2006), and the recorded behaviors are expected to reflect natural patterns (Digby et al. 2013, Kessel et al. 2014).

Active and passive strategies have been developed within the field of acoustic telemetry. Passive acoustic telemetry involves installing receivers in specific locations where tagged organisms are expected to pass; therefore, large-scale collaborative efforts are often needed to deploy receiver arrays with broad spatial coverage to maximize data collection (Lahoz-Monfort and Magrath 2021, Dwyer et al. 2023, Lennox et al. 2023). Active acoustic telemetry involves actively following a tagged organism from a boat using a hydrophone. Although it typically covers limited areas and temporal scales due to the logistical limitations of manual tracking, active acoustic telemetry offers the advantage of providing key information on the detailed movements of a few individuals (Bridges and Dorcas 2000, Heupel et al. 2006, Madalozzo et al. 2017).

Acoustic tagging methods have helped to assess short-term movement patterns and gather information on shark habitat use relative to environmental variables (e.g., depth and temperature). Nonetheless, employing these methods requires intensive effort and is limited globally, as it involves the in situ tracking of a single tagged animal at a time, which limits the number of animals that can be tagged and the duration of tracking efforts

Table 1. Comparisons between acoustic and satellite telemetry: primary uses and detection ranges.

Methodology	Description	Primary use	Detection range
Acoustic telemetry (active and passive)	Uses transmitters that emit sound signals detected and archived by receivers or hydrophones.	Studies of behavior and movement over short to medium time frames that are primarily focused on characterizing the movements of individuals in a detailed and specific manner within a given area.	Limited by the receiver network or receiver distance to the tagged organism, with distances typically spanning tens of kilometers.
Satellite telemetry	Uses transmitters that send data to satellites, allowing tracking over long distances.	Studies of long-term movements and migrations.	Global and limited only by battery life and satellite coverage.

and carries a high cost (e.g., boat, fuel, and personnel) (Curtis 2008, Kessel et al. 2014). Advances in transmitter miniaturization and battery life have enhanced the efficiency and longevity of passive and active acoustic methods. For instance, the smallest acoustic transmitters last a few days to weeks, while the largest can function from 3 to 10 years (Hellström 2022). Transmitter selection depends on factors such as the species of interest, the environment of the study site, and the research objectives (Baker et al. 2019) (Table 2).

Some countries, such as the United States, Australia, and South Africa, stand out for their research on the behavior and movement patterns of elasmobranchs using different types of telemetry (Heithaus et al. 2007, Yeiser et al. 2008, Jewell et al. 2011, Werry et al. 2012, Chapple et al. 2015, Hussey et al. 2015, Bruce et al. 2019). Previous studies have focused on the ecology, physiology, behavior, habitat use, and connectivity between oceanic and coastal systems of individual organisms (Heupel et al. 2006, Espinoza et al. 2011, Werry et al. 2012, Becker et al. 2015) and have aimed to integrate their findings into policy and management strategies, including the design of marine protected areas (MPAs) (Lombard et al. 2007). They have also been performed to observe the physical structure of the oceans of the world using the sensors embedded in acoustic tags (Pauthenet et al. 2018).

In Latin America, the earliest study using passive acoustic telemetry to track elasmobranchs was conducted by Klimley and Nelson (1984) and focused on evaluating the diel movement patterns of the Scalloped Hammerhead (*Sphyrna lewini*) at El Bajo Espíritu Santo in Mexico. In that study, the authors tracked the movements of 13 tagged sharks, revealing their consistent swimming along the seamount ridge during the day and their rhythmic departures and returns to the area. This approach highlights the advantages of using passive acoustic tracking as a remote monitoring method. In particular, animal behavior is undisturbed by the presence of researchers while the sampling

effort is increased across time and space, thereby enhancing the probability of species detection (Madalozzo et al. 2017). Moreover, passive acoustic tracking permits organisms to be monitored at different times and over extended sampling periods, making it particularly useful for revealing activity patterns across daily and seasonal cycles (Digby et al. 2013).

Both satellite and acoustic telemetry have proven effective for studying animal movements and behavior, but each method has specific limitations. For instance, satellite tags may be expensive, have relatively low data resolution depending on the transmission frequency, and require the animal to surface (e.g., SPOT tags). In contrast, acoustic telemetry is constrained by its detection range and need for receiver infrastructure in situ, which limits its effectiveness in remote or deep-water habitats. Several authors have recommended using hybrid transmitters or combining multiple telemetry technologies within the same study to overcome these limitations and provide a more comprehensive understanding of animal movements and behavior (Brien et al. 2010, Calverley and Downs 2015, Baker et al. 2019).

Despite its importance, no systematic review has assessed the current use of telemetry in elasmobranch studies in Mexico and Latin America (Kohler et al. 2012). This review provides an overview of how telemetry has been used in elasmobranch studies in Latin America, highlights current issues surrounding its use and challenges to its broader implementation (e.g., costs, output, and focus), and examines the extent to which it has contributed to elasmobranch management and conservation.

MATERIALS AND METHODS

Systematic review

We conducted a literature review following the PRISMA (Preferred Reporting Items for Systematic Reviews and

Table 2. Differences between the most commonly used acoustic and satellite tags to track elasmobranchs in Mexico and Latin America.

Tag type	Smart position and temperature tags (SPOT)	Pop-off satellite archival transmitting tags (PAT or PSAT)	Acoustic tag
Location accuracy	Highly precise and provides accurate real-time locations every time the animal surfaces.	Less precise and more prone to error than SPOT and estimates location based on solar light.	Highly precise, depending on the density of the receiver network, and provides accurate locations when the animal is within the range of the hydrophones.
Battery life	Relatively short (weeks to months) due to high energy consumption from frequent data transmissions.	Relatively long (months to years) given that transmission occurs only when the tag is released and reaches the surface.	Long (several years) due to the low energy consumption of acoustic transmitters and infrequent transmissions.
Attachment method	Tags are drilled into the dorsal fin of the shark and remain fixed until the battery depletes.	Tags are attached to the animal and are released after a predefined period, with the collected data sent to the satellite once the tag reaches the surface.	Transmitters are attached to the animal, and receivers are deployed in the study area, typically on the seafloor or on buoys.
Transmission frequency	Frequent (every time the animal surfaces).	Transmits data only upon release or when breaking the surface of the water, thus conserving battery life.	Variable given that transmitters emit signals periodically, and receivers capture these signals when the animal is within range.

Meta-Analyses) guidelines (González-de-Dios et al. 2011), which involved following a standardized review protocol using specific search codes as eligibility criteria (e.g., elasmobranchs, Latin-American works, languages, or publication status) (Moraga and Cartes-Velásquez 2015). We looked for primary and gray literature of studies involving only elasmobranchs conducted in Latin America that were published in English, Spanish, or Portuguese. An electronic search code (elasmobranchs OR elasmobranchii AND acoustic telemetry OR acoustic tracking AND spot OR pat AND LATAM) was developed, and 34 databases and repositories were searched (Supplementary Material Table S1).

Data extraction

The information was manually downloaded and systematized in a spreadsheet, in which each article was assigned an identification code and details, such as author names, publication year, study location, tag, species, and approach, were recorded. Publications that did not specify the type of tagging method, species, or family of the specimen; those conducted outside Latin America; or those focused on fish other than elasmobranchs were excluded from the review. After including

all documents in the spreadsheet, the studies were filtered by manually reviewing each criterion to ensure the quality of the information.

Classification of information

First, we classified the studies based on species, country, publication year, and the type of telemetry employed. Additionally, publications were classified based on whether they were gray or primary literature. Also, in studies that addressed more than one species, telemetry use was evaluated for each species individually. We also ensured no studies were repeated, given that some studies were first reported as gray literature and later published as primary literature. Lastly, the results from each article were analyzed by comparing their objectives, methods, and outcomes. The approach and objective of each article were synthesized into the following categories: habitat use, ethology, animal welfare, population dynamics, trophic ecology, tag effects, fisheries interactions, and management and conservation (Table 3).

The habitat use category was the predominant approach and encompassed a wide range of ecological and biological aspects, including distribution patterns and site fidelity. Kirk (2018)

defined habitat use as “the way an animal uses or consumes a collection of physical and biological resources.” Following this definition, most telemetry studies of elasmobranchs could reasonably be classified under the habitat use category. However, to avoid redundancy and better reflect the primary scientific contribution of each study, we categorized each article based on its primary objective or direct application, even if the study could be classified into secondary categories based on information in the title or text. For example, if a study on movement patterns aimed to analyze a specific behavior, such as hunting, feeding, or reproduction, it was classified under the ethology category rather than the habitat use category, as a behavioral interpretation was its core focus. More specifically, when movement data were used primarily to investigate feeding behavior or trophic position, the study was classified under the trophic ecology category, which we included to highlight the emerging use of telemetry in this ecological subfield.

A similar rationale was applied to the management and conservation category. Although most reviewed articles referred to conservation goals, in practice, only a few demonstrated direct applications of their findings to conservation policies or species management. Therefore, only studies whose results were clearly linked to concrete management actions were included in this category. For instance, the study by Santana-Morales et al. (2021) was the only one to demonstrate a direct application of telemetry data to the development or implementation of species management policies (Table 3). Data visualizations were created using the R package ‘ggsankey’ (Sjoberg 2021) in the R programming environment v. 3.2.4 (R Core Team 2018).

RESULTS

We analyzed a total of 106 scientific publications that used both acoustic and satellite telemetry to study elasmobranch populations. The publications included scientific articles from the primary literature ($n = 79$), as well as undergraduate theses, graduate theses, and technical reports of Natural Protected Areas from the gray literature ($n = 27$). Of these, 20 studies reported organisms that were tagged or tracked within the geographic boundaries of Southern California ($n = 13$); Florida ($n = 5$); temperate northeastern Atlantic, temperate northwestern Atlantic, and southwestern Atlantic ($n = 1$); and Indo-Pacific ($n = 1$), with some organism movements falling within Latin American seascapes (Weng et al. 2007, Domeier and Nasby-Lucas 2008, Medellín-Ortiz 2008, Jorgensen et al. 2012, Stewart 2016, Tyminski et al. 2015, Byrne et al. 2017, Coelho et al. 2017, Vaudo et al. 2017, Benson et al. 2018, Dewar et al. 2018, Byrne et al. 2019, Nasby-Lucas 2019, Rooker 2019, Nasby-Lucas 2020, Anderson et al. 2021, O’Sullivan 2022, Spurgeon 2022, Kanive et al. 2023, Logan et al. 2024).

Satellite telemetry comprised the method reported in most studies of the primary literature, followed by passive acoustic telemetry (Fig. 1, 2; Supplementary Material

Table S2). Nine articles employed more than one type of telemetry (Bessudo et al. 2011, Afonso 2013, Afonso and Hazin 2014, Acuña-Marrero 2017, Chávez-Calderón 2017, Rosende-Pereiro and Corgos 2018, Ruíz-Sakamoto 2018, Salinas-de-León et al. 2022, Logan et al. 2024). Mexico ($n = 31$) had the highest number of studies that included satellite telemetry, followed by Brazil ($n = 13$).

A few articles combined active and passive acoustic telemetry ($n = 3$), whereas others ($n = 6$) integrated satellite telemetry and acoustic methods. A large proportion of the reports ($n = 18$) came from the gray literature stored in university libraries and repositories (Fig. 2). Of these, only 5 reports (4.59% of the total analyzed), namely 1 from Brazil, 1 from Argentina, and 3 from Mexico, were later published in the primary literature (Hoyos-Padilla et al. 2009, Afonso 2013, Nalesso 2014, De Wysiecki 2023, Beauvais 2024).

Of the total number of studies, most were conducted in Mexico ($n = 60$), primarily in the region of Baja California and Baja California Sur ($n = 40$) (Supplementary Material Table S2; Fig. 3), followed by Brazil ($n = 16$) and Ecuador (Galápagos Islands) ($n = 13$) (Fig. 3). The study species comprised different taxa and differed greatly in behavior, feeding habits, and distributions. The most studied species were the White Shark ($n = 24$), Scalloped Hammerhead ($n = 23$), Tiger Shark (*Galeocerdo cuvier*) ($n = 14$), and Whale Shark (*Rhincodon typus*) ($n = 12$; Supplementary Material Table S2; Fig. 3).

The most frequent approach category was habitat use ($n = 94$; Fig. 3). It was found that the White Shark was the only species used to study tagging effects (Domeier et al. 2012), in addition to aspects related to its management and conservation (Santana-Morales et al. 2021). Additionally, it is essential to highlight that only 11 (10.4%) of the 106 documents reviewed focused on rays (Oceanic Manta Ray [*Mobula birostris*], Sicklefin Devil Ray [*Mobula tarapacana*], Spinetail Devil Ray [*Mobula japonica*], Munk’s Pygmy Devil Ray [*Mobula munkiana*], Yellownose Skate [*Dipturus chilensis*], and Ray [*Dipturus trachyderma*]), while 95 (89.6%) focused on sharks; no records were found for chimaeras (Supplementary Material Table S2).

DISCUSSION

The present literature review addressed the current application of acoustic and satellite telemetry to study elasmobranchs in Latin America. The first results from the use of this technology in the region emerged in 2006, and its use has increased ever since. Mexico stands out as the country that has used this technology most frequently. However, most reports and studies in institutional repositories constitute gray literature and are unavailable as primary literature, limiting the size of the audience and the impact of the studies. Additionally, the largest research focus was the ecology of the target species, mainly to elucidate habitat use. Only one study was found that focused.

Table 3. Criteria used to define the categories that classified the elasmobranch telemetry studies included in this review.

Category	General definition	Main inclusion criterion	Specific focus clarification
Habitat Use	Use or consumption of physical and biological resources by the animal (Kirk, 2018).	Studies with the primary objective of describing spatial patterns such as movements, migrations, site fidelity, or habitat use.	Although nearly all telemetry studies involve movement, only those where this was the main focus (not subordinated to another purpose) were included here.
Ethology	Study of animal behavior in its natural environment.	Studies using telemetry data to analyze specific behaviors such as reproduction, hunting, feeding, or social interactions.	If the main objective was to understand a particular behavior (e.g., feeding), then the study was categorized here, even if it used movement data.
Trophic Ecology	Study of trophic relationships and the position of the organism in the food web.	Studies investigating feeding behavior, trophic habits, or space use related to foraging.	If the behavior analyzed was specifically related to feeding, then the study was categorized here to highlight this emerging use of telemetry.
Animal Welfare	Assessment of the impact of tagging or tracking on the health, behavior, or physiology of the animal	Studies evaluating adverse effects of tagging, post-release survival rates, or stress related to handling.	Included methodological studies focused on the welfare of the tagged individual.
Population Dynamics	Processes affecting the size, structure, or spatial distribution of populations.	Studies focused on population connectivity, survival rates, recruitment, population structure, or dispersal	The main objective was to understand population-level processes rather than individual behaviors or movements.
Tag Effects	Impact of telemetry devices on animal performance or device performance.	Studies assessing tag performance, duration, accuracy, shedding rates, or mechanical/physiological impacts.	Differed from those focused on animal welfare in that the focus was more technical or methodological.
Fisheries Interactions	Interactions between elasmobranchs and fisheries.	Studies documenting bycatch, movements into fishing areas, or risks of interactions with fishing gears or efforts.	Included studies aimed at identifying the overlap with fishing activities.
Management & Conservation	Direct applications of results to species, habitat management, or conservation policies.	Only studies with findings that were explicitly used to develop, influence, or implement concrete management actions or policies.	Although many studies mentioned conservation as a general motivation, only those with documented management impacts were included (e.g., Santana-Morales et al. 2021).

Currently, global reviews, such as those by Renshaw et al. (2023) and Hammershlag et al. (2011), have focused on satellite tagging studies of sharks. The reviews by Kessel et al. (2014) and Matley et al. (2022) presented a comprehensive analysis of how the acoustic detection ranges of aquatic animals have been considered and assessed. However, no work has focused on evaluating different types of telemetry to study elasmobranchs, not only sharks or aquatic fauna, in Mexico or Latin America.

Improving tagging and tracking techniques is complicated due to high costs (Hebblewhite and Haydon 2010, Skupien et al. 2016), a lack of basic information (Thiem et al. 2010), and the limited number of comprehensive reviews focused specifically on the use of telemetry in marine fishes (Cooke et al. 2011). Given this context, many authors have suggested combining telemetry, hybrid transmitters, and other technologies within the same study to overcome the limitations inherent to each tracking technology (Brien et al. 2010, Calverley and Downs 2015, Baker et al. 2019).

Satellite telemetry

Across Latin America, studies using satellite telemetry have shed light on the relationships between the movements and behaviors of species, such as the Whale Shark and Blue Shark (*Prionace glauca*), their prey, and limiting oceanographic characteristics, such as the depth of the oxygen minimum zone in the water column (Oñate-González 2008, Mayorga-Martínez 2011).

Since the first transmitter-equipped shark was tracked in 1965, at least 26 shark species have been tracked, including demersal, pelagic, reef, and deep-sea species, as well as some of the largest species like the White Shark, Whale Shark, and Megamouth Shark (*Megachasma pelagios*) (Nelson et al. 1997). These findings have made notable contributions to improving management and conservation efforts. This review highlights the multiple applications of telemetry studies (Fig. 1).

In Brazil, Queiroz (2020) and other authors have utilized data from fishers, catch records, and video images alongside telemetry data to study the habitat use of the Galapagos Shark (*Carcharhinus galapagensis*). In the Gulf of Mexico, Ajemian et al. (2020) used telemetry to identify differences in Tiger Shark distribution patterns related to ontogeny and seasonality and evaluate variability in regional movement rates linked to sex. These wide-ranging applications of telemetry demonstrate its versatility in addressing diverse research objectives and offering critical insights into the ecology and behavior of different species.

Acoustic telemetry

While elucidating habitat use was the primary approach of most telemetry studies, some studies focused on understanding the ethology and trophic ecology of elasmobranchs, including the Tiger Shark, White shark, and other

shark species (Papastamatiou et al. 2022, Salinas-de-León et al. 2022, Rangel 2023). Additionally, and more recently, while the primary goal of studies like those by Herrera et al. (2024) and Nalesso et al. (2019) was to understand the habitat use and movement patterns of sharks, these studies also showed a clear intention towards applying telemetry findings to more concrete and tangible management and conservation outcomes. For instance, the trophic ecology research by Rangel (2023) in Brazil integrated stable isotope analysis with telemetry data to inform conservation strategies tailored to species-specific dietary niches and energy requirements. Similarly, Salinas-de-León et al. (2019) combined satellite telemetry with trophic data to identify critical feeding grounds and ontogenetic shifts in the diet of the Tiger Shark in the Galapagos Marine Reserve, which contributed to refining protected area boundaries and zoning strategies that are still in use today. In another example, Afonso et al. (2014) examined trophic-mediated spatial partitioning among pelagic elasmobranchs, highlighting how interspecific dietary differences influence spatial use patterns, which has supported ecosystem-based fisheries management in the region.

These examples demonstrate how telemetry data can move beyond academic knowledge to shape practical, lasting management actions across Latin America when integrated with other approaches. Indeed, such efforts may serve as a model for the larger-scale protection of elasmobranchs and other endangered marine species. A better understanding of the ecology of shark movements is essential for designing effective protection strategies (Heupel 2015). Among the most effective and widely recommended measures is reducing interactions with fisheries, which directly decrease anthropogenic pressures on these vulnerable species.

In Mexico, most of the applications of active acoustic telemetry have focused on evaluating habitat use, with the White Shark being most frequently studied (Hoyos-Padilla 2009, Hoyos-Padilla 2016, Aquino-Baleyto et al. 2021, Santana-Morales 2021). To a lesser extent, there are also studies on the Scalloped Hammerhead, Oceanic Manta Ray, and Pacific Sharpnose Shark (*Rhizoprionodon longurio*) (Trejo-Ramírez 2017, Rosende-Pereiro 2018, Ruíz-Sakamoto 2018). In addition, the first records of active acoustic telemetry use in Latin America date back to Guadalupe Island, Mexico, in 2006 (Hoyos-Padilla 2009). The use of telemetry in this location has been crucial for improving our understanding of White Shark biology and ecology in Mexican waters and for informing conservation and management plans (Hoyos-Padilla 2016).

Baja California, Mexico, is a hotspot for telemetry

Due to its geographic proximity to the United States and collaborative work across institutions, Baja California stands out as the Latin American region with the highest number of publications using telemetry tracking technology. Some telemetry studies have reported that individuals marked off

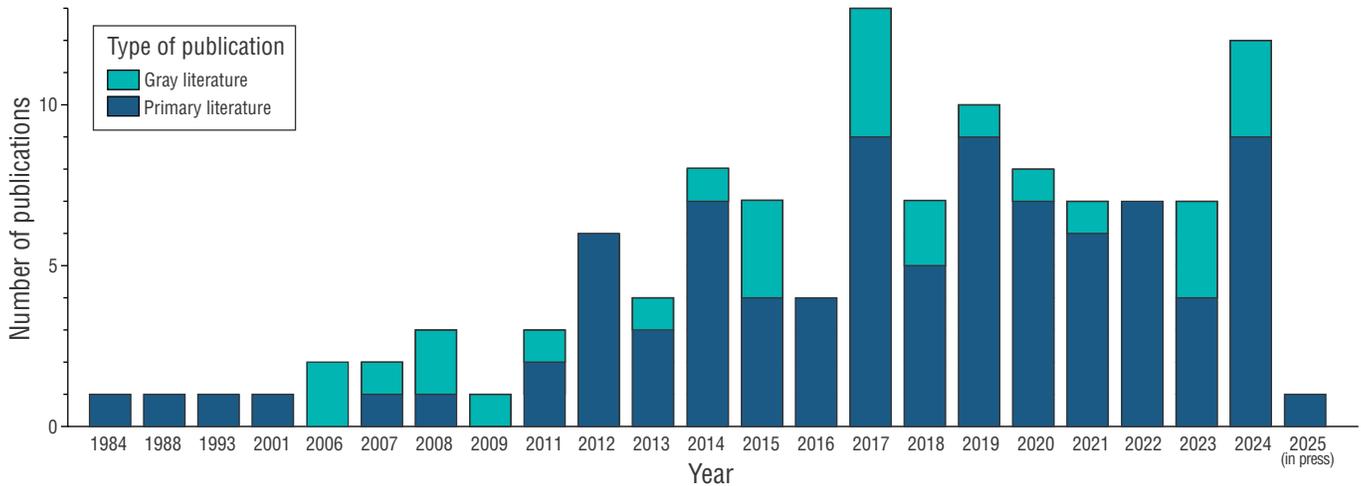


Figure 1. Number of scientific articles (primary literature) and gray literature published using telemetry by year in Latin America.

California, USA, crossed the border into the waters of Baja California, Mexico (Domeier et al. 2012, Nasby-Lucas 2019, White et al. 2019, Anderson et al. 2021, Kanive et al. 2023). These studies support Baja California being the region with the most telemetry studies in this review and a geographical hotspot for which Renshaw et al. (2023) and Hussey et al. (2015) also reported a high number of satellite and acoustic telemetry applications, respectively.

Furthermore, among the binational studies included in this analysis, all ($n = 18$) but one employed telemetry to describe the movements of the Mako Shark (*Isurus oxyrinchus*) along the California and Baja California coasts (e.g., Medellín-Ortiz 2008) and correspond to the primary literature. This fact highlights the greater use of telemetry as a research tool in the region and the number of primary literature contributions compared to those of other regions in Latin America.

Mexico is the only country in Latin America in which studies have specifically addressed the effects of tagging (Domeier et al. 2012) and other aspects related to the management and conservation of elasmobranchs (Santana-Morales et al. 2021). Both lines of research focused on the White Shark in the Guadalupe Island Biosphere Reserve, which is located within the Exclusive Economic Zone of the Mexican Pacific. The reserve serves as one of the few known critical aggregation sites for the White Shark worldwide and potentially functions as a feeding, mating, or nursery ground (Domeier and Nasby-Lucas 2012, Malpica-Cruz et al. 2013, Hoyos-Padilla 2016). The ecological conditions of the reserve enabled the development of wildlife tourism in the form of cage diving, which was globally renowned and operated from the early 2000s until its official suspension in January 2023 by decree of the Mexican government (Meza-Arce et al. 2020, SEMARNAT 2023). Therefore, the combination of these geographical, ecological, and economic interests likely allowed Baja California to become one of the most extensively studied areas using telemetry in Latin America.

Specific challenges to telemetry research and output in Latin America

Hellström et al. (2022) considered modern acoustic telemetry to be a low-cost, maintenance-free technology. However, its implementation in Latin America still faces logistical challenges, as costs often exceed local average research budgets and funding is typically directed toward charismatic species (Habib et al. 2014). Furthermore, the importance of selecting the most appropriate telemetry technology, based on factors like habitat type, target species, and research objectives, has been identified as limitation to researchers adopting these tools (Jacob and Rudran 2012, Skupien et al. 2016). These constraints, together with the regional economic context, limit the overall development of marine research and the specific implementation and advancement of telemetry studies focused on elasmobranchs and other marine species in Latin America.

Many authors, including Cooke et al. (2008), Obrist et al. (2010), and Dwyer et al. (2023), have considered acoustic tracking to be a useful, low-cost technology that reduces the overall monitoring cost. However, telemetry remains expensive for most Latin American countries with limited research budgets and in which the costs of acquiring new technology must be balanced with the need for more intensive, frequent, and detailed data collection (Zenteno-Savín 2007). In addition, transmitters and other items (e.g., antennas and signal receivers) increase the cost of this type of research.

In the case of satellite telemetry, GPS transmitters are considered the most expensive to acquire, and their use also involves satellite data transmission fees (Franklin et al. 2009, Skupien et al. 2016). Unlike acoustic telemetry, satellite telemetry is not limited by the spatial distribution of monitoring stations. Skupien et al. (2016) reported that each GPS logger used in their study cost approximately \$1,225 (USD) while each VHF transmitter cost \$183–300 (USD). These price differences can make satellite telemetry cost restrictive.

Additionally, the costs of field expeditions, such as fuel, salaries, repairs, duration, food for scientific personnel, and other logistics, can equal or even exceed the amount invested in the telemetry devices. For this reason, researchers using satellite telemetry often resort to smaller sample sizes, which can compromise the robustness of the study design and limit population-level inferences (Hebblewhite and Haydon 2010, Recio et al. 2011).

Technical aspects aside, from a historical perspective, researchers who are not native English speakers face greater difficulties in producing scientific publications (Ferguson and Pérez-Llantada 2011). Therefore, much of the scientific production from Latin America is published in low-impact, local journals in languages other than English (Ramírez-Castañeda 2020). Indeed, 22.6% of the documents reviewed in this study were theses or reports in Spanish or Portuguese, and 79.1% were not published as part of the English-language scientific literature, limiting their visibility and relevance. Some measures aimed to reduce this bias include the provision of review and translation services by international journals, the possibility of publishing in both English and the native language of the researcher (Meneghini and Packer 2007), and the promotion of free English writing courses at universities (Ferguson and Pérez-Llantada 2011).

In addition to language issues, the investment of Latin American governments in research directly influences academic production (Man et al. 2004). As such, budget constraints limit research and monitoring, and high publication fees cause valuable information to remain as gray literature or behind paywalls, thus limiting the audience. Lawson (2015) suggests that fee waivers should be offered to authors from low- or middle-income countries to boost the publication of high-quality scientific content from countries that host many species associated with conservation concerns. Our results showed that between 2006 and 2024, only some years included primary literature publications focused on elasmobranch telemetry while gray literature was generated in all years, reinforcing the conclusion that in Latin America, much scientific information (e.g., graduate theses) does not undergo peer review or publication in scientific journals (Man et al. 2004, Lawson 2015).

Habib et al. (2014) conducted a similar review to ours, focusing on telemetry technology applications in India and analyzing 82 studies that covered 47 species from four taxonomic classes. Most of these studies aimed to gather primary data, such as home range, migration patterns, movement behavior, and habitat preferences. These findings align with our review of Latin American telemetry studies. The reviews identified similar challenges for both regions that were also highlighted by Darras et al. (2016) and Kessel et al. (2014). Key issues included limited battery duration, the need for tag replacement, small sample sizes, premature tag release, difficulties in obtaining tagging permits or capturing animals, imprecise location data, challenges in data transmission, and limitations in the range of acoustic hydrophones (Tables 1 and 2).

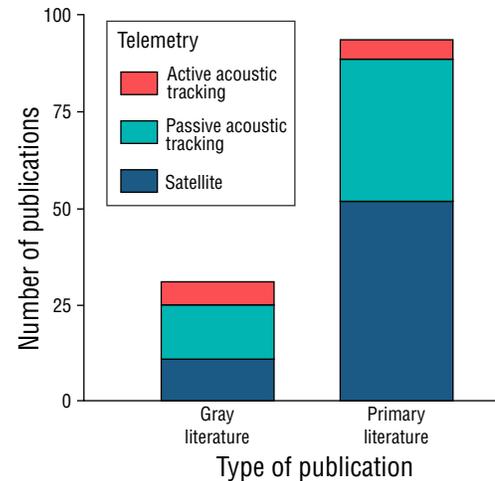


Figure 2. Number of scientific articles (primary literature) and gray literature that employed different types of telemetry in Latin America.

Telemetry for elasmobranch management and conservation

Assessing the application of results obtained from telemetry studies on elasmobranchs in Latin America is important. For example, while most of the published literature using telemetry on elasmobranchs claims conservation implications, the link between most of these studies and direct conservation and management actions is usually weak at best (Campbell et al. 2015, Jeffers and Godley 2016, Mitchell et al. 2023). However, many scientists affirm that more data will lead to better management and suggest evaluating the return on investment from research using animal-borne telemetry devices (Maxwell et al. 2015).

Indeed, telemetry provides valuable insights into the migratory behavior of elasmobranchs and can inform interactions with human activities. For example, the regional model developed by Salazar-Cervantes (2023) using satellite telemetry aimed to understand the biological and environmental factors that determine the distribution of the Silky Shark (*Carcharhinus falciformis*) and the overlap with fishing activities in the Mexican Pacific. The Silky Shark is not officially protected in Mexico; thus, focused management studies that build on these early results could improve fisheries management, reduce bycatch, and support the development of conservation strategies to ensure the survival of populations.

Even though the Official Mexican Standard NOM-059 (DOF 2010) protects species, such as the White Shark, Basking Shark (*Cetorhinus maximus*), and Whale Shark, and NOM-029-Pesca (DOF 2007) regulates the exploitation of sharks as fishing resources, evidence of elasmobranch over-exploitation still exists (Mollet et al. 1996, Holts 1998, Castro 1999, Shivji et al. 2005, Smith et al. 2009, Cartamil 2011, Santana-Morales et al. 2020, Sosa-Nishizaki et al. 2020).

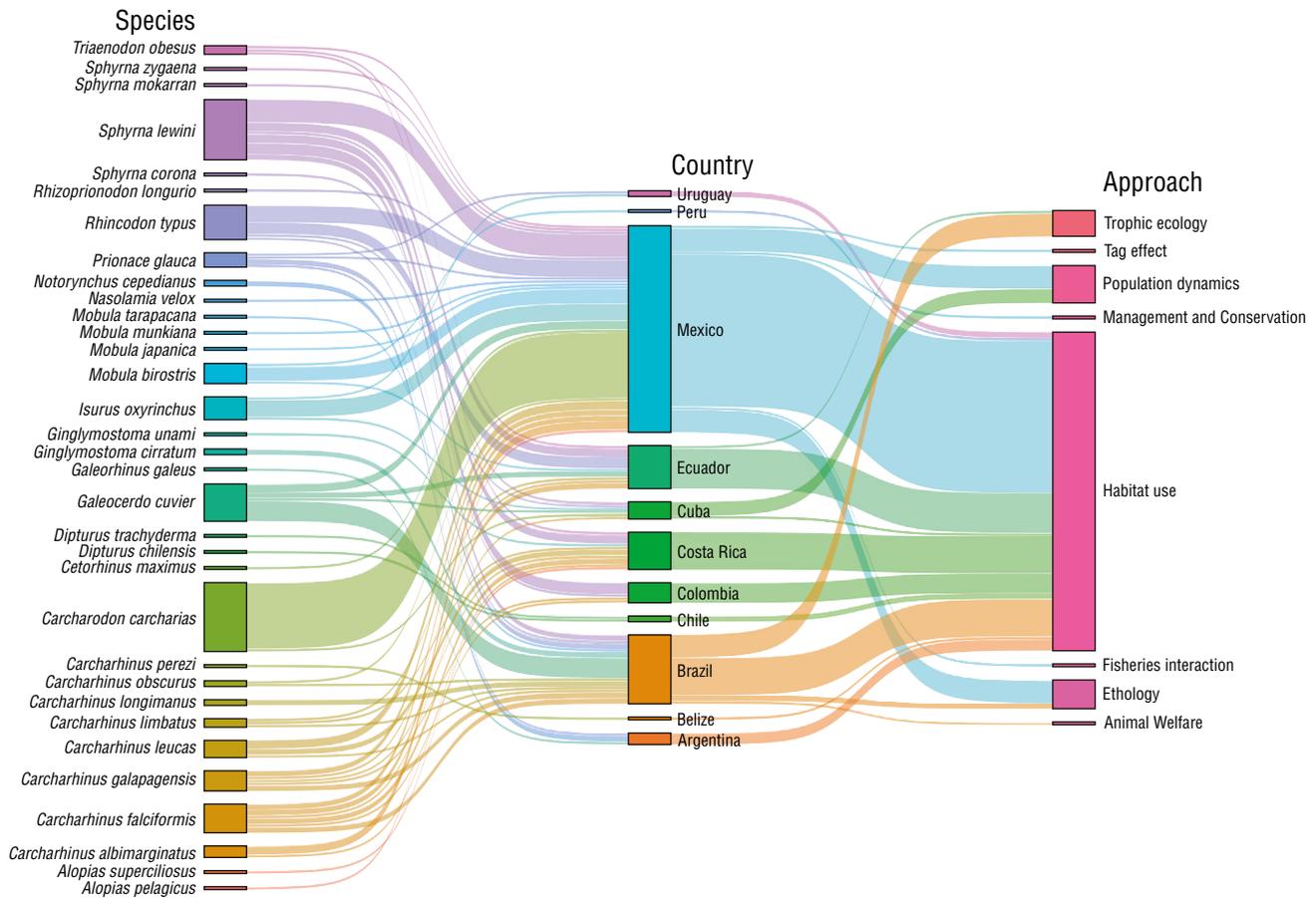


Figure 3. Relationships between species, research focus employing telemetry, and countries in Latin America.

Moreover, notable knowledge gaps remain regarding elasmobranch behavior, migration, and general ecology (Sundström et al. 2001, Heupel and Simpfendorfer 2008).

Elasmobranchs are the oldest living vertebrates on Earth (Edwards et al. 2019) and are usually K-selected species (Conrath and Musick 2012), which makes them particularly vulnerable to anthropogenic pressures and underscores the importance of filling knowledge gaps through telemetry. For example, for large-bodied offshore species, such as the Silky Shark that exhibits a low population renewal rate (Márquez-Farías et al. 2006) and faces overfishing and environmental threats, telemetry-based knowledge can prove critical for the design and implementation of appropriate management actions. For offshore species, a well-designed acoustic receiver array may be more appropriate to elucidate critical areas and migratory patterns (Lennox et al. 2023). Therefore, differences between coastal and offshore species, especially regarding spatial behavior and habitat use, can influence the effectiveness of acoustic telemetry, particularly regarding receiver placement and the detection range.

Given the potential of telemetry-derived data to inform resource management and conservation, and the high costs involved in collecting these data (e.g., the financial costs of

equipment and salaries, potential for mortality, and reduction in reproduction output [Cooke et al. 2008, Brownscombe et al. 2022]), it is essential to evaluate the benefits of telemetry for conservation. Also, researchers must be encouraged to utilize telemetry technology with an underlying conservation rationale to target their research towards gathering robust data to propel actions that maximize species survival and persistence and improve fisheries management (Liang et al. 2023).

Given the large investment and complex logistical needs of applying telemetry to studying elasmobranchs, careful planning is advised (e.g., Habib et al. 2014). Indeed, when study questions are carefully chosen and the study is well-designed, a single deployment of tags can yield notable insights. Telemetry data can also uncover unexpected information that can guide management efforts. For example, Bradley et al. (2018) revealed illegal shark fishing within a sanctuary when satellite tags were transmitted from a vessel, indicating illegal capture, transfer at sea, and transport to the Marshall Islands. Tolotti et al. (2015) used telemetry to assess the vulnerability of the Oceanic Whitetip Shark (*Carcharhinus longimanus*) to longline fisheries in Brazil. In addition, Aldana-Moreno et al. (2020) conducted telemetry-based monitoring in the Revillagigedo National Park,

a no-take reserve and a World Heritage Site of the United Nations Educational, Scientific, and Cultural Organization (UNESCO), to support the conservation of the endangered Scalloped Hammerhead. These examples show how telemetry can provide helpful information for future management and conservation purposes beyond addressing purely ecological and biological questions.

Additionally, in many cases, tracking trajectories are shared on public websites or through other media, enhancing the dissemination of information and its impact by facilitating effective scientific communication (Cooke et al. 2017). There are only a few examples of data analysis to inform management decisions, and even fewer using telemetry-derived data (Liang et al. 2023). For example, radio tracking studies in the United Kingdom revealed that the Common Pipistrelle Bat (*Pipistrellus pipistrellus*), a protected species that cannot be easily studied based solely on observations, exploits specific habitats and thus requires tailored conservation measures (Davidson-Watts and Jones 2006). Moreover, biotelemetry research on anadromous salmon (*Salmo* spp. and *Oncorhynchus* spp.) has led to an improved understanding of mortality events from catch-and-release fishing interactions and physiological factors that influence spawning failure, which in turn justify the restrictions placed on fished populations (Nielsen et al. 2009, Drenner et al. 2012).

While telemetry technology has been increasingly used worldwide for marine species management and policy, its application, particularly in Latin America, remains limited, with few studies effectively bridging research and conservation actions for elasmobranchs. Although some reviews have focused on different taxa and have discussed the potential for using telemetry technology for marine species management (e.g., Cooke et al. 2008 [salmon]; Jeffers and Godley 2016 [sea turtles]) and policy (Barton et al. 2015), they have underemphasized the importance of defining clear links between research and management actions.

Only Mascarenhas-Junior (2023) of the Federal University of Pernambuco, Brazil, has truly addressed the need to ground the information from a Latin American perspective in his review of telemetry studies on the spatial use and movements of crocodylians. However, there is currently no work that similarly addresses elasmobranchs. Santana-Morales et al. (2021) were the only authors to provide conservation and management applications for an elasmobranch (i.e., the White Shark) based on active acoustic telemetry in Latin America. While there will always be a need for basic ecological research and discovery, the current biodiversity and conservation crisis (Ceballos 2020, Dulvy 2021, WWF 2024, Wang 2025), combined with the limited number of telemetry studies with direct applications for the conservation and management of elasmobranchs, highlights a critical gap in the need for these data.

Given the global investment in telemetry devices for threatened species, we have an ethical and practical obligation to maximize research investments that benefit conservation. We need new tools and frameworks to effectively link

the growing catalogue of animal telemetry-derived data to conservation and management actions to improve the return on investment of these efforts. Approaches that explicitly evaluate how scientific data can reduce uncertainty in decision-making, such as the value of information analysis, should play an increasingly important role in guiding research priorities. For example, fusing telemetry data with other environmental and threat-based databases can help identify high-risk areas of management concern and inform bycatch reduction efforts for critically endangered species. This type of data analysis and approach could also be applied to other populations and species with available telemetry and point-source data (Liang 2023).

DECLARATIONS

Supplementary Material

The supplementary material for this work can be downloaded from: <https://www.cienciasmarinas.com.mx/index.php/cmarias/article/view/3541/420421215>.

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Data Availability

The data for this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare that they have no conflict of interest.

Author Contributions

Conceptualization: CIVA, LMC; Data curation: CIVA; Formal analysis: CIVA; Investigation: CIVA, LMC; Methodology: CIVA, LMC; Supervision: LMC, OSM; Validation: LMC, OSM; Visualization: CIVA, LFAS; Writing—original draft: CIVA, LMC; Writing—review & editing: CIVA, LMC, OSM, LFAS.

Use of AI Tools

The first author of this work used AI tools to translate technical terms while drafting the English version of the manuscript.

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