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Contributions of bioacoustics to the scientific knowledge of marine mammals in Latin America

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Abstract

We review and document scientific publications on marine mammal bioacoustics in Latin America between 1971 and 2021, showing early scarcity and an increase through time. Marine bioacoustic studies how marine fauna produce and receive sounds that facilitate their life functions. Bioacoustics explores the biology and ecology of marine mammals, difficult or impossible to carry out using only traditional visual methods. From the first published study on the free-living common bottlenose dolphin in the Gulf of Mexico in 1953, acoustic studies on marine mammals have increased; most of its growth occurred in the 2000s. The objective of this study was to document the history and development of marine mammal bioacoustics in Latin America. We conducted a systematic search of scientific peer-reviewed literature on the Web of Science from 1971 to 2021, using keywords involving 18 acoustic and 16 marine mammal terms. We reported the countries where studies were carried out, the focal species, and the research topics. The oldest paper found was published in Chile in 1971. The 2010s yielded the most publications (n= 10), compared to the 1970s (n = 4), 1980s (n = 8), 1990s (n = 12), and the 2000s (n = 49). The publication rate increase between 1971 and 2021 is likely due to the increased development and use of affordable autonomous recording devices. The countries with most publications were Brazil (n = 60), Mexico (n = 46), and Ecuador (n = 29). Those with the least studies were in the Caribbean region. The most studied species were the humpback whale (*Megaptera novaeangliae*) (n = 46), the sperm whale (*Physeter macrocephalus*) (n = 43), and the bottlenose dolphin (*Tursiops truncatus*) (n = 40). These species are highly vocal, widely distributed, and accessible in several habitats, facilitating their study. The most analyzed research topics were inter- and intraspecific differences in vocalizations (n = 104), acoustic signal descriptions (n = 74), and association of acoustic signals and behavior (n = 59). The use of bioacoustics in abundance, distribution, habitat use, and anthropogenic effects was scant in the list of publications reviewed for this study, but these topics are predicted to be pursued more often by researchers in the future as they are needed to establish mitigation policies for the species and their habitat conservation.

Keywords:
bioacoustic history, acoustics, cetaceans, conservation, pinnipeds, sirenians

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Introduction

Bioacoustics is a tool that has been increasingly employed during the 2010-2020 decades to expand the knowledge on marine mammals' biology and ecology. Among its various applications, the most common is recording of sounds produced by animals and analyzing them to test specific hypotheses on signal structure, use, and function (Penar et al., 2020). Bioacoustics has been used in wild marine mammal research since 1953 (Kellogg et al., 1953) when the vocalizations of the

common bottlenose dolphin (*Tursiops truncatus*) were compared between individuals in captivity and in the wild. Since then, it has commonly been used as a complementary method to visual surveys to study marine mammal biology and ecology (Macaulay et al., 2017) that can also be implemented independently in adverse weather conditions or at night (Soldevilla et al., 2010). In many cases, acoustics is used alone to monitor for presence of many species and to measure the soundscapes they live in (Tervo et al., 2012).

The first bioacoustic studies were carried out using manual and cabled hydrophones towed behind vessels during visual surveys. Later, researchers used bottom-mounted instruments where hydrophones were deployed on the ocean floor for passive recording of the biophony within detection range (Cummings et al., 1968). In 1995, a large scale bottom-mounted instrumentation - the Ocean Bottom Seismometer (OBS) - was installed to monitor for seismic activity, and was discovered to have also recorded baleen whale vocalizations, like blue and fin whale songs (Sousa-Lima et al., 2013). By the 2000s many types of different recording devices had been developed, all of them being similar waterproof, largely tubular, designs built by independent labs but with variable storage and battery capacities, and sampling rates (Mellinger et al., 2007; Sousa-Lima et al., 2013). Overtime, bioacoustics has been used to study at least 106 marine mammal species (M. Chávez-Andrade, unpub. data) using single hydrophones or in arrays, towed from a vessel, affixed to a buoy or to an anchor, or integrated in acoustic tags, sonobuoys, gliders, and drones (*e.g.* Swartz et al., 2003; Gerrodette et al., 2011; Baumann-Pickering et al., 2013; Bittencourt et al., 2018; Dombroski et al., 2020; Frouin-Mouy et al., 2020).

Bioacoustics has made it possible to explore many research topics across all oceans. These include the description of vocalizations (Oswald et al., 2003), determining the function of calls (Hayes et al., 2004), extrapolating behavior from acoustic signals that have documented associated functions (Martin et al., 2021), documenting spatio-temporal variation of vocalizations (Archer et al., 2020), tracking the evolution of the acoustic signals themselves (May-Collado et al., 2007a; 2007b; Filatova et al., 2012), and tracking movement patterns (Dunn & Hernandez, 2009). Also, to study the distribution of a species or groups of species (Holst et al., 2017), estimating the abundance of a single species (Jaramillo-Legorreta et al., 2019), cue-counting (Frasier et al., 2016), estimating masking and other effects from anthropogenic noise on marine mammals behavior (Parks et al., 2007; Heenehan et al., 2019), density estimation (Marques et al., 2009), and reducing bycatch (Mangel et al., 2013). The study of anthropogenic effects has been particularly useful in non-biological industries such as seismic testing and resource extraction (Smultea et al., 2013) because it has enabled governmental agencies to establish mitigation measures for different species in the presence of various disturbance sources (*e.g.* Rutenko et al., 2007; Roch et al., 2011; Au et al., 2013; Amano et al., 2017; Taylor et al., 2017; Luís et al., 2021; Kowarski et al., 2023).

Although bioacoustics has been used extensively in Latin American countries for diverse fauna and a general review would be informative, our scope will be reduced to studies in marine mammals. For the purpose of this study, Latin America was considered to be made by 29 countries where people speak three romance languages (Spanish, Portuguese, and French) plus some English in some Caribbean countries, and Dutch in Suriname. Even though the Gulf of Mexico is part of the Caribbean Sea, fit in US waters, studies from that area were not included in this study. The objectives of this study were to 1) explore the timeline of advances in bioacoustics studies in Latin American countries, 2) identify the countries where marine mammal studies have been carried out using acoustic methods and enumerate how many studies were done in each country, 3) quantify the marine mammal species studied in each country, and 4) determine the research topics addressed in each country and for each marine mammal species. This study is the first to compile all such information about bioacoustics in Latin American countries. As such, it identifies gaps where studies are needed to generate more knowledge and to apply it in ways like the conservation of species and their habitats.

Materials and Methods

A systematic search of peer-reviewed papers on marine mammal bioacoustics was carried out in the Web of Science using two sets of keywords. The set of 18 acoustic terms were: repertoire, song, whistle, click, frequency, frequencies, sound, boing*, call*, buzz*, coda*, acoustic*, echolocation, vocal*, bioacoustics, trill*, biosonar*, and communication. The set of 13 marine mammal terms including common names and taxonomic categories were: “marine mammal*”, cetacea*, whale, dolphin*, porpoise, pinniped*, seal*, “sea lion*”, sirenia, manatee*, “sea cow”, “sea otter*”, and “marine otter*”. The quotation marks are used to instruct the algorithm to look for the phrase quoted between them, the * sign indicates the algorithm to use any term that includes the word and any elements other than letters that follow, *e.g.* it is a wildcard. We filtered this first list to extract peer-reviewed papers. Gray literature was not considered in this study due to the difficulty in consulting it, although it is still considered worthwhile. We selected those papers reporting on research from Latin America according to its regions. Latin America consists of three regions: North and Central America, South America, and the Caribbean. The North and Central America region is comprised of the eight countries of Central America and Mexico, the South America region includes 13 countries, and the Caribbean region includes three countries and five dependencies (Britannica, 2017). Bolivia and Paraguay were not included in this paper because they are landlocked. To determine the extent of territorial waters that belong to each Latin American country where the study was conducted, we followed the political geography delimitation proposed by Britannica (2017). We determined the trends in the number of publications per country between 1971 and 2021. For each paper, we identified the studied species for later estimations of the total number of marine mammal species studied on each country. Scientific names were validated according to the Committee on Taxonomy of the Society for Marine Mammalogy (2022). The exception was the Araguaian boto (Araguaian river dolphin, *Inia araguaiensis*), which is not accepted by the Committee

on Taxonomy (2022). However, in this study we considered *I. araguaiensis* as a separate species given that some papers have found differences in the vocalizations of the different *Inia* species (Melo-Santos et al., 2019; 2020; 2021). A research topic was assigned using the 13 following categories: abundance and population density; anthropogenic effects; association of acoustic signals and behavior; description, preferences, and habitat use; geographical or temporal vocalizations variations; hearing, vocalization, and recognition capabilities; individual and species identification; inter and intraspecific differences in vocalizations; learning, communication, and acoustic recognition; localization, species monitoring, and mitigation policies; spatio-temporal distribution; size of the animals; and acoustic signal descriptions (Supplementary Material 1). We estimated the number of research topics studied in each country and for each species. We found 16 papers focused on the comparison of research methods, and the development of algorithms, software, and devices. Those papers were not considered in this study because they were not in line with the intent of tabulating only biological and ecological research of marine mammals in Latin America.

Results

Overall trends

The first paper of bioacoustical studies on marine mammals in Latin America is from Chile and it was published in 1971 (Cummings & Thompson, 1971; Fig. 1A) about vocalizations of the blue whale (*Balaenoptera musculus*). Within the study period there were five periods over which bioacoustical publications could not be found (1972 - 1974, 1976 - 1977, 1983 - 1985, 1987 - 1989, 1994 - 1995) (Fig. 1A). The average number of publications between 1971 and 1996 was 0.7 paper per year, with a maximum of three papers both in 1981 and 1993 (Fig. 1A). Bioacoustic scientific publications were then sporadic until 1996 when papers were published every year from 1996 onwards until 2021. The average publication rate between those years was seven papers per year. From the 2000s the average number of papers annually was 4.9, while in the 2010s the average was 10 papers per year. During the 2010s, the total number of papers (2010s: n = 100) was twofold compared to the previous decade (2000s: n = 49). In fact, papers from the 2010s constituted 48.8% of the total publications over the previous three decades (1970s - 1990s, Fig. 1B). The first two decades of the 21st century (2000 - 2010) have seen most of the marine mammals' bioacoustic papers in the study's timespan (n = 149, 72.7%). From the 2010s onwards, an increase in the number of publications was observed, up to 18 papers were published in 2019 (Fig. 1A). The higher rate of publication (15.6%) continued into the 2020s, when 16 publications were published in 2020 and 2021each (Fig. 1A).

Country-specific trends

We found 205 papers that documented bioacoustic research carried out in 24 of the 27 Latin American countries whose waters marine mammals inhabit permanently or seasonally (*e.g.* during migration). Four countries accounted for 51.2% (n = 155) of the studies: Brazil (19.8%, n = 60), Mexico (15.2%, n = 46), Ecuador (9.6%, n = 29), and Chile (n = 6.6%, n = 20, Fig. 2A). Countries with a low number of publications included Haiti (0.7%, n = 2), Belize (1%, n = 3), and Saint-Barthélemy (1%, n = 3). Suriname, Guyana, and French Guiana were countries with no publications (Fig. 2).

During the 1970 decade, studies were carried out almost exclusively in countries corresponding to the Caribbean region, except for Chile (Winn et al., 1975; Winn & Winn, 1978; Hafner et al., 1979) (Fig. 3). In 1980, Argentina published its first bioacoustical study (Clark & Clark, 1980). During the rest of the 1980s, studies were also carried out in Mexico (Winn et al., 1981) and Ecuador (Weilgart & Whitehead, 1988) (Fig. 3). By the end of the 1980s, marine mammal bioacoustics had been published from 54.2% (n = 13) of Latin American countries. Although no trend was observed in the number of publications per year and country, a pattern was found in the number of publications up to the 1990s in the Caribbean region. Most of the publications were produced at the end of that decade. After that, studies were infrequent, except in Puerto Rico (Fig. 3). After 1997, studies were carried out in Peru and Chile (Weilgart & Whitehead, 1997). This second Chilean paper was published 26 years after the first one (Fig. 3). In Brazil, studies have been carried out since 2001 (Monteiro-Filho & Monteiro, 2001), with no studies published

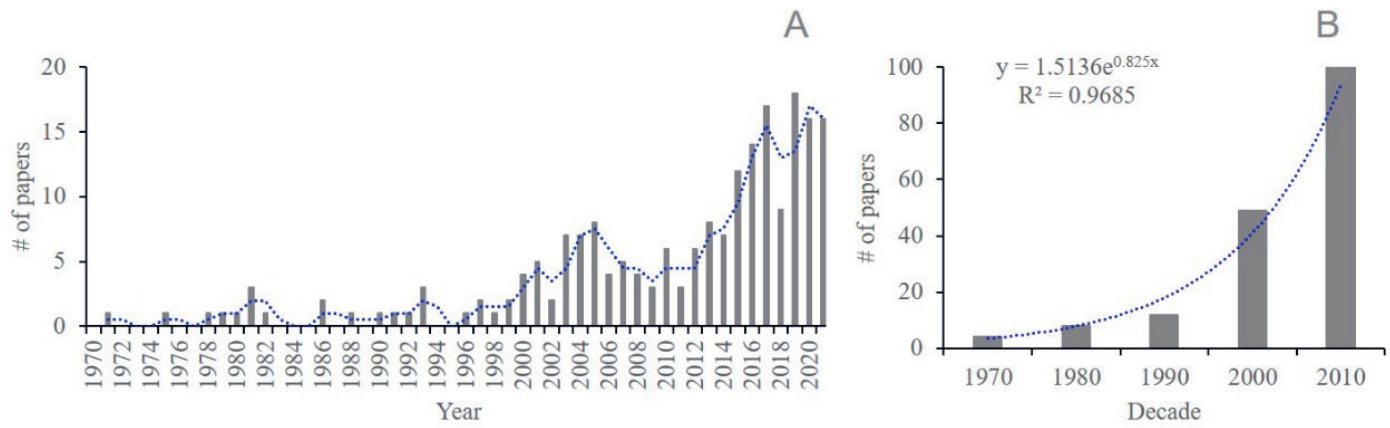

Figure 1. Trends in the number of publications per year (A) and per decade (B) on marine mammal bioacoustics in Latin American countries.

in 2003 and 2011, giving a total of 19 years of bioacoustics studies occurring in this country. In 2016, studies were carried out in 15 countries (Fig. 3). In Mexico, bioacoustic papers have been published for 22 years. The earliest paper we found was published in 1981 (Winn et al., 1981), and then since 2011 there have been publications every year. Ecuador and Peru showed two peaks of continuous publications (Fig. 3). Finally, Chile has 14 years of published research history and from 2017 to 2021 papers were published each year.

Trends by research topic and by countries

In this section, the 205 papers were analyzed, 41 of them have more than one species studied, or covered more than one country, giving a total of 463 studies. Across Latin America, 51.2% (n = 237) of the studies focused on inter- and intraspecific vocalizations differences (22.5%, n = 104), acoustic signal descriptions comprised 16% (n = 74), and association of acoustic signals and behavior contributes with the 12.7%, (n = 59; Fig. 4). The least studied research topics

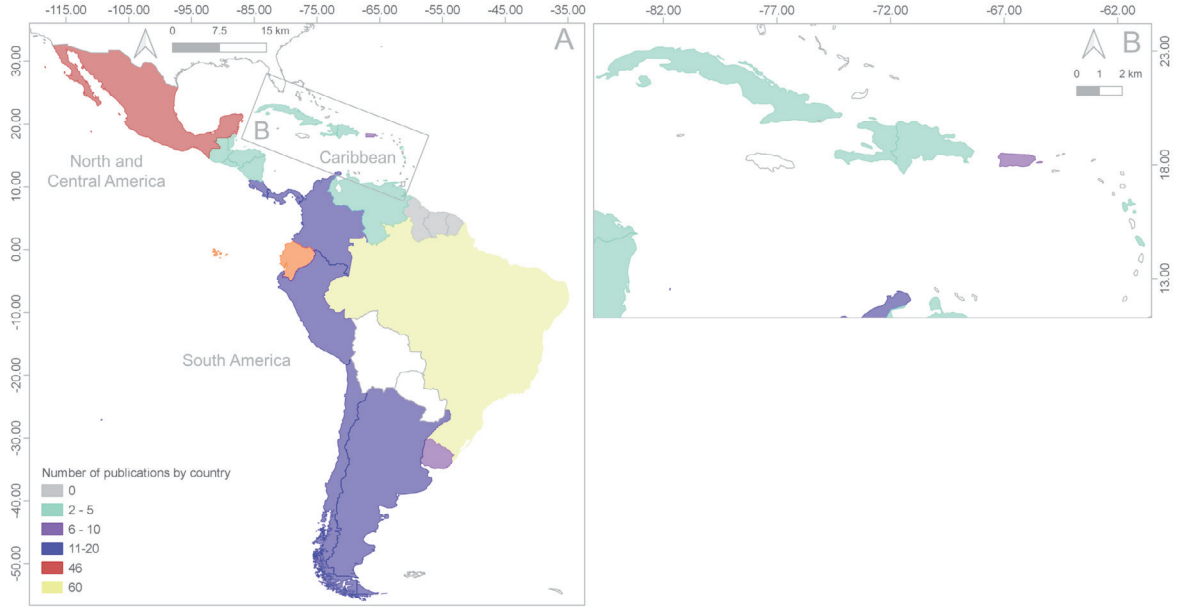

Figure 2. Number of publications in Latin American countries. Colors indicate the number of publications in bioacoustics of marine mammals in each country. A. North, Central, and South America. B. The Caribbean.

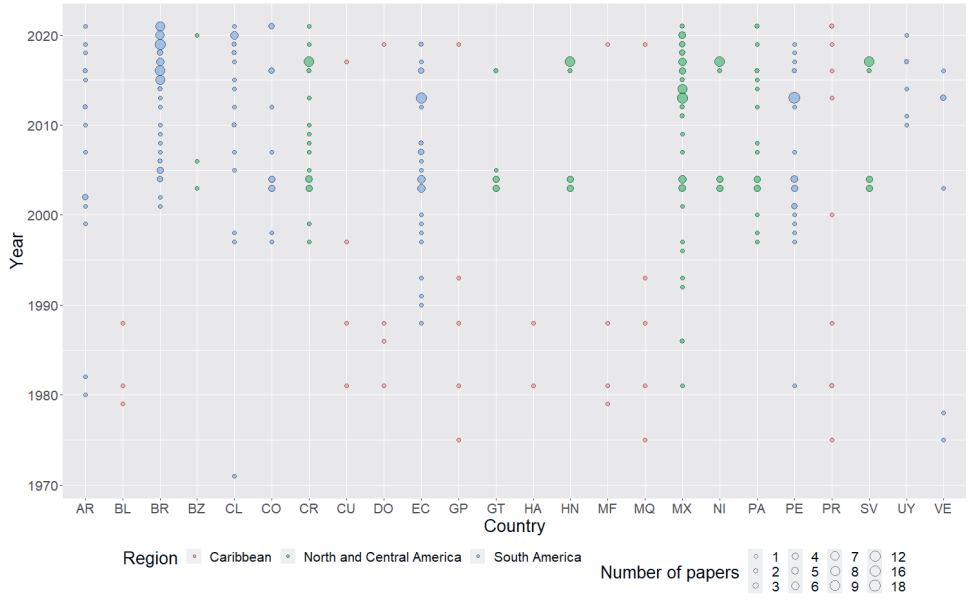

Figure 3. Number of papers published by country and by year. Circle size indicates the number of papers published in a specific year by a given country. AR (Argentina), BL (Saint-Barthélemy), BR (Brazil), BZ (Belize), CL (Chile), CO (Colombia), CR (Costa Rica), CU (Cuba), DO (Dominican Republic), EC (Ecuador), GP (Guadeloupe), GT (Guatemala), HN (Honduras), HT (Haiti), MF (Saint Martin), MQ (Martinica), MX (Mexico), NI (Nicaragua), PA (Panama), PE (Peru), PR (Puerto Rico), SV (El Salvador), UY (Uruguay), VE (Venezuela). Countries are arranged in alphabetical order.

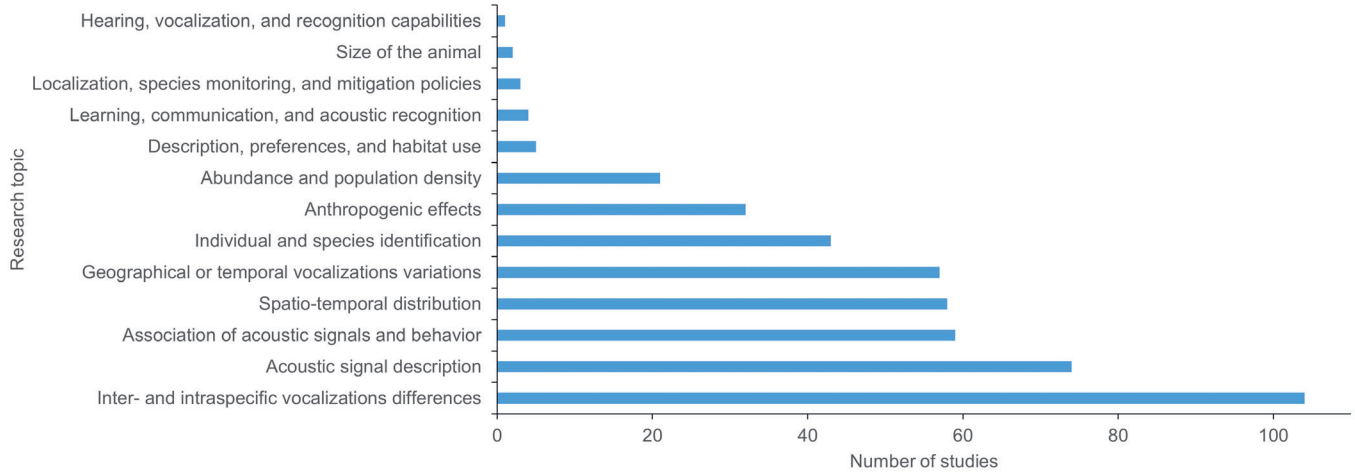

Figure 4. Number of studies by research topics in Latin American countries.

were description, preferences, and habitat use (1.1%, n = 5); learning, communication, and acoustic recognition (0.9%, n = 4); localization, species monitoring, and mitigation policies (0.6%, n = 3); animal size (0.4%, n = 2); and hearing, vocalization, and recognition capabilities (0.2%, n = 1) (Fig. 4).

The number of research topics analyzed in each of the Latin American countries tended to decrease along a geographically southbound continuum (Fig. 5). Ecuador (n = 11), Mexico (n = 10), and Peru (n = 9) were the countries where most research topics were found; eight topics were common to these countries. In general, in countries of Central America and the Caribbean, the number of research topics analyzed was minimal (Fig. 5). In Belize, Cuba, and Haiti, only two research topics were studied (Fig. 5B, 5C). We observed a trend to study similar topics in Central American, Caribbean, and Pacific coast countries (Fig. 5). In all those regions, inter and intraspecific vocalization differences was the primary topic studied. In Central America, this trend of research topic similitude was also observed in spatio-temporal distribution (Fig. 5B). In Caribbean countries (Fig. 5C), the geographical or temporal vocalizations variations were the most common research topics, whereas in the Latin American countries of the Pacific coast association of acoustic signals and behavior, and acoustic signal descriptions were the most common (Fig. 5). In Ecuador, Mexico, and Peru the most common research topic was association of acoustic signals and behavior (n = 16, n = 14, n = 12 respectively, Fig. 5A and 5B). The most studied research topic in Brazil was acoustic signal descriptions (n = 21, Fig. 5A).

Publications by species

Bioacoustical publications from the 24 Latin American countries covered 45 marine mammal species. In one paper, species is not specified: Martin et al. (2019). Seven species accounted for 50.9% (n = 234) of the marine mammal bioacoustic studies. The most studied species were humpback whale (10%, n = 46), sperm whale (9.3%, n = 43), common bottlenose dolphin (8.7%, n = 40), spinner dolphin (*Stenella longirostris*, 7%, n = 32), pantropical spotted dolphin (*S. attenuata*, 6.1%, n = 28), striped dolphin (*S. coeruleoalba*, 5%, n = 23), and the blue whale (4.9%, n = 22). Five species were grouped in 1.1% of the studies, each of these species was studied once (Table 1).

Studies by species, country, and research topic

A pattern was detected in research topics for the different marine mammal groups. A bias towards odontocetes (Supplementary Material 1 and 2) was observed when studying anthropogenic effects, association of acoustic signals and behavior, geographical or temporal vocalizations variations, individual and species identification, and inter- and intraspecific vocalizations differences. Mysticetes tended to be studied in topics such as abundance and population density. Seven research topics were studied in five pinniped species, while in the only sirenian inhabiting coastal waters of Latin America, the West Indian manatee (*Trichechus manatus*), six research topics were addressed (Table 3).

We observed a trend to study similar species in Central American, Caribbean, and Pacific coast countries (Table 1). The largest number of species studied was in Mexico (n = 26, Fig. 5A), with the fin whale (*Balaenoptera physalus*, n = 8, Table 2) being the most studied species. In Peru, 20 species were studied (Fig. 5A, Table 1), and eight species have a maximum of three studies (Table 2). In Brazil and Ecuador, 19 species were studied (Fig. 5A, Table 1). The most studied species in Brazil was the Guiana dolphin (*Sotalia guianensis*, n = 17), while in Ecuador the sperm whale (n = 16) was the most frequently studied (Table 2). In Chile, seven species were studied (Fig. 5A, Table 1), the blue whale being the most common (n = 11). In Guadeloupe, Haiti, Martinique, Dominican Republic, Saint-Martin, and Saint Barthélemy, the sperm whale and the humpback whale (Table 1) were studied equally as often, while in Belize only the West Indian manatee (n = 3) was studied (Tables 1 and 2). The fewest species were studied in the Caribbean countries, except for Costa Rica which boasted research of many species (Fig. 5C). In 29.2% of these countries, only one and two species were studied (Table 3).

The largest number of research topics were on humpback whale, sperm whale, and common bottlenose dolphin (n = 8 each) (Table 3). The humpback whale was studied in 19 countries (Table 1), making it the most studied in 33.5% (n = 9) of the Latin American countries (Table 2). The most researched topic on the humpback whale was geographical or temporal vocalizations variations (n = 18, Table 3). Studies on the sperm whale were carried out in 14 countries (Table 1); in five of these countries,

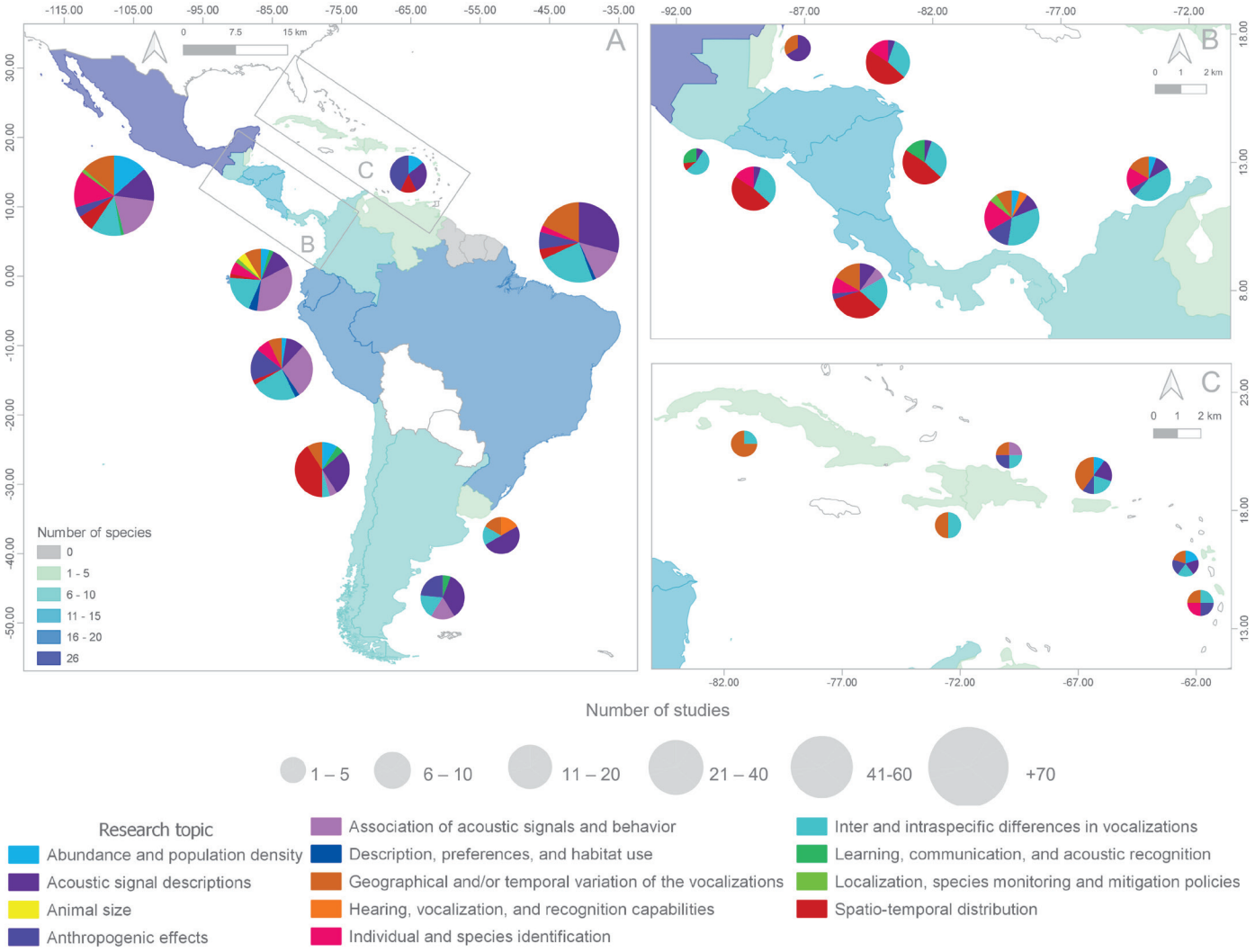

Figure 5. Number of species and research topics studied in Latin American countries. A: Latin America, B: Central America, C: Caribbean. Colors inside pie graphs indicate the research topic. The size of the pie graph indicates the number of studies conducted in each country. Supplementary Material 1 and 2 provide detailed information about the species studied, the number, and research topic in each of the Latin American countries.

it was the most studied species (Table 2). The main research topic for this species was the inter and intraspecific vocalization differences (n = 16, Table 3). The common bottlenose dolphin was studied in 15 countries, with the highest number of studies recorded in Panama, Peru, and Uruguay (Table 1 and Table 2). The main research topic for the common bottlenose dolphin was related to individual and species identification (n = 10, Table 3). The majority of studies on spinner, pantropical spotted, and striped dolphins were conducted in Central American countries (Table 2), and these studies focused on inter and intraspecific vocalization differences, varying slightly in the number of studies and the countries where these species were studied (Table 3). The striped dolphin was also most studied (n = 10) for individual and species identification.

Inter and intraspecific vocalization differences were studied in 22 species, with the spinner dolphin being the most studied in this research topic (n = 21, Table 3). Vocalizations were described for 27 species; the focus was on the Bryde's whale (*Balaenoptera edeni*) (n = 12). Association of acoustic signals and behavior was studied in 28 species, with the Guiana dolphin and common bottlenose dolphin (n = 4 each, Table 3) being the most common species. Abundance and population density were studied in seven species, with the sperm whale being the most frequently studied (n = 7). Anthropogenic effects were most commonly studied regarding the common bottlenose dolphin (n = 6) (Table 3).

Discussion

Overall trends

Bioacoustical studies for worldwide wild marine mammals date back to 1953 (Kellogg et al., 1953). However, it was not until the 1970s that this type of research began to be applied in Latin American countries. One possible explanation for the low number of publications on bioacoustics in marine mammals is that visual surveys were more common during the first decades (1970 - 1990). Also, the fact that there were technological limitations for recording and storing sounds from the aquatic environment, and a limited amount of recording equipment

Table 1. Number of studies by species in each Latin American country. The number inside each cell is the number of studies. AR (Argentina), BL (Saint-Barthélemy), BR (Brazil), BZ (Belize), CL (Chile), CO (Colombia), CR (Costa Rica), CU (Cuba), DO (Dominican Republic), EC (Ecuador), GP (Guadeloupe), GT (Guatemala), HN (Honduras), HT (Haiti), MF (Saint Martin), MQ (Martinica), MX (Mexico), NI (Nicaragua), PA (Panama), PE (Peru), PR (Puerto Rico), SV (El Salvador), UY (Uruguay), VE (Venezuela), TO (Total of studies).

Species	AR	BL	BR	BZ	CL	CO	CR	CU	DO	EC	GP	GT	HN	HT	MF	MQ	MX	NI	PA	PE	PR	SV	UR	VE	TO
Arctocephalus australis (South American fur seal)																				3					3
Arctocephalus galapagoensis (Galapagos fur seal)										1															1
Balaenoptera acutorostrata (Common minke whale)					1		2						1				1	1			1	1			8
Balaenoptera borealis (Sei whale)	1																1								2
Balaenoptera edeni (Bryde's whale)			2			1	1			1		1	1				5	1	1	1		1			16
Balaenoptera musculus (Blue whale)					11		2			2		1					4			2					22
Balaenoptera omurai (Omura's whale)			1																						1
Balaenoptera physalus (Fin whale)					2												8								10
Berardius bairdii (Baird's beaked whale)																	2								2
Cephalorhynchus commersonii (Commerson's dolphin)	3																								3
Cephalorhynchus eutropia (Chilean dolphin)					1																				1
Delphinus delphis (Common dolphin)			1			1	2			2		1	2				3	2	1	3		2		1	21
Eschrichtius robustus (Gray whale)																	4								4
Eubalaena australis (Southern right whale)	3		3		1																				7
Feresa attenuata (Pygmy killer whale)										1							1			1					3
Globicephala macrorhynchus (Short-finned pilot whale)							1			1			1				1	1		2		1			8
Globicephala melas (Long-finned pilot whale)			1																	1					2
Grampus griseus (Risso's dolphin)			1				1	1		1			1				2	1		2		1			11
Indopacetus pacificus (Longman's beaked whale)																	2								2
Inia araguaiaensis (Araguaian river dolphin)			2																						2
Inia geoffrensis (Amazon river dolphin)			7							1										1					9
Inia sp.			1			1																			2
Lagenodelphis hosei (Fraser's dolphin)						1	1			2							2		1	2					9

Species	AR	BL	BR	BZ	CL	CO	CR	CU	DO	EC	GP	GT	HN	HT	MF	MQ	MX	NI	PA	PE	PR	SV	UR	VE	TO
Lagenorhynchus cruciger (Hourglass dolphin)	1																								1
Lagenorhynchus obscurus (Dusky dolphin)	1									1										2					4
Megaptera novaeangliae (Humpback whale)		2	4		1	3	2	1	3	2	3		1	1	3	3	5	1			6	1	1	3	46
Mesoplodon densirostris (Blainville's beaked whale)																	2								2
Mirounga angustirostris (Northern elephant seal)																	2								2
Not determined																	1								1
Orcinus orca (Killer whale, orca)			2														1								3
Otaria byronia (South American sea lion)	3																						2		5
Phocoena sinus (Vaquita)																	5								5
Phocoena spinipinnis (Burmeister's porpoise)	2																			3					5
Physeter macrocephalus (Sperm whale)		1	1		5	3	1	2	1	16	2			1	1	2			3	3	1				43
Pontoporia blainvillei (Franciscana)	3		3																				1		7
Pseudorca crassidens (False killer whale)						1	2			2		1	2				2	2	1	2		2			17
Sotalia fluviatilis (Tucuxi)			6																	1					7
Sotalia guianensis (Guiana dolphin)			17				2																	1	20
Stenella attenuata (Pantropical spotted dolphin)			1			2	3			3		2	3				3	3	2	3		3			28
Stenella coeruleoalba (Striped dolphin)						2	2			3		2	2				3	2	2	3		2			23
Stenella frontalis (Atlantic spotted dolphin)			4																					1	5
Stenella longirostris (Spinner dolphin)			4			2	3			3		2	3				4	3	2	3		3			32
Steno bredanensis (Rough-toothed dolphin)			4							1							2			1					8
Trichechus manatus (West Indian manatee)				3													1		2		1				7
Tursiops truncatus (Common bottlenose dolphin)			7			1	5			2		1	2				5	2	6	3	1	2	2	1	40
Zalophus wollebaeki (Galapagos sea lion)										1															1
Ziphius cavirostris (Cuvier's beaked whale)																	2								2
Overall total	**17**	**3**	**72**	**3**	**22**	**18**	**30**	**4**	**4**	**46**	**5**	**11**	**19**	**2**	**4**	**5**	**74**	**19**	**21**	**42**	**10**	**19**	**6**	**7**	**463**

Table 2. Marine mammal species bioacoustical studies in Latin American countries (1971 – 2021)

Country	Number of species studied	Species most studied	Number of studies
Brazil	20	*Sotalia guianensis*	17
Ecuador	19	*Physeter macrocephalus*	16
Chile	7	*Balaenoptera musculus*	11
Mexico	26	*Balaenoptera physalus*	8
Panama	10	*Tursiops truncatus*	6
Puerto Rico	5	*Megaptera novaeangliae*	6
Costa Rica	15	*T. truncatus*	5
Argentina	8	*Cephalorhynchus commersonii, Eubalaena australis, Otaria byronia, Pontoporia blainvillei*	3
Belize	2	*Trichechus manatus*	3
Colombia	11	*M. novaeangliae, P. macrocephalus*	3
Dominican Republic	2	*M. novaeangliae*	3
El Salvador	11	*Stenella attenuata, S. longirostris*	3
Guadeloupe	2	*M. novaeangliae*	3
Honduras	11	*S. attenuata, S. longirostris*	3
Martinica	2	*M. novaeangliae*	3
Nicaragua	11	*S. attenuata, S. longirostris*	3
Peru	20	*Arctocephalus australis, Delphinus delphis, Phocoena spinipinnis, P. macrocephalus, S. attenuata, S. coeruleoalba, S. longirostris, T. truncatus*	3
Saint Martin	2	*M. novaeangliae*	3
Venezuela	5	*M. novaeangliae*	3
Cuba	3	*P. macrocephalus*	2
Guatemala	8	*S. attenuata, S. coeruleoalba, S. longirostris*	2
Saint-Barthélemy	2	*M. novaeangliae*	2
Uruguay	4	*O. byronia, T. truncatus*	2
Haiti	2	*M. novaeangliae, P. macrocephalus*	1

Table 3. Number of studies by research topic in the marine mammal species in Latin American countries. The number inside each cell is the number of studies. In one paper no genus or species could be identified (Martin et al., 2019). AB (abundance and population density), ANT (anthropogenic effects), BEH (association of acoustic signals and behavior), HAB (description, preferences, and habitat use), GTV (geographical or temporal vocalizations variations), CAP (hearing, vocalization, and recognition capabilities), ISP (individual and species identification), INT (inter and intraspecific differences in vocalizations), LCR (learning, communication, and acoustic recognition), LMM (localization, species monitoring, and mitigation policies), STD (spatial-temporal distribution), SIZ (size of the animals), VOC (acoustic signal descriptions), TO (total general). See common names in Table 1.

Species	AB	ANT	BEH	HAB	GTV	CAP	ISP	INT	LCR	LMM	STD	SIZ	VOC	TO
Arctocephalus australis								1					2	3
Arctocephalus galapagoensis										1				1
Balaenoptera acutorostrata	1										5		2	8
Balaenoptera borealis	1												1	2
Balaenoptera edeni					2			1			1		12	16
Balaenoptera musculus	1	1	1		4						10		5	22
Balaenoptera omurai					1									1
Balaenoptera physalus	1		1		3			1		1	2		1	10
Berardius bairdii							2							2
Cephalorhynchus commersonii								1	1				1	3
Cephalorhynchus eutropia													1	1
Delphinus delphis		2	3					11			5			21
Eschrichtius robustus		1	1								1		1	4
Eubalaena australis		1	1								1		4	7
Feresa attenuata			3											3
Globicephala macrorhynchus		1	3								4			8
Globicephala melas		1						1						2
Grampus griseus			3		3			1			4			11
Indopacetus pacificus							2							2

Species	AB	ANT	BEH	HAB	GTV	CAP	ISP	INT	LCR	LMM	STD	SIZ	VOC	TO
Inia araguaiaensis			1										1	2
Inia geoffrensis			2	1	1			3					2	9
Inia sp.								2						2
Lagenodelphis hosei			3										6	9
Lagenorhynchus cruciger								1						1
Lagenorhynchus obscurus		1	2										1	4
Megaptera novaeangliae	5	6	3	1	18		2				6		5	46
Mesoplodon densirostris							2							2
Mirounga angustirostris					1			1						2
Orcinus orca			1					1					1	3
Otaria byronia		1	1					2	1					5
Phocoena sinus	5													5
Phocoena spinipinnis		3		1									1	5
Physeter macrocephalus	7		2	1	9			16	2			2	4	43
Pontoporia blainvillei		1	1		1								4	7
Pseudorca crassidens			3				10				4			17
Sotalia fluviatilis		1	2		1			2					1	7
Sotalia guianensis		1	4		6		2	1					6	20
Stenella attenuata			3					20			4		1	28
Stenella coeruleoalba			3				10	10						23
Stenella frontalis		1	1					2					1	5
Stenella longirostris			3		1			21			4		3	32
Steno bredanensis			3					2			1		2	8
Trichechus manatus		1		1	1	1	1						2	7
Tursiops truncatus		8	4		5		10	3		1	6		3	40
Zalophus wollebaeki			1											1
Ziphius cavirostris							2							2
Overall total	**21**	**31**	**59**	**5**	**57**	**1**	**43**	**104**	**4**	**3**	**58**	**2**	**74**	**462**

was available. The lack of marine mammal studies by acoustic methods in some Latin American countries, such as those in the Caribbean region, is possibly related to the lack or absence of knowledge on this field, the lack of trained personnel to carry out this type of research, scarce or non-existent funding for the purchase and use of recording devices, and other more pressing local research priorities. On the other hand, in the 2010s, more accessible technology became available, and this turning point was reflected in the number of publications that occurred post- 2010 (over 50% of the total found in this review). Technological improvement, development of new equipment, and an increased interest in the different topics in bioacoustics turned into research, and publications. Currently, the development of recording devices such as sonobuoys, gliders, and acoustic tags continues even though these have to date been used sparingly in Latin American countries (*e.g.* Oswald et al., 2007; Saddler et al., 2017; Bittencourt et al., 2018; Dombroski et al., 2020). Another reason for the growth in the number of publications may be due to the increase in specialized journals publishing papers on marine mammals or specifically on bioacoustics.

In addition, there are now many trained personnel and researchers capable of carrying out this type of research. It is likely that the academic environment, in which there are grants for developing countries (such as those in Latin America), is also helping research. Sometimes, foreign researchers in Latin American countries accept students for undergraduate or graduate studies with theses focused on marine mammal bioacoustics in their countries of origin, or foreign researchers establish collaborations with local people. There are national and also more international grants and scholarships that encourage this type of research today than there were in past decades. Courses and lectures are also offered both online and in person, which favor training more people in this type of research. Thus, it is expected that in future years these recording devices will continue to be more affordable and within the reach of more Latin American countries and, consequently, the number of publications will also continue to increase. It is perhaps because of the above reasons that during the years 2020 and 2021, 15.6% of the total bioacoustic studies were published.

Country specific trends

In Latin American countries, acoustic methods are acknowledged to be commonly applied as a complementary tool to visual methods. In some South American countries, there are well-established researchers or research centers dedicated to the study of marine mammals, and their incorporation of more acoustic methods over time could have influenced the number of publications consistently increasing since the 1970s. For example, in Argentina, there is the Whale Conservation

Institute; in Chile there is the Blue Whale Center and the Chilean Antarctic Institute; and in Mexico two federally-funded research centers CICESE and CICIMAR, and two State Universities UABCS and UABC, all of them in the Baja California Peninsula. All these institutions have experienced faculty on marine mammal research. In Brazil, there are several NGOs and universities whose researchers focus on the study of marine mammals. However, having research centers is not necessarily reflected in the number of publications on bioacoustics, except for Brazil and Mexico, which are first and second in publishing on this subject. In general, the number and presence of researchers dedicated to marine mammal research in Central American countries is estimated to be over 20 scientists; some work for governmental agencies, others are associated to the University of Costa Rica and Universidad Maritima International of Panama, and many lead non-profit organizations such as Panacetacea.org. However, not all these scientists use acoustic methods in their research (L. J. May-Collado, University of Vermont, pers. comm., 14 November 2022). In Belize, there is no research center or university dedicated to the study of marine mammals, but both the university and the government partner strongly with associations such as the Clear Water Marine Aquarium and Wildlife Conservation Society, among many others, and much of the research is conducted by these organizations (L. D. Olivera, Universidad Juárez Autónoma de Tabasco, pers. comm., 13 September 2022). The few existing studies that are exclusive to a country (except in Costa Rica) were projects that were generally led by foreign researchers (*e.g.* Thode et al., 2000; Nowacek et al., 2003; Stafford et al., 2005).

The high number of studies in Mexico is determined mainly by the amount of research conducted in the Mexican Pacific and is possibly related to the proximity to the United States. In turn, the number of studies conducted in the Pacific coast Latin American countries is determined by acoustic-visual or acoustic-only monitoring, where surveys were carried out from the USA to Mexico (*e.g.* Baumann-Pickering et al., 2013, 2014; Širović et al., 2017) or to Peru, (*e.g.* Oswald et al., 2003; 2004; 2007; Gruden et al., 2016).

Mexico, Brazil, Chile, and Argentina have extensive coastlines, which could be a contributing factor to the number of studies, assuming that the number of resident or migrating marine mammals is proportional to the coast length. The exception would be Ecuador, whose coastline is short and yet was one of the countries with the largest number of studies. The countries located in the Caribbean region have a considerably smaller coastline than the rest of the countries. In addition, we believe that the economy in the countries and the high cost of bioacoustical devices are limiting factors to research and scientific publications.

Species

The number of species studied in each country seems to be related to the species richness and to the interest in a particular species. For example, in Mexico 26 of the 44 species reported were studied (Heckel et al., 2018). Ecuador, Peru, Brazil, Mexico, and Argentina are the countries with the highest marine mammal species richness (Pompa-Mansilla et al., 2011), and the countries where the greatest number of species were studied.

The fact of studying similar species and topics in most of the countries of the Pacific coast and the Caribbean region can be due to the fact that in several papers the surveys were carried out from the USA to Peru (Pacific Ocean) (*e.g.* Oswald et al., 2003; 2004; 2007; Gruden et al., 2016) or through several Caribbean islands (*e.g.* Winn et al., 1981; Weilgart & Whitehead, 1988; Moore et al., 1993; Heenehan et al., 2019). This pattern did not hold for countries such as Ecuador, Brazil, and Puerto Rico, since it seems that these studies were directed toward species such as the sperm whale, the Guiana dolphin, and the humpback whale, respectively. Uruguay is a complete outlier, where there does not seem to be any preference toward a particular species. In Belize, even though it is in an area of intermediate richness (24-26 species, Pompa-Mansilla et al., 2011), only the Antillean manatee was studied. Similarly, in Haiti, whose northern portion has a high richness of marine mammals, few species were studied.

Overall, the three most studied species, humpback whale, sperm whale, and common bottlenose dolphin, are abundant and widely distributed species, which most likely facilitates data collection (IUCN, 2022) and are also among the most studied species of cetaceans worldwide. Of these three cetaceans, the humpback whale is among the species of greatest interest in bioacoustics studies in Latin America. This may be because humpback whale males produce elaborate songs during the breeding season (Cerchio et al., 2001) and their songs can help establish connectivity among breeding populations (*e.g.* Cerchio et al., 2001; Darling et al., 2019; Mercado & Perazio, 2022; Schulze et al., 2022), also seem to be particularly fascinating to humans. Recent song structure studies throughout their breeding grounds in Central (Chereskin et al., 2019) and South America (*e.g.* Oña et al., 2017; 2019; Español-Jiménez & van der Schaar, 2018) highlight the importance of continuing the monitoring of this species using passive acoustic monitoring stations. In recent years, humpback whales have been studied not only at breeding grounds but also at feeding sites (Clark & Clapham, 2004; Parks et al., 2015; Español-Jiménez & van der Schaar, 2018) and information about their social behavior has been included (Dunlop et al., 2007; Rekdahl et al., 2015; Oña et al., 2017; 2019).

The sperm whale and the common bottlenose dolphin are the two most studied species, especially for topics about the variability in their acoustic repertoires (Tyack, 1997; Schulz et al., 2011) given that they have great vocalization capacities and complex communication systems (Lilly & Miller, 1961; Janik, 2009; Schulz et al., 2011) with characteristic vocalizations commonly emitted during socialization (codas or whistles, Whitehead & Weilgart, 1991; Frankel, 2009). The bottlenose dolphin is one of the species that produces its own signature whistles (Caldwell & Caldwell, 1965). In the wild, it is possibly one of the most frequently sighted species in Latin countries, further facilitating data collection.

The high number of studies on the spinner, pantropical spotted, and striped dolphins could be explained by the studies conducted from Mexico to Peru along the Pacific coast (*e.g.* Oswald et al., 2003; 2004; Rankin et al., 2012; Gruden et al., 2016), unlike studies conducted in the South Atlantic Ocean directed at only the spinner dolphin (*e.g.* Camargo et al., 2006;

Rossi-Santos et al., 2008; Moron et al., 2015; Simões Amorim et al., 2019). Resident species, like the fin whale, allow them to be studied by acoustic methods throughout the year with an emphasis on the breeding season. The blue whale has acquired a general interest status for studying it by acoustic methods in its feeding grounds (*e.g.* Buchan et al., 2018; Lewis et al., 2018; Szesciorka et al., 2020), breeding sites (*e.g.* Thompson et al., 1996, Paniagua-Mendoza et al., 2017), and during its migration (*e.g.* Stafford et al., 1999, Monnahan et al., 2014; Oestreich et al., 2020). During the boreal winter, one of the blue whale's main breeding and calving grounds is the Gulf of California (Sears et al., 2013), which may explain why most of the studies on this species have been carried out in Mexico.

Endemic and restricted distribution species seem to have failed to attract attention to studies by acoustic methods. It is possible that their restricted distribution limits their detection and consequently their study. However, the analysis and descriptions of acoustic signals could facilitate subsequent detection of them latter. Pairing acoustics with visual methods could actually confirm these species' presence and behavior. The way that bioacoustics can aid in the preservation of species with restricted distributions is exemplified by the vaquita (*Phocoena sinus*). Despite its being an endemic and critically endangered species, acoustic studies have been conducted to estimate population size and to suggest urgent mitigation policies in an attempt to save it from extinction (Gerrodette et al., 2011; Jaramillo-Legorreta et al., 2017; 2019; Taylor et al. 2017; Thomas et al. 2017). Similar bioacoustic studies on the Galapagos fur seal (*Arctocephalus galapagoensis*) and Galapagos sea lion (*Zalophus wollebaeki*) could be implemented.

Research topics and species

The trend observed when studying different research topics across the various marine mammal groups perhaps is determined by the nature of their vocalizations and their species-specific biology. In mysticetes, population abundance and density have been studied assuming standard cue rate of their vocalizations, where the number of individuals can be relatively easily estimated, but new research by Guazzo et al. (2019) and Martin et al. (2022) would suggest this is not the case. In whistling odontocetes and those that form large groups and have many overlapping vocalizations, density estimation becomes more complex. Studies have been conducted where it is possible to determine abundance and density using clicks, as in the vaquita (Jaramillo-Legorreta et al., 2017), underlining the importance of bioacoustics for determining number of abundant or rare species.

The least studied research topics in Latin American countries could be due to the greater control and experience required to carry out control versus treatment(s) experiments. In pinnipeds, thanks to their amphibious lifestyle, experiments have been carried out on land to analyze the physical and acoustic reactions they present to their conspecifics (*e.g.* Attard et al., 2010; Charrier et al., 2013; Terhune, 2016). Going forward to expand research on this topic, these methodologies could be applied to species with distributions in Latin America such as the Galapagos and Guadalupe (*Arctocephallus phillippii townsendi*) fur seals, and the Galapagos sea lion amongst other species.

Anthropogenic effects on odontocetes have largely been analyzed on how vocalizations are modified in the presence of boats (May-Collado & Wartzok, 2008; May-Collado & Quiñones-Lebrón, 2014; Leão Martins et al., 2018; Perez-Ortega et al., 2021; Gagne et al., 2022). In addition, it has been observed that these noisy circumstances also affect their behavior, including feeding (*e.g.* Romeu et al., 2017). Bioacoustics has also allowed the evaluation of techniques to avoid bycatch through the use of pingers (*e.g.* Monteiro-Neto et al., 2004; Mangel et al., 2013; Clay et al., 2019), concluding these devices were effective during control periods reducing net interactions. Pingers are devices that transmit short high-pitched signals at brief intervals for purposes of detection, measurement, or identification. The data obtained through the analysis of feeding behavior and noise may be translated into establishing mitigation and conservation policies for a species. Bioacoustics has also provided information on different behavioral circumstances, for example, differences between day and night. Deconto & Monteiro-Filho (2016) found that whistles, burst pulses, and low-frequency narrow-band sounds were more frequent at night in Guiana dolphin, as these individuals require greater acoustic communication in the absence of light, mainly for social communication. Other behavior include foraging (*e.g.* Ladegaard et al., 2017), and behavior changes in the presence of predators (*e.g.* Andriolo et al., 2015); all information that would be impossible to obtain with visual methods alone.

Geographical or temporal vocalizations variations, and individual and species identification allow the recognition of stocks, as is the case of the humpback whales (Hawkey et al., 2020), and the identification of species and individuals through the knowledge of their acoustic repertoire (*e.g.* Oswald et al., 2003; Baumann-Pickering et al., 2013; Lima & Le Pendu, 2014). This last topic is of relevance because it can help in the discovery of new species. Some studies have recorded mysticetes and odontocetes acoustic signals, but the match between vocalizations and species has not been achieved (*e.g.* Ward et al., 2017; Giorli et al., 2018; Pinto & Chandrayadula, 2021). Another example is from San Quintin, Baja California, Mexico, where researchers detected an unknown vocalization during simultaneous visual surveys. These researchers are currently analyzing the recordings to find evidence for the discovery of a new species (G. Cárdenas-Hinojosa, Comisión Nacional de Áreas Naturales Protegidas, pers. comm., 17 August 2022). At this time, *Inia geoffrensis* is recognized with only two subspecies: *I. g. boliviensis* and *I. g. geoffrensis* (Committee on Taxonomy, 2022). However, there is a proposal that up to three species be recognized: *I. geoffrensis, I. boliviensis*, and *I. araguaiensis* (Hrbek et al., 2014) which counters the Committee on Taxonomy of the Society for Marine Mammalogy's claim (2022) that there is still not enough morphological and genetic evidence to support three distinctions. On top of this, Melo-Santos et al. (2019; 2020; 2021) conducted studies in which they described the vocalizations of *Inia* spp. concluding that three species may exist. The authors found differences in the characteristics of the vocalizations that could support molecular and morphological information to determine if they are to be considered new species.

Recommendations

Latin American countries should carry out a more diverse array of bioacoustic studies. These studies have proven essential to improve and update conservation policies. Several topics have a representative number of studies. However, a more detailed perusal of any given country or a specific species shows that the number of studies is small in both instances, underlining both the variability and lack of depth in the number of studies per species, and research topics in each country. Thus, there is an opportunity to increase knowledge in many research topics that can lead to species conservation and protection. Studies on description, preferences, and habitat use by acoustic methods are relevant since it would allow a detailed analysis of the environment where the animals thrive. These studies would reveal the way in which a species use the habitat extensively and help to establish conservation measures not only for the species but also for the entire ecosystem, acting as umbrella species. Few studies have been also carried out on localization, species monitoring, and mitigation policies, all of them important for species and site conservation policies.

The state of marine science has made it almost mandatory to apply bioacoustics in critical habitats and habitats with vital importance for species, especially for endemic species with restricted distribution and under some IUCN risk category or national legislations. All the research topics analyzed are relevant; however, it is particularly necessary to carry out studies on topics such as abundance and population density, anthropogenic effects, distribution, preferences, and habitat use, all of them critical to designing effective management plans and to establish policies that will allow for the preservation of species and their habitats. These methods are also effective for studying rare species and highlight threatened species. They can also help to identify critical habitats for marine mammals. Conservation should not be a privilege of wealthy countries. Conservation and bioacoustics should be an egalitarian tool to preserve natural habitats and species across the world.

Conclusions

The geographical distribution of the studies on bioacoustics in Latin America is not uniform, with countries like Brazil and Mexico leading in the number of publications. This might be explained by a number of causes, such as large number of research institutions, extensive shorelines, and identified priority research topics studied through bioacoustics in those countries.

This review shows the increased application of bioacoustics to study the diversity of marine mammal species and their biology and ecology in Latin America during the past 50 years. Latin America is ripe with interest in conservation, so bioacoustics should become a more accessible specialty. This being said, the growth trend in more cost-effective methods of marine mammal monitoring by bioacoustical techniques is expected to continue in Latin America. Efforts to provide training and resources to the countries where such studies are rare do exist but could expand. The training required to empower people to become bioacousticians should become part of key conservation priorities.

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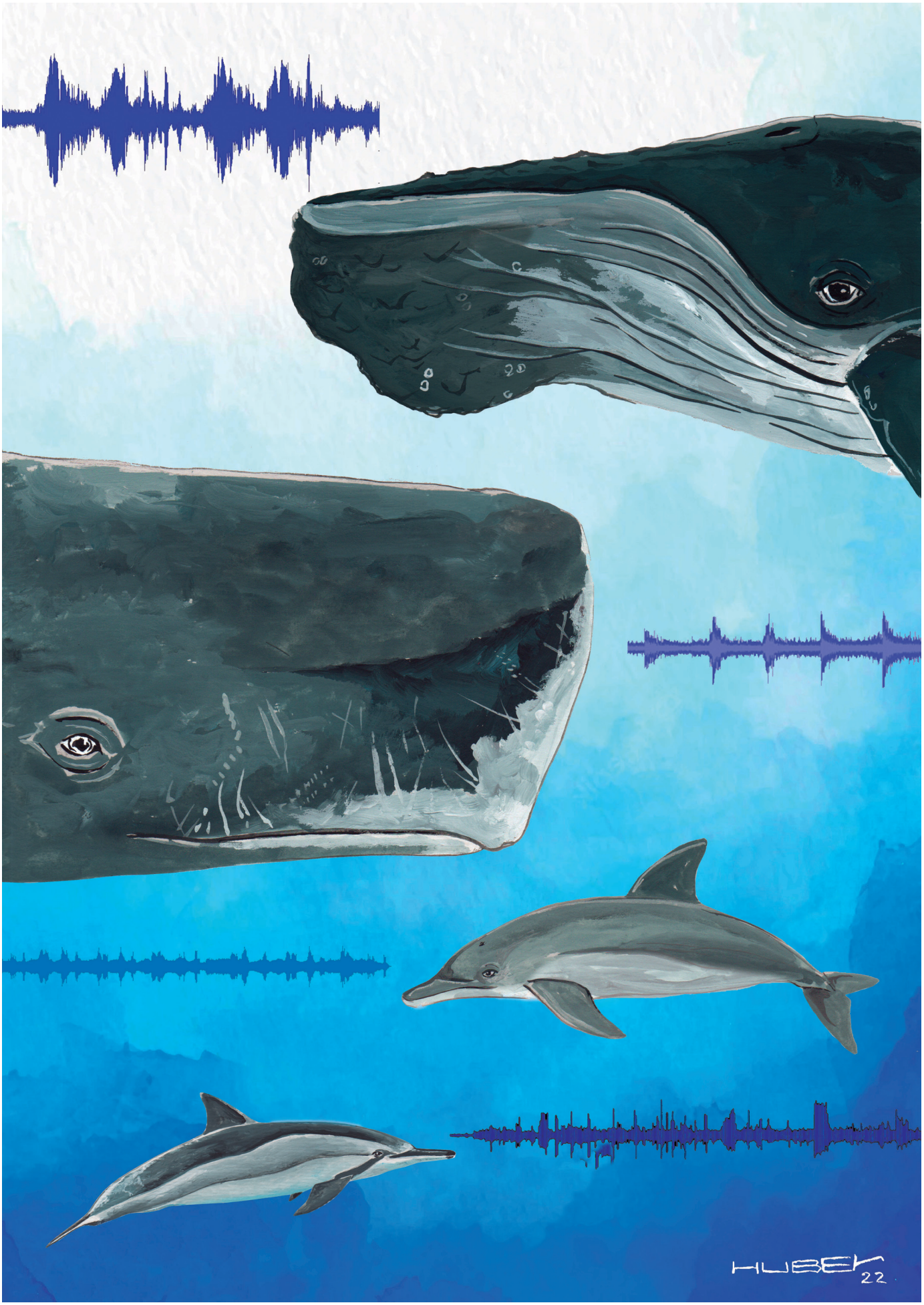
Supplementary material

Supplementary Material 1. Number of acoustical studies by marine mammal species conducted in Latin American countries. The number of studies in this table (n = 463) is greater than the number of published papers (n = 205) because 41 papers analyzed more than one species and/or more than one country. Research topic abbreviations include: AB (abundance and population density), ANT (anthropogenic effects), BEH (association of acoustic signals and behavior), HAB (description, preferences, and habitat use), GTV (geographical or temporal vocalizations variations), CAP (hearing, vocalization, and recognition capabilities), ISP (individual and species identification), INT (inter and intraspecific differences in vocalizations), LCR (learning, communication, and acoustic recognition), LMM (localization, species monitoring, and mitigation policies), STD (spatio-temporal distribution), SIZ (size of the animals), VOC (acoustic signal descriptions). Inside each cell is the abbreviation of the Latin American country including: AR (Argentina), BL (Saint-Barthélemy), BR (Brasil), BZ (Belice), CL (Chile), CO (Colombia), CR (Costa Rica), CU (Cuba), DO (Dominican Republic), EC (Ecuador), GP (Guadeloupe), GT (Guatemala), HN (Honduras), HT (Haiti), MF (Saint Martin), MQ (Martinica), MX (Mexico), NI (Nicaragua), PA (Panama), PE (Peru), PR (Puerto Rico), SV (El Salvador), UY (Uruguay), VE (Venezuela). Inside parenthesis is the number of the respective references in Supplementary material 2.

Supplementary Material 2. List of papers found on the Web of Science related to bioacoustics in marine mammals in Latin American countries.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