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Review

Detecting, counting and following the giants of the sea: a review of monitoring methods for aquatic megavertebrates in the Caribbean

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Abstract
The Caribbean is a mega-diverse and bio-geographically important region that consists of the Caribbean Sea, its islands, and surrounding coastlines. Among the billions of aquatic species inhabiting this region, the mega-vertebrates stand out for their social, economic and ecologic relevance. However, the Caribbean has been threatened by climate change, poverty, pollution, environmental degradation and intense growth of the tourism industry, affecting megafauna species directly and indirectly. Population monitoring plays a critical role in an informed conservation process and helps guide management decisions at several scales. The aim of the present review was to critically examine the methods employed for monitoring marine megafauna in the Caribbean, so as to create a framework for future monitoring efforts. In total, 235 documents describing protocols for the monitoring of sirenians, cetaceans, elasmobranchs, sea turtles and crocodilians in the Caribbean region, were reviewed. The methods included community-based monitoring (interviews, citizen science and fisheries monitoring), aerial surveys (by manned and unmanned aerial vehicles), boat-based surveys (including manta tow, and side-scan sonars), land-based surveys, acoustic monitoring, underwater surveys, baited remote underwater video, mark–recapture, photo-identification and telemetry. Monitoring efforts invested on aquatic megafauna in the Caribbean have been highly different, with some species and/or groups being prioritised over others. The present critical review provides a country-based overview of the current and emerging methods for monitoring marine megafauna and a critical evaluation of their known advantages, disadvantages and biases.

Additional keywords: Atlantic sea, crocodilians, elasmobranch, marine mammals, megafauna, sea turtles.

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Introduction

The Caribbean region stands out for its beauty and biodiversity. It also encompasses several low-income countries; poverty is widespread throughout both the mainland and islands countries, where an average of 38% of the population is impoverished (Barker 2002). In consequence, the economic investment in natural-resource management, enforcement and monitoring is still low, despite the regional intergovernmental cooperation for marine conservation (Barker 2002). As all aquatic systems on the Earth, the Caribbean is threatened by climate change, pollution and environmental degradation (Lewsey *et al.* 2004). A constantly growing tourism industry adds additional impacts on these ecosystems and species (Holder 1988).

Overall, large-bodied species play an important role in the trophic dynamic of aquatic ecosystems, consuming large amounts of food necessary to maintain their large biomass, and control prey populations (Morissette *et al.* 2006; Castelblanco-Martínez *et al.* 2012; Heupel *et al.* 2014). Some megavertebrates (marine mammals and elasmobranchs) have *K*-selected life-history features (i.e. longevity, late maturation, large size, and small number of progeny) that make these species particularly prone to hunting and/or fishing, boat collisions, pollution and other anthropic-related threats (Hooker and Gerber 2004*a*).

Reliable abundance and distribution estimates are critical for the management and conservation of aquatic megafauna species. In the long term, the ability to detect changes in population sizes over time is a key aspect of any assessment of impacts of potentially harmful human activities on aquatic fauna, and can be instrumental in promoting political will to develop legal protections to prevent further losses (Giglio *et al.* 2015). Nevertheless, geographically and methodologically consistent survey protocols have rarely been replicated with sufficient frequency to allow detection of population trends before decreases in population sizes exceed safe boundaries (Taylor *et al.* 2007). Aquatic mega-vertebrates often display long-distance movements, wide home ranges and migratory behaviours. Thus, for many of those species, it is challenging to derive population estimates and knowledge on their habitat use needed to inform conservation planning (Witt *et al.* 2009).

The aim of the present work was to critically examine the methods employed for monitoring marine mammals (cetaceans and sirenians), elasmobranchs (rays and sharks) and reptiles (sea turtles and crocodilians) in the Caribbean Sea, so as to propose new directions to future monitoring efforts.

Methods

Study area

We limited the research to the 'Caribbean Sea', roughly defined as consisting of the Caribbean Sea, its islands and surrounding coasts. The Caribbean Sea is bounded to the south by South America, to the west by Central America, and the north by the Greater Antilles. Our study included information from the Greater Antilles, the Lesser Antilles, and the continental countries with Caribbean coastlines and islands from Central America (Mexico, Belize, Guatemala, Honduras, Costa Rica and Panama) and South America (Colombia, Venezuela, Guyana, Suriname and French Guyana). For large continental countries (Mexico, Colombia and Venezuela), we narrowed the search to studies developed within the Caribbean Region politically defined for each country.

The Caribbean region spans the deep tropics and subtropics. Because of the tropical maritime location, temperature changes throughout the region are generally small, and rainfall is by far the most important meteorological element (Taylor and Alfaro 2005). The Caribbean is a semi-enclosed tropical sea widely considered oligotrophic, but that is influenced by nearly 20% of the annual discharge of the world's rivers (Orinoco and Amazon rivers) and by seasonal upwelling along the southern margin (Müller-Karger *et al.* 1989). As part of the western hemisphere warm pool, the Caribbean Sea features a body of very warm water (warmer than 28.5°C; Wang and Lee 2007). Tropical storms and hurricanes are seasonally common in the northern Caribbean (Taylor and Alfaro 2005), deeply affecting ecosystem function and structure.

Data compilation

In the first phase of the review, all relevant information was compiled on aquatic megavertebrate species reported in the study area. Marine megavertebrates inhabiting the Caribbean include a broad range of birds, mammals, reptiles and fish that undoubtedly have an important economic and ecological impact at a regional level. However, we narrowed down the list of species to marine mammals, sea turtles, crocodilians, sharks and rays, so as to simplify the analysis.

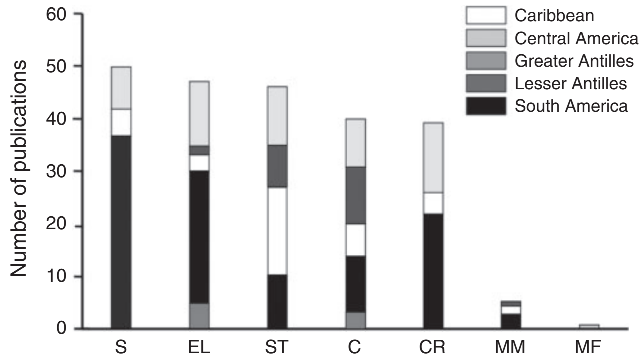

Fig. 1. Number of publications per megafauna group and region. S, Sirenia; EL, elasmobranchs; ST, sea turtles; C, Cetacea; CR, Crocodilia; MM, marine mammals; and MF, megafauna.

We conducted an extensive literature review using databases, including Web of Science, Current Contents, Aquatic Sciences and Fisheries Abstracts, BIOS Previews, Zoological Record, SCOPUS, BiblioLine, Google Scholar and Cambridge Scientific Abstracts. Keywords used in our searches were as follows: 'sea turtles', plus 'Caribbean', plus 'monitoring'. The searches were sorted by relevance, and the first 100 pages were included for all papers published between 1990 and the end of 2018 (the last searches were conducted 13 December 2018). We selected all the publications showing results of megafauna population monitoring, including studies concerning abundance estimates, movements and distribution, health assessments, threats, climate-change effects and others. Studies regarding very specific aspects of the species biology, behaviour, physiology, taxonomy, rehabilitation or genetics were not considered. For each of the records in the database, we completed the following information: group (Cetacea, Sirenia, Chondrichtyes, Sea Turtles, Crocodilia, others), species, method, country, region (South America, Central America, México, Greater Antilles, Lesser Antilles), and type of document (book, conference proceeding, journal article, report, thesis). A triangulation process was performed in an attempt to avoid replicating results, i.e. results from same research published in two or more documents. In the case of replicated studies, we selected the most relevant document and removed the rest from the database. The relative importance of the document was assigned according to its type in the following order: report > thesis > conference proceeding > journal article; therefore, 'journal article' was the preferred document type.

This article does not contain any studies with animals performed by any of the authors.

Results

We found and reviewed 352 documents, including reports, thesis, book chapters, journal articles and conference proceedings. After careful filtering and review, 235 documents were selected to be incorporate in the final database (Fig. 1). There was an increase in the volume of publications during the past

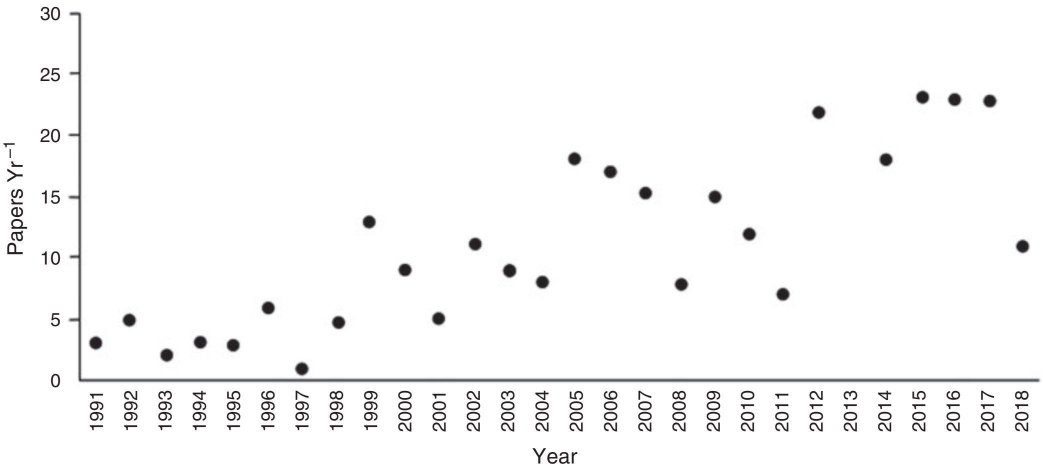

Fig. 2. Inter-annual variation in publication records regarding megafauna monitoring in the Caribbean.

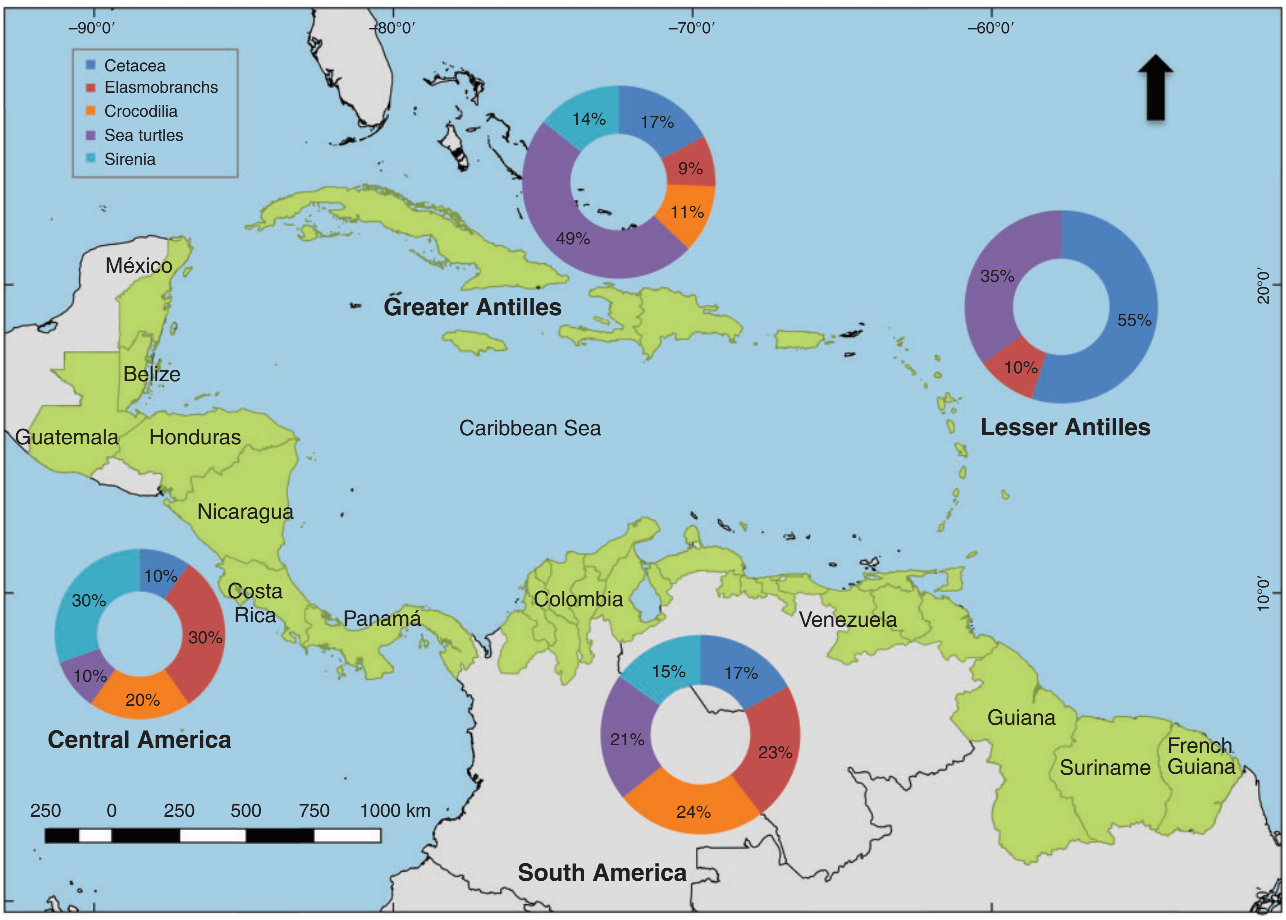

Fig. 3. Percentage of studies performed by megafaunal group and regions inside the Caribbean sea. (■), Countries included in the review.

decade compared with the 1990s and early 2000s (Fig. 2). The region with more publications on megafauna monitoring was Central America (36%), followed by South America (23%) and Greater Antilles (15%). Only 9% of the publications corresponded to Lesser Antilles (Fig. 3). Although 13% of the papers mentioned more than 10 species each, more than 70% of the records corresponded to research devoted to only one species. The most common species was the Antillean manatees

Table 1. Species of megafauna targeted in the consulted documents and their conservation status according to the International Union for the Conservation of Nature

IUCN category	Marine mammal	Shark or ray	Crocodilian	Sea turtle
Critically endangered			*Crocodylus rhombifer*[A] *C. intermedius*[A]	*Eretmochelys imbricata*[A] *Lepidochelys kempii*
Endangered	*Trichechus manatus manatus*[A]	*Rhincodon typus*[A]		*Chelonia mydas*[A]
Vulnerable	*Physeter macrocephalus*[A]	*Mobula birrostris*[A] *Diplobatis guamachensis*	*Crocodylus acutus*[A]	*Caretta caretta*[A] *Dermochelys coriacea*[A] *Lepidochelys olivacea*
Near threatened		*Pseudobatos percelles* *Aetobatus narinari*[A] *Carcharhinus perezi*[A] *Galeocerdo cuvier*[A] *Negaprion brevirostris*[A] *Prionace glauca*[A]		
Least concern	*Tursiops truncatus*[A] *Stenella attenuate* *S. coeruleoalba* *Steno bredanensis*[A] *Grampus griseus*[A] *Peponocephala electra* *Lagenodelphis hosei* *Ziphius cavirostris* *Balaenoptera edeni* *Megaptera novaeangliae*[A]	*Urobatis jamaicencis*[A] *Sphyrna tiburo* *Rhizoprionodon porosus* *Narcine bancroftii*	*Crocodylus moreletii*[A] *Melanosuchus niger* *Caiman crocodilus*	
Data deficient	*Stenella frontalis* *S. longirostris* *S. clymene* *Sotalia guianensis* *Globicephala macrorhynchus* *Pseudorca crassidens* *Kogia breviceps* *K. sima* *Delphinus capensis*[A] *Orcinus orca*[A] *Mesoplodon europaeus* *Balaenoptera physalus*	*Hypanus americanus* *Hypanus guttatus*[A]		

[A]Publication is devoted to only one species.

Trichechus manatus manatus (50), American crocodile *Crocodylus acutus* (17), leatherback turtle *Dermochelys coriacea* (11) and whale shark *Rhincodon typus* (10). Table 1 shows the species targeted by the consulted authors and its conservation status according to IUCN (2019).

The documents described a total of 13 different methods for population monitoring of megafauna in the Caribbean, which we classified as indirect or direct methods. The latter can be divided in non-intrusive and intrusive methods.

Indirect methods

These methods aim to gather megafauna information through the consultation of a variety of information sources such as, published/unpublished literature, interviews and stranding networks.

Reviews and stranding networks

This method consists in conducting an exhaustive search from a variety of sources including peer-reviewed journal articles, databases, books, theses, technical reports and scientific collections. Additionally, it often includes reports of strandings and opportunistic sightings collected by local stranding networks. This method has been used in marine mammals, reptiles and elasmobrachs (Tables S1–S3, available as Supplementary material to this paper).

Interviews and fisheries monitoring

Interviews with local inhabitants aim to obtain data about ecology, distribution and threats, and are normally addressed to knowledgeable adult individuals, regularly males (e.g. commercial fishermen, former hunters, indigenous waterfront residents, natural-resource professionals; Correa-Viana *et al.* 1990; Mou-Sue *et al.* 1990). Commonly used techniques included structured, semi-structured and unstructured interviews; closed-ended or open-ended questions; focus groups or group interviews; participative observation and oral histories (Ortega-Argueta *et al.* 2012). Interviews are a low-cost monitoring technique that can be applied as a first approach to evaluate the general distribution, relative abundance in places with no previous monitoring studies, and mortality sources needed. Interviews were applied for monitoring sea turtles and crocodilians in Colombia and Venezuela (Table S3).

Fisheries monitoring is one of the most used indirect methods to evaluate elasmobranches because of their importance in fisheries dynamic. This method involves collecting the information directly from the fishery camps, and includes both interviews with fishermen and documenting catch data. In the Caribbean, this approach has been used extensively to examine the biological, ecological and demographic parameters of blue (*Prionace glauca*), reef (*Carcharhinus perezi*), lemon (*Negaprion brevirostris*) and blacktip sharks (*Carcharhinus limbatus*) in Mexico, Colombia and Venezuela (Table S2).

Citizen science

Citizen science is a research technique that enlists the public in collecting data across an array of habitats and locations over long spans of time (Bonney *et al.* 2009). Citizen scientists have been used to monitor cetacean populations for decades, primarily through shore-based observation programs (Embling *et al.* 2015). In the Caribbean, citizen-science programs are uncommon, or the collected data are still not available. Volunteers of the cetacean sighting projects of the Leeward Dutch Antilles recorded 20 new reliable records of cetaceans (Debrot *et al.* 1998), but the authors warrant that many additional records were obtained but could not be used by the study because they were inconclusive or incompletely documented (Table S1).

Various volunteer-based projects have specifically counted sharks at local, regional and global scales. In the Greater Caribbean, an analysis of the spatial and temporal trends of the yellow stingray (*Urobatis jamaicensis*) was based on reports of trained volunteer divers, collected by the Reef Environmental Education Foundation (Ward-Paige *et al.* 2011). Likewise, data collected through citizen-science programs were used to explore the contemporary distribution and sighting frequency of sharks on reefs in the Greater Caribbean and assess the possible role of human pressures on observed patterns (Ward-Paige *et al.* 2010; Table S2).

Direct methods

During the application of direct methods, the researchers visit the habitat of the targeted species and attempt to detect the individuals visually or acoustically (non-intrusive methods). They also include the protocols of capture, tagging and tracking (intrusive methods).

Stationary platforms

Stationary platforms can be excellent to conduct low-cost long-monitoring programs. Although the sampling area covered is small relative to that in other methods, outpost at heights greater than 20 m above sea level have been demonstrated to improve the method, with an effective radial field-of-view of ~2000 m (Pardo and Palacios 2006). This method was used to observe cetaceans in coastal areas of Venezuela and Colombia (Table S1). Observations from stationary platforms are recommended for the monitoring of highly used areas by manatees (Aragones *et al.* 2012).

Aerial surveys

Data for estimating megafauna abundances are commonly collected using line- or band-transect methods. These protocols are based on the mathematical extrapolation of the number of animals observed during a collected survey. The sightings can be collected on a line (sights over a narrow track) or a band (sights over a wide band along a tracking path). Distributions of perpendicular sighting distances are used to estimate effective strip width, which is a critical transect parameter (Barlow *et al.* 2001).

Manatees have been counted by aerial surveys since the 1970s, and recently in Belize, Mexico, Venezuela, Panama, Guatemala, Honduras and Costa Rica. Cetaceans have been detected by this method around Aruba, Curacao and Bonaire, Guadeloupe, French Guiana, Martinique and Mexico (Table S1). For elasmobranches, aerial surveys are restricted to planktonic species, which are often feeding and foraging near surface. Aggregation sites of whale sharks (*Rhincodon typus*) and manta rays (*Mobula birostris*) have been studied by using aerial surveys in the Mexican Caribbean (Table S2). Aerial surveys of crocodilians have been conducted in Venezuela and Cuba (Table S3).

Recently, unmanned aerial vehicles (UAVs), or drones, have been proposed as an alternative for the light aircrafts to monitor and count marine mammals. In Belize and Mexico, DJI Phantom 3 and 4 quadcopters have been used to gather high-resolution georeferenced video and still imagery of manatees and their habitats (Ramos *et al.* 2017).

Boat-based surveys

Boat-based surveys can be conducted from a variety of boats equipped with outboard engines or catamaran sail ships. The speeds vary from low speed rates (<5 km h^{-1} or drifting with the engine off) for manatee studies, and among 10 and 15 km h^{-1} for cetaceans (Pardo and Palacios 2006). As a complement of this method, side-scan sonar has proven to be a valuable tool that can assist scientists and managers to detect manatees in complex waterways, especially in freshwater systems (Gonzalez-Socoloske *et al.* 2009). Trips made by multi-objective research cruises, geophysical and seismic vessels, ferries and wildlife-watching companies have been employed in the Caribbean as low-cost mobile platforms for cetacean surveys (Table S1). Although these platforms of opportunity are limited by the fact that route, schedule, speed and other travel parameters are out of the researcher control, they are useful to get a general picture of the relative abundance and distribution of cetaceans in specific locations (Swartz *et al.* 2002). Another advantage is that cruises usually cover a broad range of deep waters and several territories and/or countries.

Vessel surveys, usually performed in boats equipped with outboard motors, are useful to detect and count pelagic elasmobranchs (mostly planktivorous; Martínez Urrea 2016). Whale sharks are located through their evident presence of the dorsal fins or tails on surface (Hacohen-Domené *et al.* 2015; Table S2).

Boat-based surveys are the most common technique used to count and monitor abundance of crocodilians in the Caribbean and around the world (Grigg and Kirshner 2015; Table S3). It consists of travelling in predetermined routes by night on bodies of water using a boat or by foot on the edge of bodies of water, and illuminating the water edge with spotlights, lamps or flashlights, to detect eye shines of crocodilians (Grigg and Kirshner 2015). The method allows to approach the individuals and determinate their size class and species (e.g. Platt and Thorbjarnarson 2000*a*, 2000*b*). Approached individuals are often captured to obtain morphological data, determine animal's sex, collect tissue samples and to mark them. Daytime surveys follow the same method as nocturnal surveys, but the detectability relies on seeing the animal, not its eye shine (Grigg and Kirshner 2015).

Passive-acoustic monitoring

Recording and analysing marine-mammal vocalisations is an indirect and passive method used to collect evidence of a particular species and to estimate population density (Küsel *et al.* 2011). Passive acoustic monitoring (PAM) has been proposed as an inexpensive, non-invasive and novel option to estimate manatee population through vocalisations where muddy waters produce limited visibility (Rivera-Chavarría *et al.* 2015; Castro *et al.* 2015). Passive acoustic monitoring has been also useful to detect dolphins and whales where visual survey protocols have limited effectiveness or when visual data are not available (e.g. Jérémie *et al.* 2006; Weir *et al.* 2011). The most popular bioacoustics instrument used was a towed hydrophone array, that consisted of a long-reinforced cable assembled with three or more hydrophones, spaced at certain intervals (Boisseau *et al.* 2006). Other researchers also used directional sonobuoys (Swartz *et al.* 2002, 2003), which transmitted a continuous signal back to the ship on a VHF radio carrier (Table S1).

Underwater visual census (UVC)

During UVCs, an observer and dive buddy on SCUBA or snorkelling descend to the substrate and swims slowly in a predetermined direction, identifying and counting fish in a strip with a known width (Colton and Swearer 2010). During the transect, each swimmer counts the total number of each elasmobranch species (Tilley and Strindberg 2013; Table S2).

Baited remote underwater video (BRUV)

Baited remote underwater-video survey (BRUVS) is a non-invasive method for population assessments for several of marine species, but, in the Caribbean, it has been used only for shark monitoring (Table S2). The method consists of a video camera inside an underwater housing that is mounted on a metal frame with a small, pre-weighed bait source mounted on a pole in the field of view of the camera, then deployed in the selected locations during daylight hours (Bond *et al.* 2012).

Monitoring nesting and feeding grounds

The monitoring of nesting beaches is the most common approach used to determine nesting activity, reproductive success, sea level-rise impacts and population trends of sea turtles. This approach has been widely applied in the Caribbean green, hawksbill, leatherback and loggerhead sea turtles (Table S3). Two techniques are used for observing turtles in feeding grounds, namely, snorkelling and Manta tow surveys. Snorkelling surveys are conducted by two or more observers remaining within eye contact with one another, and following pre-designed transects. Manta tow surveys are conducted by on-boat observers and a snorkel diver towed behind the boat at a constant speed.

Capture, tagging and tracking

Capturing, tagging and tracking marine mammals in the Caribbean has been undertaken for manatees only in a few localised studies (in Mexico, Belize, Panama, Colombia and Puerto Rico; Table S1). Most of the manatees tagged and tracked in the Caribbean were captured from the wild within a program of manatee population assessment. However, these techniques have also been used to monitor manatees in rehabilitation–release programs (Adimey *et al.* 2012). The most common method used to capture manatees is by woven nylon nets of different sizes (Marmontel *et al.* 2012). Passive integrated transponder (PIT) tags are normally used to permanently mark manatees for future identification (Wright *et al.* 1998). All manatees instrumented and tracked in the Caribbean have been tagged with a similar kind of padded belt/harness around the caudal peduncle. The device can incorporate transmitters capable of emitting signals in fresh water, or coupled to floating radio-tags for marine environments. The manatee telemetry systems most commonly used are radio-tags of ultra-high frequency (UHF; Caicedo-Herrera *et al.* 2013), very-high frequency (VHF) and satellite-monitored transmitters (platform transmitter terminals, PTTs) integrated to GPS receivers (Marmontel *et al.* 2012).

The most common direct method of deriving basic ecological information from shark populations is through scientific long-line surveys (Table S2). A variable number of hooks is baited with pieces of resident fish species (Pikitch *et al.* 2005). Another capture method consists of a net used for bottom trawling for a certain amount of time (Benavides *et al.* 2014). Telemetry has provided valuable information on life-history parameters, stock status, behaviour, distribution and migration patterns of elasmobranchs (Kohler and Turner 2001). Satellite telemetry normally includes the use of the Argos satellite system and a radio-frequency transmitter (commonly known as PTT) attached to the host animal (Gifford *et al.* 2007). At present, two types of satellite tags are used to track elasmobranchs, including tethered tags and pop-up satellite archival tags (PSTAs; Gifford *et al.* 2007). Tethered satellite-linked recorders (e.g. smart position or temperature transmitting satellite tags, SPOTs) are designed to record several environmental parameters, such as as depth, position and temperature, and transmit data in real or near-real time (Gifford *et al.* 2007; Graham *et al.* 2012). In addition, PSTAs can archive temperature, pressure and light-level measurements while attached to the animal. After a user-set duration of 30–200 days, the PSTA tag is detached and, at the sea surface, transmits summaries of the archived data through (Hueter *et al.* 2013). Acoustic telemetry has been widely employed to study short-term movement patterns, diel movement patterns and site fidelity of sharks and rays. The following two different methodologies are used: (1) manual acoustic telemetry or active tracking, consisting in deploying an acoustic transmitter to an individual, and then following it with an hydrophone and vessel-based receiver so as to develop a continuous series of periodic positional fixes; and (2) passive acoustic telemetry, when specimens are affixed with coded acoustic transmitters and then remotely tracked by an array of stationary omnidirectional hydrophone-receivers that record the date, time and identification number of study animals as they pass through the detection range of the unit (Chapman *et al.* 2005; Table S2).

Captures were used to study the exploitation of *Caiman crocodilus* in Cuba (Berovides *et al.* 2000). This technique serves, in fact, to monitor the status of legally exploited populations of recovered species or introduced species. The trend of the number of animals killed each year informs on the density of individuals and serves to calculate exploitation rates for the following years. It can also provide important data on the population structure (i.e. sex-ratio and size classes; Berovides *et al.* 2000). This method is applicable only to complete recovered species and populations that have been authorised to be exploited by the competent authorities (Table S1). Satellite telemetry has been applied to detect movements, migration routes, critical marine habitats and behaviour of sea turtles. In the Caribbean, different models of PTTs have been used to track sea turtles (James *et al.* 2005; Cuevas *et al.* 2008). The transmitters are usually attached with fibre-glass polyester resin or epoxy resins to the second dorsal vertebral scute (Cuevas *et al.* 2008; Pabon-Aldana *et al.* 2012), by using a custom-fitted harness made of nylon webbing and polyvinyl tubing (James *et al.* 2005), or by drilling holes to the leading edge of the carapace and inserting orthopedic mini-anchors (Casey *et al.* 2010).

Mark–recapture

Mark–recapture method uses a mathematical estimation of a particular population, based on the probability that a particular animal is captured when it has been previously captured, marked and released. The models of population-size estimation from mark–recapture data and their assumptions are presented in Bayliss (1987). The photo identification (a non-intrusive variation of the marking–recapture method) is nowadays the most popular procedure employed for individual recognition of cetaceans (Wiirsig and Jefferson 1990), taking advantage of the presence of skin marks such as spots, scars, notches and colour patterns than can be used to identify at an individual level. In the Caribbean, the mark–recapture method based on photo-identification of cetaceans has been used to estimate abundance of bottlenose dolphins (*Tursiops truncatus*), rough-toothed dolphins (*Steno bredanensis*) and sperm whales (*Physeter macrocephalus*; Table S1).

The mark–recapture method has been widely used to study elasmobranchs by both conventional tags and photo-identification. Conventional tags are defined as those that can be identified visually without the use of special detection equipment (Kohler and Turner 2001). There are several types of external tags, including M-dart-tag (MT), plastic-dart-tag (PT) and roto-tag (RT; Tavares 2010). Tagging has been conducted in the Caribbean to research whale sharks and lemon sharks (Table S2). The photo ID is increasingly being utilised to investigate population composition, abundance estimates, residency and movement, demography and social behaviours of elasmobranchs in the Caribbean (Marshall and Pierce 2012; Table S2). The relevant features to identify individuals are the spot pattern in a lateral view in whale sharks (Graham and Roberts 2007), the ventral spots and dorsal colour patterning in manta rays (Martínez Urrea 2016), and the spot pattern in pelvic fins in spotted eagle rays (Cerutti-Pereyra *et al.* 2018).

The capture–mark–recapture method is also commonly used to estimate the abundance, growth and habitat use of reptile populations in the Caribbean. Turtles can be tagged while they are nesting on the beach (Hernández *et al.* 2005), or by snorkelling in foraging grounds (León and Diez 1999; Diez and van Dam 2002). The individuals are usually tagged on the front flippers with PIT, plastic, Monel or Inconel tags with a numeric code (James *et al.* 2005; Chacón *et al.* 2007; Blumenthal *et al.* 2009; Table S3). Living tags can be used as a variant of artificial tags. In this procedure, a sliver of tissue from the turtle's plastron is implanted into one of the darker top scutes on the carapace; the scute selection depends on the release year (Fontaine *et al.* 1988). Photo-identification is used as an alternative mark–recapture method, and uses the scales on sea turtles head, which is the commonly photographed part of the body (Almaguer-Valdés *et al.* 2014). Among the several methods to mark crocodilians (Bayliss 1987), the most common ones used in the region are marking by clipping dorsal tail scutes in a coded pattern (Chabreck 1963) and/or attaching numbered metal tags to the interdigital webbing of individuals (Lander-García 2003; Sánchez Herrera *et al.* 2011).

Discussion

The biodiversity of the megafauna in the Caribbean is of great ecological, cultural and economic value. Our results suggest that, regarding marine megafauna monitoring, similarly to what occurs with many other taxonomic groups, there is a highly localised concentration of collecting effort and a lack of monitoring in many areas and ecosystems (Miloslavich *et al.* 2010), particularly in low-income nations such as Haiti or Honduras.

Species of marine megafauna are usually highly mobile (Wilson 2016), and an important number of them perform migration routes that visit several nations in the Caribbean (e.g. Nivière *et al.* 2018). Although the country-based monitoring is valuable, it is advisable to implement monitoring protocols on a regional scale. In consequence, the current challenge is to develop monitoring efforts across a wider range of species and ecosystems, because it could show collective, emergent patterns of movement and habitat use and allow identification of multi-species hotspots at a regional scale (Hays *et al.* 2016). The creation of marine protected areas (MPAs) as a tool for ecosystem-based management has been also relevant for marine-megafauna monitoring (Hooker and Gerber 2004*b*). However, less of 10% of the ocean is considered protected (Klein *et al.* 2015), and many of the MPA fail to meet thresholds for effective and equitable management processes, leading to suboptimal conservation outcomes (Gill *et al.* 2017).

Because megafauna species exhibit typically a long life span and slow population growth, a robust monitoring must be conceived within a long-term scale, to implement adequate conservation and management policies. However, quantifying those parameters represents a challenge, especially because marine and marine megafauna usually move through extensive areas. Additionally, to be valuable, monitoring methods must be sound, repeatable and inexpensive. Thus, accuracy is related with the effort made to cover the area adequately. It is also important to ensure that the monitoring methods can be replicable every year (or even every season for some species), and, thus,

Table 2. Methods for aquatic megafauna monitoring in the Caribbean

X indicates that the method can be employed in that group. BRUV, baited remote underwater video; PAM, passive acoustic monitoring; UAVs, unmanned aerial vehicles (drones); UVC, underwater visual census

Parameter	Advantage	Disadvantage	Sirenians	Cetaceans	Elasmobranchs	Sea turtles	Crocodiles
Review	Inexpensive	Relies on published data	X	X	X	X	X
Interviews	Inexpensive	Usually useful only as a first approach	X	X	X	X	X
Citizen science	Inexpensive. Facilitates community involvement and empowering	Requires careful interpretation of data and estimation of data reliability	X	X	X	X	X
Fisheries monitoring	Inexpensive if it is indirect Facilitates community involvement and empowering	Expensive if it is direct Requires an established fishery at the study area			X		
Aerial surveys	Ideal to collect abundance in large areas and/or low-density populations Does not affect animal behaviour Allows to collect additional information (e.g. coordinates, tracks)	Expensive, replication is limited Detection is affected by turbidity, glare and bottom type Requires an experienced pilot	X	X	X	X	X
UAVs	Useful to collect data for behaviour and photo-ID Allows to collect environmental data Allows to collect additional information (e.g. coordinates, tracks) Does not affect animal behaviour under following specific protocols of altitude and velocity for each species	Limited autonomy (flight time and distance), depending on battery duration Detection is affected by turbidity, glare and bottom type Able to collect data for density estimates only in highly dense areas or hotspots Experience required	X	X	X	X	X
Boat surveys	Ideal to collect abundance in large areas and/or low-density populations May affect animal behaviour	Affected by climate conditions Expensive	X	X	X	X	X
Manta tow	Easy to conduct without experience	Could affect the organism's distribution because of the engine noise Expensive			X	X	
Acoustic surveys, PAM	Uninvasive and inexpensive Useful to detect animals where visual survey protocols have limited effectiveness or when visual data are not available		X	X			
Land-based surveys	Ideal to conduct low-cost, long monitoring programs	Reduced area covered	X	X		X	X
UVC	Traditional survey with the possibilities to compare results Does not need to much training Low cost compared with aerial surveys Do not need any equipment	Could affect the organism's distribution due to the presence of the researchers Depends on the climate conditions			X	X	X
BRUV	Could be used in various stations at the same time Useful to photo identify organisms No negative impact on the subject animals Cost effectiveness	Limited monitoring time, depending on battery duration Abundance and distribution of the organisms could be influenced by the bait type Limited field of view			X		

(*Continued*)

Table 2. (Continued)

Parameter	Advantage	Disadvantage	Sirenians	Cetaceans	Elasmobranchs	Sea turtles	Crocodiles
Nesting grounds	Ideal to conduct demographic studies and foto ID on adult females Tissue samples can be obtained	No juvenile information is collected Requires long-term efforts and frequent patrolling				X	X
Photo-identification	Uninvasive, inexpensive	In the case of low-density species, requires high field effort Some marks (scars) may change along the life-time	X	X	X	X	
Mark–recapture	Ideal to conduct demographic studies and photo ID on juveniles (esto es cierto para tortugas, no se para los otros grupos) Distribution can be monitored	Experience required Adult individuals are difficult to capture Expensive	X	X	X	X	X
Catching and sacrifice	Ideal for demography monitoring	Used only in legally exploited population of certain species					X
Telemetry	High-definition data on animal movements in real time	Expensive Require middle to long-term follow-up	X	X	X	X	X

costly methodologies are probably not the wisest choice. Additional aspects that should be taken into account include ethics of animal welfare, reliability of the results and costs. Therefore, the choice of the most suitable protocol will depend on: (1) the biology and conservation status of the targeted species and/or group, (2) the objectives of the monitoring and, (3) the incurred costs (Table 2). Some species under fishing pressure, such as sharks and rays, might need a full stock assessment based on high-quality data, whereas others such as some fully protected marine mammals, may need only continuous census. Expensive and long-term studies usually mean better-quality and accurate data, but depending on the species-management challenges, some creative and pragmatic approaches are also valid to follow up the population. Thus, the recommended approach is to direct intensive research and monitoring to high-risk species (Noss 1990), whereas less intensive but broader monitoring can be directed to the whole community of megafauna species.

Methods involving the participation of local stakeholders, students and academic groups are urgently recommended for the aquatic megafauna in the Caribbean. Interviews are an inexpensive and non-invasive way to obtain first-hand information on the distribution, conservation status and mortality, particularly related to exploitation activity, of species. Interviewees may choose to hide certain information because they are afraid of punishment, or, alternatively, exaggerate or invent information to impress the interviewer (Franzini *et al.* 2013). However, the obtained information enables the collection of several important base-line data (Correa-Viana *et al.* 1990; Carr 1993), and can be a crucial starting point in developing monitoring programs. In the Caribbean, a region of growing concerns about human impacts on the environment, alongside financial constraints on research, citizen science must have an increasing importance. The involvement of the public in scientific megafauna research should be reconciled not only as a means of collecting scientific data cost-effectively, but as a means of collecting invaluable information in conservation biology, informing policy and conservation-management practices (Conrad and Hilchey 2011). Researching in fishing camps may also represent a simple and cheap way to collect basic information on the biology and conservation of megafauna species that are considered fishing targets (as some elasmobranchs), or that are by-catch of the fishing activity (as sea turtles).

Aerial surveys have been used as the primary method to monitor marine megafauna in areas where the landscape ecological features permit the necessary conditions for clear visibility (e.g. Martin *et al.* 2016). In the Caribbean, the technique was generally applied to count manatees, but the effort has been intermittent. Additionally, since these aerial surveys were designed to count manatees, the flights were restricted to coastal and shallow areas. Few efforts have been allocated in flying deep areas where cetaceans, sea turtles and pelagic elasmobranchs can be detected. We suggest implementing multi-specific aerial surveys designed to cover ecological variable areas (e.g. by depth and salinity) across the entire Caribbean to generate robust, long-term datasets for all aquatic megafauna groups. As a complement, we propose the implementation of protocols monitor marine megafauna using small-unmanned aerial vehicles (drones), which can be a more affordable method to collect similar information (Table 2).

Boat surveys are used regularly to observe and count marine megafauna, particularly air-breathing and/or pelagic species. It is important to continue monitoring several species by this technique (i.e. cetaceans, planktivorous elasmobranchs and crocodilians) for which there are already well standardised protocols of counting, photo-ID and abundance determination. We also suggest integrating bio-acoustic monitoring (for cetaceans) and manta-tow (for elasmobranchs and sea turtles) to boat-based surveys.

Finally, capturing, marking and tagging are protocols that provide highly reliable data on animal health, population sizes and movement patterns of the aquatic megafauna (Hays *et al.* 2016). Although these procedures are costly, particularly for large-bodied animals, they can be worth their implementation because of the quality of data that can be obtained.

Conflicts of interest

The authors declare no conflicts of interest.

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