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Artificial reefs in the Caribbean: A need for comprehensive monitoring and integration into marine management plans

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A B S T R A C T

Caribbean coral reefs are in decline and the deployment of artificial reefs, structures on the sea bottom that mimic one or more characteristics of a natural reef, is increasingly often considered to sustain ecosystem services. Independent of their specific purposes, it is essential that artificial reefs do not negatively affect the already stressed surrounding habitat. To evaluate the ecological effects of artificial reefs in the Caribbean, an analysis was performed on 212 artificial reefs that were deployed in the Greater Caribbean between 1960 and 2018, based on cases documented in grey (n = 158) and scientific (n = 54) literature. Depending on the availability of data, reef type and purpose were linked to ecological effects and fisheries management practices around the artificial reefs. The three most common purposes to deploy artificial reefs were to create new dive sites (41%), to perform research (22%) and to support ecosystem restoration (18%), mainly by stimulating diversity. Ship wrecks (44%), reef balls© (13%) and piles of concrete construction blocks (11%) were the most-often deployed artificial reef structures and metal and concrete were the most-used materials. The ecological development on artificial reefs in the Caribbean appeared to be severely understudied. Research and monitoring has mostly been done on small experimental reefs that had been specifically designed for science, whereas the most commonly deployed artificial reef types have hardly been evaluated. Studies that systematically compare the ecological functioning of different artificial reef types are virtually non-existent in the Caribbean and should be a research priority, including the efficacy of new designs and materials. Comparisons with natural reef ecosystems are scarce. Artificial reefs can harbor high fish densities and species richness, but both fish and benthos assemblages often remain distinct from natural ecosystems. Studies from other parts of the world show that artificial reefs can influence the surrounding ecosystem by introducing non-indigenous species and by leaking iron. As artificial reefs attract part of their marine organisms from surrounding habitats, intensive exploitation by fishers, without clear management, can adversely affect the fish stocks in the surrounding area and thus counteract any potential ecosystem benefits. This study shows that over 80% of artificial reefs in the Caribbean remain accessible to fishers and are a risk to the surrounding habitat. To ensure artificial reefs and their fisheries do not negatively affect the surrounding ecosystem, it is imperative to include artificial reefs, their fisheries and the surrounding ecosystem in monitoring programs and management plans and to create no-take zones around artificial reefs that are not monitored.

1. Introduction

Since the 1970s, the amount of living coral cover on Caribbean coral reefs has been greatly reduced due to coral mortality caused by diseases (Gladfelter 1982; Aronson and Precht 2001), water pollution, hurricanes and periods with higher than average seawater temperature (Hughes 1994; Gardner et al., 2003; Jackson et al., 2014). In addition, Caribbean coral reefs are severely overfished (Hughes et al., 1994; Vermeij et al., 2019). The combination of habitat degradation and overfishing has resulted in reduced fish stocks (Paddack et al., 2009), biodiversity and

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fisheries productivity (Rogers et al., 2014). As Caribbean coral reefs continue to degrade, they are less able to fulfill their important ecosystem functions (Graham et al., 2007; Newton et al., 2007). On a local level, artificial reefs might help to stem the losses as they can restore the lost three-dimensional habitat for fish (Baine 2001; Becker et al., 2018; Lima et al., 2019) and can provide hard substrate for epibenthic communities, including coral recruits and gardened coral fragments (Young et al., 2012).

Artificial reefs can be defined as submerged structures deliberately placed on the seabed to mimic some functions of a natural reef, such as protecting, regenerating, concentrating and/or enhancing populations of living marine resources (Baine 2001). Although the first records of artificial reef use are more than 3000 years old (Riggio et al., 2000), they became common use in 18th century Japan (Lee et al., 2018) and spread to the USA and Europe in the 19th century (McGurrin et al., 1989; Fabi et al., 2011). Although fish attraction was historically the main reason for artificial reef deployment (Polovina 1991), often to create new fishing grounds or to increase fishing efficiency (Lee et al., 2018), they were also used for other purposes such as trawling obstacles for fisheries management and for coastal protection (Lima et al., 2019). In the second half of the 20th century, observations of high fish densities on WWII wrecks resulted in an increase of artificial reef use in Japan and the USA (Lee et al., 2018) and increased fishing yields on these artificial reefs made the practice spread to the rest of the world (Lima et al., 2019). The Caribbean region was relatively late in adopting the use of artificial reefs. The first record we found was an artificial reef made of 800 concrete construction blocks, which was deployed in the US Virgin Islands in 1960 for research purposes (Randall 1963).

Nowadays, increased fishering yields are still a main reason for artificial reef deployment (Baine 2001; Fabi et al., 2011; Becker et al., 2018), but artificial reefs are also built for ecosystem restoration, habitat protection, as scuba diving object and for many other purposes (Lima et al., 2019). To cater to these different purposes, many different types of artificial reefs have been developed and deployed. Comparing artificial reef performances is complicated, because this depends on a variety of variables, such as size (Tupper and Hunte 1998; Abelson and Shlesinger 2002), material (Fitzhardinge and Bailey-Brock 1989), complexity (Charbonnel et al., 2002), age (Perkol-Finkel and Benayahu 2005), depth (Jaxion-Harm and Szedlmayer 2015), isolation (Shulman 1985), and the geographic region (David et al., 2019) and habitat type in which the reef is deployed (Yeager et al., 2011). Additionally, objectives and success criteria are highly dependent on the intended purpose of the artificial reef (Baine, 2001; Fabi et al., 2011). Independent of their purpose, it is crucial that artificial reefs do not harm the surrounding ecosystem. Uncolonized artificial structures can, for example, provide a stepping stone for non-indigenous benthic species to colonize the surrounding ecosystem (Glasby et al., 2007; Airoldi et al., 2015). Also, artificial reefs can attract marine life from neighboring habitats, which can subsequently be removed and ultimately even depleted by fishers (Bohnsack 1989). It is yet unknown to what extent fisheries on artificial reefs in the Caribbean are managed and to what extent artificial reefs are located within marine protected areas (MPAs).

Ideally, the knowledge and experiences acquired with artificial reef use should be carefully documented and widely shared to optimize further artificial reef deployment. Unfortunately, artificial reefs in the Caribbean have been poorly studied (Baine et al., 2001; Lima et al., 2019) and while reviews do exist on artificial reef deployments in Europe (Jensen 2002; Fabi et al., 2011), the USA (McGurrin et al., 1989) and Asia (Chou, 1997), there are no overviews available yet regarding artificial reefs in the Caribbean. As Caribbean coral reefs continue to decline, the deployment of artificial reefs will be considered more and more often. To support science-based decision making regarding artificial reef deployment, the need for a baseline overview of Caribbean artificial reefs and their effect on the surrounding ecosystem is evident. The objective of this study was to provide such an overview, based both on scientific and grey literature. We included information such as artificial reef type, location, deployment year, intended purpose, material, ecological development and fisheries management status.

2. Methods

In this study, we adopted the definition of artificial reefs proposed by Baine (2001): "structures placed on the seabed intentionally with the purpose to mimic one or more characteristics of a natural reef". Marine infrastructure such as oil platforms, piers, marinas, harbours and breakwaters were therefore excluded, as well as floating FADs (fish aggregation devices). Wrecks were included only if they were sunk specifically with the purpose of creating an artificial reef. We focussed on artificial reefs in the Caribbean Sea and included all islands and countries bordering this water body. Because of their similar environmental and geographical characteristics, the Bahamas and the Turks and Caicos islands were included but the Gulf of Mexico and Florida were excluded. Within the greater Caribbean, six distinct regions were distinguished: the Bahamas, Eastern Caribbean, Greater Antilles, Southern Caribbean, Southwestern Caribbean and Western Caribbean (Fig. 1).

We conducted an extensive internet search using Google Scholar and Google to find as many artificial reefs as possible, as described in respectively scientific (SL) or grey literature (GL). As search terms we combined the country or island name with "artificial reef", "man-made reef", "wreck", "fish aggregation", "lobster aggregation", "lobster casita", "coral restoration" and "reef ball". In a pilot study, a longer list of key words was used and combined with one randomly chosen country from each region. All key words that did not yield any extra cases during the pilot study, were not used for the main study. Islands belonging to a larger country were searched individually using the same search terms if they were larger than 300 km^2. The sources compiled were carefully screened to avoid double counting. For countries and islands where French, Spanish or Dutch was the first language, the search was repeated with translated search terms. All artificial reefs included in this study were deployed before 2019. This approach is not exhaustive and a number of artificial reefs have likely been missed. Even so, our results should be sufficient to indicate trends and by clearly specifying our search approach, the results should be replicable and robust.

In a few sources, multiple artificial reefs were described that were deployed at different locations (Haughton and Aiken 1989; Lalana et al., 2007; Wells et al., 2010; Delgadillo-Garzon and Garcia 2009; Tessier et al., 2015; Gittens et al., 2018). Risk (1981), Tupper and Hunte (1998) and Reguero et al. (2018) described more than one type of reef at the same location. For all of these cases, the different reefs were analysed as separate entities. However, if multiple small reefs of the same type were built in close proximity at the same location, the reefs were considered as one entity.

2.1. Analysis

The following characteristics were extracted from each separate source: geographic coordinates, material composition, type of reef, year of deployment (age), depth, purpose and number of units forming a single reef. In addition, we determined whether any ecological monitoring was performed and if so, used the results of these studies to link artificial reef type (e.g. ship wrecks or reef balls©) to their fish habitat function and the material used (e.g. concrete or metal) to benthic development. If the characteristics were not described in the first identified source, additional sources were used to identify as many characteristics as possible. As the focus of our study was to assess the effect of artificial reefs on the natural ecosystem, we did not include their socio-economic effects. In order to illustrate source, type of reef and purpose in time, the deployment year of the artificial reefs was used. This was known for 180 of the 212 cases. The other 32 cases were excluded from temporal analysis.

Location descriptions were used to determine the rough GPS position

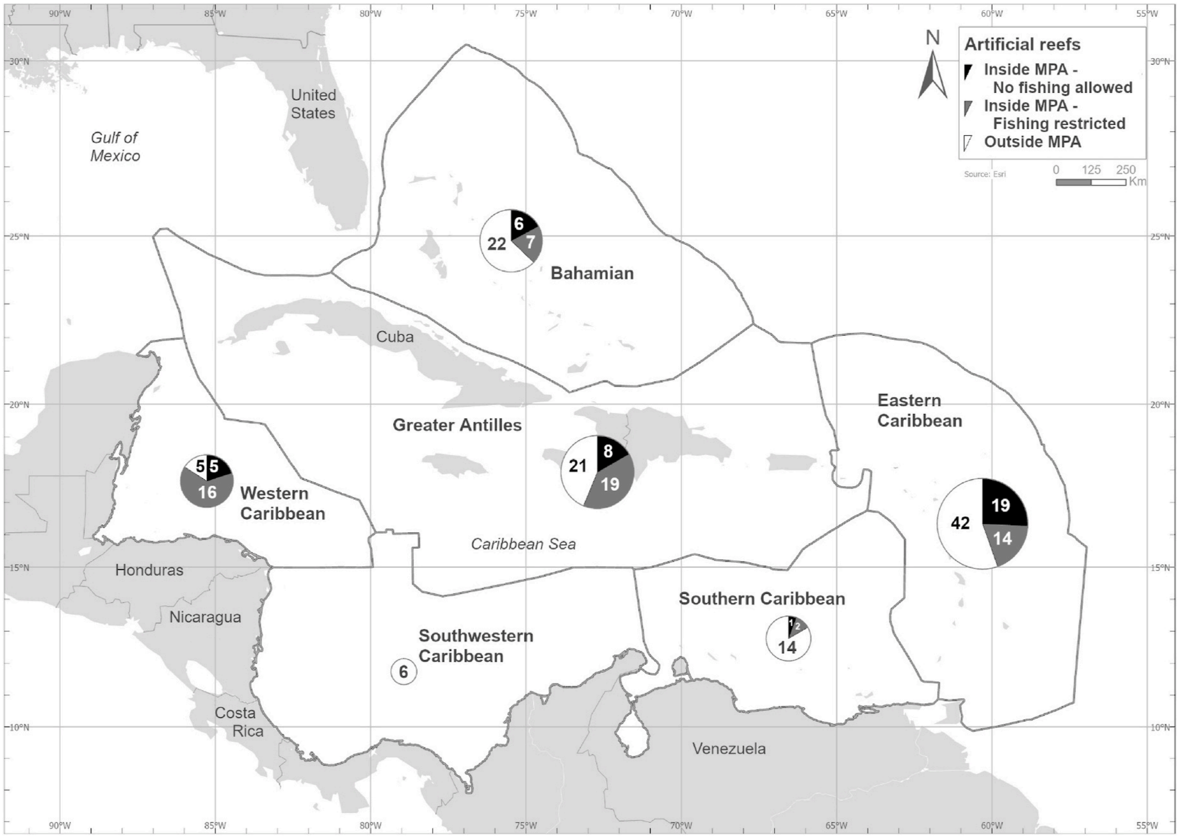

Fig. 1. The protection status of artificial reefs in the Caribbean per sub-region. The pie-chart size indicates the total number of reefs in the specific sub-region and the numbers within the pie-chart indicate the number of reefs per protection status.

of the artificial reef using Google Earth Pro (V. 7.February 3, 5776) in case the exact GPS position was not known. For nine cases it was not possible to determine a rough GPS position, these reefs were excluded from spatial analysis. Coordinates were loaded into Arcmap (V.10.6.1.) along with MPA shapefiles downloaded from The Atlas of marine protection (http://www.mpatlas.org/map/mpas/). The 'Intersect' tool in Arcmap created output containing only data overlapping each other and was used to determine which of the artificial reefs were located within an MPA. If an artificial reef was located in an MPA, we used publicly available information on the MPA to determine if any fishing regulations were in place. A distinction was made between no take zone (no fishing allowed) and restricted fishing. Our full database is available as an interactive map: https://bit.ly/3hkI1kB.

3. Results

3.1. Overview

In total, 212 artificial reef cases were identified, 54 from scientific literature (SL) and 158 from grey literature (GL). Most cases were found

Table 1
Type of described artificial reefs (n) per purpose and in total. The types are sorted based on their used material. * = not elsewhere identified.

Type	Main material(s)	Coastal protection	Create new dive site	Ecosystem restoration	Increase fishing yield	Research	Other purpose	Unknown	Total	% of total
Concrete construction blocks	Concrete	0	0	2	1	20	0	0	**23**	11%
Reef balls©	Concrete	9	5	8	0	3	2	1	**28**	13%
Concrete structures*	Concrete	2	2	5	0	1	1	0	**11**	5%
Ship wrecks	Metal	0	72	10	4	0	1	6	**93**	44%
Plane wrecks	Metal	0	6	1	0	0	3	0	**10**	5%
Motor vehicles	Metal	0	2	1	0	1	1	0	**5**	2%
Mineral accretion technique	Metal	0	0	6	0	3	0	0	**9**	4%
Metal structures*	Metal	0	0	3	0	2	0	0	**5**	2%
Tires	Rubber	0	0	0	5	0	0	0	**5**	2%
Lobster shelters	Wood, metal, concrete	0	0	0	0	10	0	0	**10**	5%
Piles of natural rock	Natural rocks	0	0	1	3	2	0	0	**6**	3%
Other	Coral rubble, conch shells	0	0	1	1	5	0	0	**7**	3%
Total		**11**	**87**	**38**	**14**	**47**	**8**	**7**	**212**	**100**
% of total:		5%	41%	18%	7%	22%	4%	3%	**100**	

using English search terms (SL: n = 51, GL: n = 155), followed by Spanish (SL: n = 3, GL: n = 2) and French (SL: n = 0, GL: n = 1). No extra cases were found using Dutch search terms. Most of the artificial reefs we identified (n = 76, 36%) were located in the Eastern Caribbean, followed by the Greater Antilles (n = 50, 24%), the Bahamas (n = 35, 17%), Western (n = 26, 12%), Southern (n = 18, 8%) and Southwestern (n = 7, 3%) Caribbean, respectively (Fig. 1). The most commonly described artificial reefs in the Caribbean were ship wrecks, reef balls© and piles of concrete construction blocks, in that order (Table 1). To a lesser extent, also concrete structures (other than reef balls© or construction blocks), plane wrecks and lobster shelters were described. Finally, mineral accretion technique (MAT) structures, other metal structures, piles of natural rocks, motor vehicles and tires were least often described. Metal and concrete were by far the most-used materials for artificial reefs in the Caribbean, due to the common deployment of ship wrecks, reef balls© and concrete construction blocks. Well-defined purposes had been formulated for 205 of the artificial reefs in our database. In declining order, the stated objectives for artificial reefs were found to be: the creation of a new dive site (n = 87, 41%), research (n = 47, 22%), ecosystem restoration (n = 38, 18%), increase fishing yield (n = 14, 7%), coastal protection (n = 11, 5%), creation of a movie set-up (n = 4, 2%), dumping (n = 2, 1%), mooring (n = 1, 0.5%) and an artificial reef deployment training (n = 1, 0.5%). The last four categories are summed under "other purpose" in Table 1. Ecosystem restoration was used as an overarching purpose, for example for restoring three dimensional structure, the fish abundance or biodiversity. Most sources were unclear what they actually wanted to restore.

For 180 of the 212 artificial reef cases, the deployment year could be determined. The first described deployment of an artificial reef in the Caribbean was in 1960 in the US Virgin Islands and consisted of a pile of concrete construction blocks (Randall 1963). Apart from this case, the 1960s had very little documented artificial reef deployment (Fig. 2). Artificial reef deployment in the Caribbean took off in the 1970s, with most cases described in scientific literature. Since the late 1980s, cases described in grey literature increasingly outnumbered cases described in scientific literature. Especially in the last two decades, hardly any new cases were published in scientific literature, while the number of cases described in grey literature continued to increase. The ecological development of only 50 of the 212 reef cases were monitored in some way, of which for 48 cases the results are publicly available, 45 of which in the scientific literature. This means that only limited new information on the ecological development of artificial reefs has recently become available.

3.2. Analysis per artificial reef type

Among the most frequently described artificial reefs in the Caribbean (n = 23, 11%) are "experimental reefs": small sized reefs (around 1 m^3), usually made from concrete construction blocks, which were mostly deployed in the Bahamas, Cuba and in the US Virgin Islands. As research was the most frequently reported (87%) purpose to deploy this type of artificial reef, it is not surprising that especially these reefs have been described in the scientific literature (83%). Most construction block reefs were deployed in the 1980s and in the 2010s (Fig. 3). The number of building blocks used to make one reef ranged from 3 to 800, but was mostly between 10 and 60, while up to 35 replicate reefs were built in some cases. Some of the studies performed with construction block reefs focused on a pre-selected biological mechanism, for example recruitment patterns of fish (Shulman et al., 1983) and lobster (Lalana et al., 2007) or the effect of habitat complexity and shelter opportunity on the fish assemblage (Beets and Hixon 1994; Gratwicke and Speight 2005). The first study focusing on the fish habitat function of piles of construction blocks simply described the fish density and species richness around this type of artificial reef (Risk 1981), while some follow-up studies also compared the fish assemblage with those of a nearby natural reef. The fish density and species richness at one to two year-old, shallow (2–5 m) artificial reefs was lower than the fish density on natural reefs (Carr and Hixon 1997; Zapata 2014), while species composition sometimes was similar (Alevizon et al., 1985; Carr and Hixon 1997) and sometimes different (Beets and Hixon 1994). Systematic comparisons between different types of construction block reefs revealed that reefs with more and smaller holes supported a higher fish abundance, while artificial reefs with a higher rugosity had a higher species richness (Gratwicke and Speight 2005). Studies including the effect of the seascape concluded that artificial reefs placed on dense seagrass beds harbored higher fish abundances than artificial reefs deployed on patchy seagrass beds or bare sand areas (Shulman 1985; Yeager et al., 2011). Piles of concrete construction blocks proved physically not stable over longer periods (Ogden and Ebersole 1981; Beets and Hixon 1994). Therefore, most of the concrete construction-block reefs described in these studies may currently not be functional anymore and this artificial reef type is basically unsuitable for large scale application.

Specially made reef balls© are the second common (n = 28, 13%) type of artificial reef in the Caribbean and have been deployed in every Caribbean sub-region, especially in the Dominican Republic and Sint Maarten. Reef balls© were almost exclusively deployed in the late 1990s and early 2000s (Fig. 3). Coastal protection was the most frequently

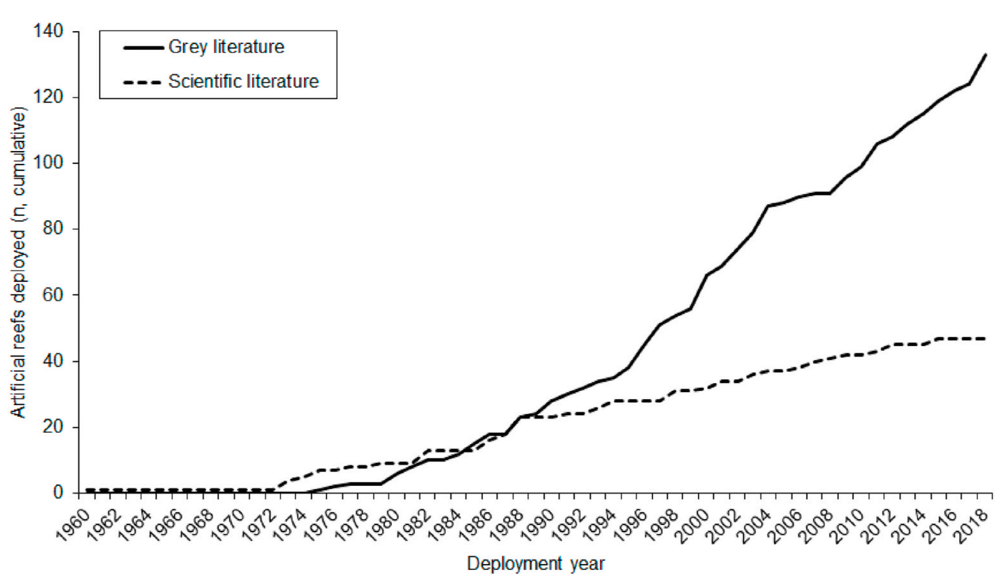

Fig. 2. Cumulative number of artificial reefs deployed per year described in grey and scientific literature.

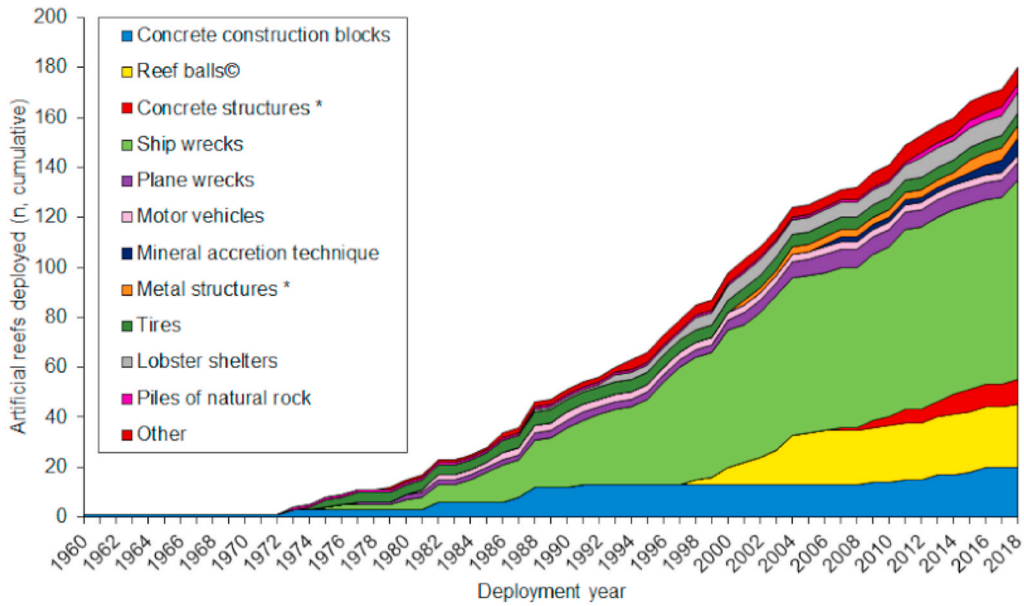

Fig. 3. Cumulative number of artificial reefs per type in time, described in grey and scientific literature. * = not elsewhere identified.

reported (32%) purpose for deploying reef balls©, although they were also often deployed for ecosystem restoration (29%) and sometimes to create a dive site (18%). Reef balls© were mostly deployed in shallow water, usually between 1 and 4 m deep and sometimes deeper (12–19 m) for research purposes. Often, many reef balls© were used to form one reef; the largest single reef in our database consisted of 3500 reef balls© and there were 12 other cases reported with more than 150 reef balls©. Reef ball© reefs were mostly (89%) documented in grey literature. Despite their common use, their ecological development has hardly ever been monitored, and if so, it only included survival and growth of coral transplants for a relatively short period of time (Ortiz-Prosper et al., 2001; Cummings et al., 2015). As coastal protection was the main reason to deploy reef balls© in the Caribbean, monitoring of fish abundance and coral cover may often not have been considered relevant. However, also the success of the coastal protection function was never monitored. A few (n = 11, 5%) dedicated concrete structures other than reef balls© were described for the Caribbean and all of these were deployed between 2007 and 2018. The most frequently reported (45%) purpose for deployment of these concrete structures was ecosystem restoration, followed by coastal protection and creation of a new dive site (both 18%). Only one of these concrete structures was monitored and this was the only case described in scientific instead of grey literature. In this study, 10 "Taino" structures, were deployed in a shallow (1 m) seagrass bed in Puerto Rico (Sander and Ruiz 2007). Fish density and species richness on the artificial reef was higher compared to natural reefs and seagrass beds in the same depth zone. Especially fish in the smallest size class (1–5 cm) were very abundant on the artificial reef, indicating that it was used as a nursery structure (Sander and Ruiz 2007).

Ship wrecks are by far the most commonly (n = 98, 44%) deployed type of artificial reef in the Caribbean, in all sub-regions with the exception of the southwestern Caribbean. The first ship was scuttled in 1974 and deploying this type of artificial reef remained popular during the entire period studied (Fig. 3). Creating a new dive site was the most frequently (77%) reported purpose for scuttling ships, although it was sometimes done for ecosystem restoration (11%) or even to create a movie set-up. Ships were, in line with their main purpose, deployed in relatively deep water, the average depth of all cases was 24 m. Despite being a popular choice for creating artificial ecosystems, only one wreck was monitored and described in the scientific literature. This wreck, deployed in Guadeloupe at 30 m depth, was monitored for two years after deployment. The wreck had a slightly lower fish biomass than average natural coral reefs (Bouchon et al., 2010), but direct comparisons with nearby natural reefs were lacking.

As with ship wrecks, plane wrecks (n = 10, 5%) were mostly (60%) deployed to create a new dive site. In addition, three planes (30%) were sunk to create a movie set-up. All plane wrecks were described in grey literature and, to our knowledge, no monitoring was performed on the ecological development on this type of artificial reef. While plane wrecks were always deployed individually, artificial reefs made of motor vehicles (n = 5, 2%) usually consisted of 100 or more cars, trucks and sometimes autobuses (Bortone et al., 1988; Friedlander and Beets 1992). Motor vehicle reefs were deployed for a number of purposes (Table 1) and the resulting fish assemblages described for two of them in scientific literature. In Barbados, large (100 m^2) artificial reefs made of 10 cars per reef had a comparable fish species composition to nearby natural reefs after two years (Tupper and Hunte 1998). In Guatamala, a high fish density but low species richness was reported for a motor vehicle reef deployed on a seagrass bed. However, constant fishing pressure might have affected its fish assemblage (Bortone et al., 1988).

Tailor-made metal structures can be used to make more complex artificial reefs and are lighter and thus easier to deploy than concrete structures (Lima et al., 2019). A few (n = 5, 2%) metal reef structures were reported in the Caribbean, all between 2000 and 2015 and all but one were deployed in Colombia. Three of them were meant for ecosystem restoration, and two for research and described in scientific literature (Delgadillo-Garzón and García 2009). For these two reefs, at 16 and 20 m depth, an increase of fish and benthic biodiversity was reported, although no comparisons with nearby natural reefs were performed. A special application of metal structures is the mineral accretion technique (MAT), formerly patented by Biorock™. MAT exposes metal structures *in situ* to a low voltage electrical current. A MAT system consists of a power supply connected to an anode. The anode is placed in the sea, close to the metal reef structure that serves as a cathode. The current causes electrolysis of the seawater and the accretion of calcium carbonate on the cathode (Hilbertz and Goreau 1996). Applying MAT is claimed to enhance coral recruitment, survival and growth (Goreau and Hilbertz 2005). Nine cases (4%) of MAT treated structures were reported for the Caribbean. The first MAT structures in the Caribbean were deployed around Jamaica in the 1980s, but ecological development of these structures stopped after the power was cut off after two years (Goreau and Hilbertz 2005). Between 2006 and 2018, eight other MAT cases were deployed in Jamaica, Curaçao, Grenada, St. Barths and on the

Turks and Caicos islands. Although all MAT structures were intended for ecosystem restoration (67%) or research (33%), with two cases being described in scientific literature, no results on ecological development are publicly available. These cases were described by Wells et al. (2010) who focused on the hurricane resistance of two MAT structures, deployed at around 5 m depth.

Tires were one of the first materials used to create artificial reefs in the Caribbean (Haughton and Aiken 1989; Friedlander and Beets 1992). Being so-called “materials of opportunity”, they were seen as an ideal combination of getting rid of waste items and enhancing fishing yields at the same time (Friedlander and Beets 1992). Most tire reefs in the Caribbean were deployed in the 1970s, although one reef was built in 1986 (Friedlander and Beets 1992). All tire reefs (n = 5, 2%) described for the Caribbean were deployed with the purpose of enhancing fishing yields and have been described in scientific literature. Of three of these reefs, ecological results were available. In the US Virgin Island 500 tires were deployed at 35 m depth. The tires did not form a single structure, but were scattered over the bottom. As a consequence fish densities remained low (Friedlander and Beets 1992). In Jamaica, two tire reefs were constructed with 1000 and 300 tires, which were bound into bundles. The reefs locally increased the fish abundance and species richness, but no comparisons were made with natural reefs (Haughton and Aiken 1989).

Lobster (*Panulirus argus*) shelters or “casitas” were initially introduced as fishing gear, but can also function as an artificial reef to create extra shelter for juvenile lobster (Polovino 1991; Sosa-Cordero et al., 1998; Gittens et al., 2018). Lobster shelters consist of a roof made from concrete or metal that rests on PVC or lumber, creating a low shelter with multiple openings. We found 10 cases (5%) of lobster shelter reefs in the Caribbean, deployed between 1993 and 2012. All but one of them (90%) were deployed for research and described in scientific literature. All cases were from the Bahamas, Cuba or Mexico, the countries in which lobster shelters are commonly used in fisheries (Polovino 1991; Ramos-Aguilar et al., 2003). Lobster shelter reefs were deployed in shallow (2–4 m) water and consisted out of 1–18 individual shelters. Monitoring was focused on the habitat function for juvenile lobster, of which lobster shelters were found to harbor high densities, especially if the surrounding habitat was suitable for foraging and limited in natural shelter opportunities (Eggleston et al., 1992; Sosa-Cordero et al., 1998; Briones-Fourzán and Lozano-Álvarez 2001; Lozano-Álvarez et al., 2009). Although lobster shelters can also provide a habitat for fish, this function was never investigated or described.

In only six cases (3%), artificial reefs were made of piles of natural rocks and all of these were deployed in the Eastern Caribbean and Greater Antilles. The most often reported purposes were to increase fishing yields (50%) and research (33%). Although five of the six cases have been described in scientific literature, very little information has become available about rock reefs. A deployment year was described for only three cases (1973, 2012, 2016) and a deployment depth (4 m) was only reported for two cases. Risk (1981) is the only study that included ecological observations. Although based on a single replicate, higher fish densities and species richness were found on a natural rock reef compared to a concrete building block reef, while a combination of the two materials yielded the highest fish abundance and species richness (Risk 1981).

Seven artificial reefs (3%) were pooled under the category "other". Five of these (77%) were deployed for the purpose of research and described in scientific literature. Forrester (1995) used piles of coral rubble to investigate fish recruitment. Rudolph (2012) described 350 ceramic “Ecoreef” modules deployed in Jamaica at 8 m depth. This artificial reef resulted in a substantial increase in fish density, which was mainly explained by large numbers of French grunts. Berrios and Timber (2005) described three small artificial reefs made from concrete culvert pipes, wood and metal, which were deployed at 6 m depth in Puerto Rico. The artificial reefs harbored a higher fish abundance and species richness compared to control plots on bare sand. Finally, Shulman (1985) and Beets (1989) described artificial reefs made from conch shells in the US virgin islands, which were deployed at 6 m depth. These conch shell reefs were used to study the effect of distance to the main reef on recruitment of fish to the artificial reef (Shulman 1985) and to study the effect of pelagic streamers on the fish density and species richness of the artificial reef (Beets 1989). Shulman (1985) found that fish densities were higher on artificial reefs close to a natural reefs, but attributed this to the reduced cover of seagrass around these artificial reefs. Beets (1989) showed that pelagic streamers on artificial reefs results in higher fish densities and species richness.

3.3. Fisheries management around artificial reefs

The GPS coordinates of 206 artificial reefs were determined and used to assess the fisheries management of the area of deployment. Of these cases, 110 (53%) were located outside MPAs, 58 (28%) were located in a restricted fishing zone of an MPA and only 38 (18%) were located within a no take zone of an MPA (Fig. 1). The sub-regions with the highest percentage of artificial reefs within a no take zone of an MPA were the Eastern Caribbean (25%), the Western Caribbean (20%) and the Bahamas and Greater Antilles (both 17%). The Southwestern and Southern Caribbean had zero and one artificial reef, respectively, within a no take zone of an MPA. In the Eastern Caribbean, Greater Antilles and Bahamas, most of the remaining artificial reefs (56%, 44% and 63% of the totals for that region, respectively) were located outside an MPA, while in the Western Caribbean most of the remaining artificial reefs (64% of the total for that region) were located in a restricted fishing zone of an MPA. In the Southern and Southwestern Caribbean, 88% and 100% of the artificial reefs were located outside an MPA.

4. Discussion

We here provide an overview and assessment of the purpose and deployment of artificial reefs in the Caribbean for the last five decades (1962–2018), whether their ecological development was monitored, and what the fisheries management was of the area they were deployed in. The main materials used for the artificial reefs in the Caribbean (metal: 58%; concrete 29%) contrast sharply with those used in the rest of the world. This can be especially ascribed to the much greater use of ship wrecks in the Caribbean (44%) compared to the rest of the world (8%, Lima et al., 2019). Worldwide, concrete (49%) was the most popular material, while metal (25%) came in second (Lima et al., 2019), which can be especially ascribed to the much greater use of ship wrecks in the Caribbean (44% of all artificial reefs) compared to the rest of the world (8% of all artificial reefs) (Lima et al., 2019). This difference may be explained by the fact that the current study included grey literature, in which many of the metal shipwrecks in the Caribbean were described, while Lima et al. (2019) did not include grey literature in their review of worldwide artificial reef deployment. The exclusion of grey literature might also partly explain the lower percentage of reef balls© worldwide (7% worldwide, 12% Caribbean) (Lima et al., 2019), because the reef ball© cases found in the current study were mostly described in grey literature. Concrete building blocks accounted, worldwide, for 10% of all artifial reefs (Lima et al., 2019), which is almost similar to our study. This further strengthens the hypothesis that the inclusion of grey literature results in a different relative contribution of types and materials, because concrete building blocks were almost exclusively described in scientific literature. The biggest difference that cannot be related to the inclusion of grey literature is the lower percentage of concrete structures other than reef balls© and building blocks, which was 31% worldwide (Lima et al., 2019) and only 5% in the Caribbean.

Worldwide, the number of scientific studies focusing on artificial reefs increased exponentially since the first publication in 1962 (Lee et al., 2018; Lima et al., 2019). Although artificial reef deployment in the Caribbean is becoming increasingly popular, the number of scientific publications on the subject per year is growing at a much lower rate.

Only 11 cases describe reefs currently deployed for purposes other than research and were ecologically monitored as well. Of these, only two included a comparison with natural reefs (Sander and Ruiz 2007; Rudolph 2012), which is essential to put the results in context (Carr and Hixon 1997) and only two compared multiple artificial reef designs (Risk 1981; Hylkema et al., 2020). Although Hylkema et al. (2020) was published outside the time range of our study, we use their conclusions in this discussion.

4.1. Fish assemblages on artificial reefs

Results of the few studies that monitored ecological development on artificial reefs in the Caribbean showed that artificial reefs locally increased fish densities and species richness compared to bare sand or seagrass within one to two years after deployment (Haughton and Aiken 1989; Berrios and Timber, 2005; Sander and Ruiz 2007; Rudolph 2012; Hylkema et al., 2020). Concrete artificial reefs (Sander and Ruiz 2007) and ceramic artificial reefs (Rudolph 2012) had a higher fish density and species richness than nearby natural reefs. This is in line with results from other parts of the world, which show that artificial reefs can indeed harbor high fish densities, biomass and species richness. Reef balls© in the Caribbean (Hylkema et al., 2020) and in estuarine bays in Australia (Mills et al., 2017; Folpp et al., 2020) had a higher fish abundance and species richness than the surrounding soft sediment habitat. Fish densities and biomass on wrecks were similar (Fowler and Booth 2012) or even higher (Arena et al., 2007) tto those on nearby natural reefs. Hylkema et al. (2020) and Abelson and Shlesinger (2002) reported high fish densities and fish species richness for artificial reefs made from natural rock piles in the Caribbean and Red Sea, respectively. The fish density and species richness on rock piles was higher than surrounding bare sediment and comparable to reef balls© (Hylkema et al., 2020), but comparisons with natural reef ecosystems were lacking (Abelson and Shlesinger 2002; Hylkema et al., 2020).

Small and experimental reefs made of concrete building blocks in the Caribbean harbored a species composition comparable to that of nearby natural reefs within two years after deployment (Alevizon et al., 1985; Carr and Hixon 1997). However, in another study, Beets and Hixon (1994) found a difference in fish species composition on the same type of reef compared to nearby natural reefs. In other parts of the world the fish species composition on reef balls© (Folpp et al., 2013; Mills et al., 2017; Komyakova et al., 2019), wrecks (Arena et al., 2007; Fowler and Booth, 2012; Simon et al., 2013) and natural rock reefs (Burt et al., 2013) also were found to be distinct from that of the nearby natural reefs. This can possibly be explained by differences in the structure of the surrounding natural reef or the moment of monitoring after deployment. For wrecks, the similarity to natural reefs increased with wreck age of up to 65 years old (Arena et al., 2007; Fowler and Booth, 2012; Simon et al., 2013). This ageing effect, however, is not the only prerequisite for similarity with a natural reef, as the fish species composition on a very (105 years) old metal ship wreck still was distinctly different from that of a nearby rock-based reef (Simon et al., 2013). It might be that the concrete building block reefs approach the natural reef more closely by providing a more complex and more elaborate shelter availability (Gratwicke and Speight 2005; Hylkema et al., 2020), which is absent in the usually courser built larger reefs. The difference in fish species composition between artificial and natural reefs is not necessarily problematic, but might be undesirable if the purpose of nature restoration is to come as close to the local reef community as possible, as most artificial reef communities differ in various ways from natural reef communities.

4.2. Benthic development on artificial reefs

Metal and concrete were the most frequently used materials for artificial reefs in the Caribbean, but none of these artificial reefs were monitored for benthic community development. Corals recruits can settle on metal (Fitzhardinge and Bailey-Brock 1989), so it is no surprise that corals colonize wrecks, both in the Caribbean (Vermeij 2005) and in the Indo-Pacific (Walker and Schlacher 2014). However, just as with fish assemblages, the coral communities on a three year old wreck (Walker and Schlacher 2014) and even on a more than 60 year-old wreck (Vermeij 2005) remained distinct from nearby natural reefs, as was the case with the sponge community (Pawlik et al., 2008). Although wrecks can last for a very long time (>100 year, Arena et al., 2007; Fowler and Booth 2012) the inevitable deterioration of metal surfaces results in rust and flaking, which ultimately inhibits recruitment and survival of sessile organisms (Fitzhardinge and Bailey-Brock 1989). Interestingly, multiple studies from the Indo-Pacific reported changes in the benthic community of the natural reefs surrounding a metal wreck (Work et al., 2008; Kelly et al., 2012; Carter et al., 2019; van der Schyff et al., 2020). This has been suggested to be the result of iron leakage from the degrading wreck (Work et al., 2008; Kelly et al., 2012). The elevated iron levels in algae surrounding the wrecks (Kelly et al., 2012; van der Schyff et al., 2020) suggest that wrecks can locally alleviate iron limitation occurring on many Indo-Pacific reefs. Higher iron availability can explain observed increases of cyanobacteria (Kelly et al., 2012), turf algae (Kelly et al., 2012), corallimorphs (Work et al., 2008; Kelly et al., 2012) and macroalgae (van der Schyff et al., 2020), all of which can decrease coral cover (Work et al., 2008; Kelly et al., 2012; van der Schyff et al., 2020). Metal wrecks may thus cause iron-induced phase shifts in adjacent natural reefs, turning them into so called “black reefs” (Kelly et al., 2012). Although Caribbean coral reefs are assumed to not be iron-limited in general (Roff and Mumby 2012), it cannot be excluded that increased iron concentrations around degrading iron wrecks may also affect adjacent natural coral reefs in the Caribbean. This has not yet been studied. Furthermore, Indo-Pacific wreck reefs seem to facilitate non-indigenous species. This may happen directly, as organisms attached to the ship hull are placed in a new and disturbed environment after scuttling, or indirectly, if the metal substrate or the leaking iron favors different species than those living in an iron-limited environment. Also, a newly available surface may facilitate settlement of opportunistic species.

Just like metal, concrete is a suitable substrate for coral recruitment (Fitzhardinge and Bailey-Brock 1989; Burt et al., 2009b; Al-Horani and Khalaf 2013). Multiple studies in temperate regions show that concrete marine infrastructure not only exhibits a different community composition than their surrounding natural reefs (Glasby et al., 2007; Bulleri and Chapman 2010; Airoldi et al., 2015), but also harbors a higher number of non-indigenous species (Glasby et al., 2007; Airoldi et al., 2015). This is often attributed to the high initial surface pH of concrete, which would favor alkali-resistant species over others during early succession (Dooley et al., 1999; Guilbeau et al., 2003; Dennis et al., 2018). However, a systematic comparison showed that pH is no main driver of benthic abundance, species richness or species composition (Hsiung et al., 2020), indicating that other factors affect community development on concrete structures. It is not studied to what extent the differences with natural communities could decrease as ecological development progresses, and opportunistic species disappear again during the course of succession.

High coral cover (Abelson and Shlesinger 2002) and coral recruit densities (Fox et al., 2005) were reported on natural rock piles in the Red Sea and Indonesia. Coral recruit densities on plates made from natural rocks (gabbro and granite) were higher than on most other materials, although experimental location appeared to have a greater effect than substrate (Burt et al., 2009b). Natural-rock breakwaters in the Arabian Gulf developed diverse benthic communities with high coral cover (Burt et al. 2009a, 2011; Grizzle et al., 2016), but the benthic communities were distinct from nearby natural reefs, although breakwaters of more than 25 years old resembled the natural ecosystem more closely than younger breakwaters (Burt et al., 2011).

4.3. Artificial reefs as environmental hazard

Although motor vehicle reefs can increase fish abundance (Bortone et al., 1988) and tire reefs can increase fish species richness (Haughton and Aiken 1989), these type of reefs are very unstable and are now considered an environmental hazard (Myatt et al., 1989; Lukens and Selberg 2004; Tessier et al., 2015). While tires can last for centuries, their ballast usually will not and once they become separated, they will start dispersing, potentially damaging coral reefs or littering the seabed habitat. In addition, tires have high heavy-metal concentrations, which can potentially end up in their epifouling organisms and in the food chain (Collins et al., 2002). In other parts of the world, tire reefs were even removed to prevent further damage to the benthic ecosystem (e.g. Morley et al., 2008), but we found no attempts to remove Caribbean tire reefs. Motor vehicles corrode within a couple of years and collapse before they are overgrown by organisms that can keep the structure upright (Lukens and Selberg 2004). Furthermore, they are mostly not cleaned before deployment and therefore can contaminate the local marine environment by leaching petroleum and heavy-metal toxicants (Aleksandrov et al., 2002; Collins et al., 2002; Lukens and Selberg 2004). Because of these drawbacks, no tire or motor vehicle reefs were deployed in the Caribbean anymore after 1986 (Tupper and Hunte 1998), in line with practices adopted in the rest of the world (Tessier et al., 2015).

4.4. Fisheries management of artificial reefs

Our study shows that 110 out of the 206 artificial reefs in the Caribbean are currently located outside MPAs and another 58 are located inside an MPA zone with fishing restrictions. Only 38 cases were located within an MPA zone prohibiting fishing. This means that over 80% of the artificial reefs described in this study are somehow fishable, and it is doubtful whether the fishing restrictions in the 38 other cases are truly enforced. In the Southern and Southwestern Caribbean, 100% of the artificial reefs were accessible for fishing, with most reefs being located outside an MPA. Fisheries on artificial reefs can affect both the ecology of the artificial reefs themselves and the ecology of the adjacent natural reefs. Fish presence on an artificial reef may result from local production at the artificial reef (the "Production Hypothesis") but also from attraction of fish from neighboring areas (the "Attraction Hypothesis"; Bohnsack 1989; Grossman et al., 1997; Pickering and Whitmarsh 1997). The relative contribution of these factors depends on artificial reef size, isolation and age, amongst others, and it is now generally assumed that attraction will co-occur with reef productivity (Grossman et al., 1997; Pickering and Whitmarsh 1997).

As part of the marine life around an artificial reef is attracted from the nearby ecosystem, intensive exploitation of the fish around artificial reefs can potentially lead to depletion of the fish stocks in the surrounding ecosystems (Bohnsack 1989; Brock 1994). Even if artificial reefs are deployed for fishing, possibly also to alleviate pressure from natural reefs, fisheries management and fish monitoring of both the artificial and natural reefs are crucial to prevent indirect overfishing of the surrounding habitat. Unfortunately, we did not find a single artificial reef in the Caribbean of which the surrounding habitat was monitored for this purpose. Also data about fishing pressure on artificial reefs in the Caribbean are, to our knowledge, not available and it seems unknown how many of the artificial reefs that are accessible to fishers are actually fished upon. However, given the reports that Caribbean coral reefs are severely overfished (Hughes et al., 1994; Vermeij et al., 2019), that habitat degradation further reduced fisheries productivity (Rogers et al. 2014, 2018) and that artificial reefs are known and deployed for their high fishing potential (Brock 1994) we hypothesize that most of the artificial reefs in the Caribbean are subject to fishing. The many artificial reefs in the Caribbean that are deployed for diving are well marked, and therefore these may well suffer from high, unregulated fishing pressure. This would also reduce the recreational value of the diving reefs.

Additionally, artificial reefs deployed with the purpose of increasing fishing yields seem to be underreported in the Caribbean. While increasing fishing yield is the most commonly stated objective of artificial reef programs worldwide (Baine 2001; Fabi et al., 2011; Becker et al., 2018; Lee et al., 2018), only 14 of the reported Caribbean artificial reefs were constructed to increase fishing yields. For example, of the lobster shelters or "casitas" that are commonly used by fishers from the Bahamas, Cuba and Mexico (Polovina 1991; Ramos-Aguilar et al., 2003) with sometimes over 120.000 shelters in a single bay (Polovina 1991), only 10 cases were described in grey and peer-reviewed literature, of which nine that were built for research. Fishers have little incentive to monitor, document or communicate their artificial reef use, unless they are obliged to do this by authorities or paid to aid research. Due to this underreporting of reefs deployed for fishing, the percentage of artificial reefs in the Caribbean accessible for fishing may actually be much higher than the 80% appearing from our study. The likelihood that artificial reefs are currently contributing to the regional general state of overfishing of reef resources is very high. To reduce this potentially very harmful effect of unregulated artificial reefs, more understanding and monitoring of the local reef productivity and the attraction effect are urgently needed. To enable sustainable fisheries, stricter protection and fisheries management around artificial reefs is needed, and monitoring and assessment of the indirect effect of fisheries on natural and artificial ecosystems is crucial. Given the current lack of monitoring and fisheries management, it can be concluded that fisheries on artificial reefs currently represent a serious risk to the ecology of artificial reefs as well as their adjacent natural reefs in the Caribbean.

5. Conclusions and recommendations for research and management

- Our review revealed that very few artificial reef deployments have been seriously studied and evaluated. Most of the published research of artificial reefs in the Caribbean concerned small experimental reefs, which creates a large discrepancy between the reefs studied and deployed at larger scales in practice. Comparative research is needed to better understand the mechanisms governing reef community development of multiple reef types.
- Due to the typically poor degree of documentation for artificial reefs, including the grey literature is essential to more accurately portray the actual deployment of artificial reef structures.
- Given its potentially adverse effect on the Caribbean coral reefs that already are severely under pressure, large scale deployment of artificial reefs should be considered with caution. Therefore the effects of leaking iron or the introduction of non-indigenous species, as is reported in the Indo-Pacific, should be an additional research priority for the Caribbean.
- Artificial reefs typically start out having biodiversity and fish densities that equal that of natural reefs within a time frame of a couple of years. The species composition of fish and benthos often differs from those of natural reefs, although this difference may decrease with time.
- Research into new structural designs and materials that may better be able to mimic natural habitat may support development of more natural assemblages within shorter time frames, which may be desired to improve restoration technology. Even small adaptations in structure or materials can result in increased fish densities and species richness (Sherman et al., 2002; Brotto et al., 2006; Hylkema et al., 2020), indicating the potential for improvement of the artificial reef design for dedicated purposes.
- Ship wrecks hardly provide lasting reef structures and may facilitate non-indigenous species and effects on surrounding benthic communities through iron leakage. During hurricanes they can move or collapse on the seafloor, causing additional damage to the communities surrounding them. Based on our review, the use of scuttled vessels for habitat restoration purposes should be discouraged.

- Given the paucity of research done on the large number of artificial reefs deployed by fishers without any form of documentation or registry, it is urgent to study positive or negative effects on marine habitats and marine flora and fauna. The use and deployment of artificial reefs by fishers need to be closely monitored and managed at a national level as an integral part of the fisheries management plan. Without adequate scientific studies, and in light of deficient or totally lacking fisheries management, the added value of artificial reefs in terms of habitat and ecosystem restoration remains merely hypothetical and the reefs may presently do more harm than good, even to the region's fisheries resources.
- Given their tendency to draw in fish from surrounding natural habitat which thus becomes more vulnerable to targeted overfishing, fishing activity on or around artificial reefs needs to be regulated and limited to prevent overfishing of the artificial reef itself as well as the surrounding ecosystem. Such management needs to be supported by fish monitoring studies and no-take zones should be created around artificial reefs that are not monitored.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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