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Marine artificial reefs, a meta-analysis of their design, objectives and effectiveness

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A B S T R A C T

Artificial Reefs (AR) show a wide diversity and vary in their construction materials, shape and purpose, as illustrated by the present analysis of 127 scientific papers. AR have been deployed for different purposes, including fisheries improvement, ecological restoration of marine habitats, coastal protection or purely scientific research. Statistical analyses using 67 variables allow us to characterize the design, objectives and monitoring strategies used for AR. An effectiveness indicator comprised of three categories (low, moderate and high) was adapted from previous studies and applied to the present dataset in terms of the objectives defined in each scientific paper. The effectiveness of various monitoring approaches was investigated and recommendations were formulated regarding environmental parameters and the assessment of ecological processes as a function of AR type. These analyses showed that inert materials like concrete associated with biomimetic designs increase the benefits of reefs to the local environment. This study also compared effectiveness between the different economic, ecological or scientific objectives of AR projects and reveals that fisheries projects showed the highest efficiencies but points out the weakness of environmental assessments for this type of project. In conclusion, the analyses presented here highlight the need to use a panel of complementary monitoring techniques, independently of the initial purpose of the artificial structures, to properly assess the impact of such structures on the local environment. It is recommended to adopt approaches that associate structural and functional ecology. An improved characterization of the role of AR should be integrated into future assessments, taking into account the complex framework of ecosystem structure and trophic relationships.

Abbreviations: AHC, Ascending hierarchical classification; AR, Artificial reefs; ARMS, Autonomous Reef Monitoring Structures®; Eco, Ecological; MA, Material; Obj, Objectives; MCA, Multiple correspondence analysis; TC, Techniques

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1. Introduction

Artificial reefs (AR) are man-made structures emplaced in aquatic environments that serve as habitats or shelters for organisms. AR have long been used to attract fish and the development of these structures has been intensified over the three last decades (Baine, 2001; Lowry et al., 2014; Santos et al., 2011). In the present study, we consider an artificial reef as a structure intentionally placed on the seabed aiming to mimicking natural reef functions that are able to protect, regenerate, concentrate and enhance populations of marine organisms (Guillen et al., 1994; Hunter and Sayer, 2009; Walles et al., 2016). This includes the protection (Silva et al., 2016) and regeneration of habitats (FAO, 2015) or the fisheries enhancement (Hackradt et al., 2011). However, AR with a defined objective such as ecosystem protection may have both positive and negative impacts on the local environment (Brickhill et al., 2005; Firth et al., 2016). This term excludes artificial islands, cables, pipelines, platforms, mooring and structures for coastal defence (e.g. breakwaters and dykes) which were primarily constructed for other purposes, as well as devices developed for fish aggregation that were used simply to attract fish in certain fishing areas, and wrecks that are accidentally present on the sea bed (FAO, 2015).

Despite the number and the diversity of projects and objectives of AR, their overall effectiveness have rarely been fully demonstrated. The assessment of AR performance is complex because of the multivariable factors and co-variation among descriptors to be taken into consideration. There is a tendency for research to obscure the main objectives of AR placement and many examples can be cited where self-assessment appears to be lacking in terms of evaluating performance (Baine, 2001). Monitoring is often limited to only a few species and/or the immediate environment with no complementary techniques using approaches such as process or structural ecology (Baine, 2001). Moreover, monitoring periods are highly variable, ranging from days to years. Research on AR involving studies of ecosystem functioning need to respond to the increased development of more sophisticated and complex techniques based on isotopes, organic indicators or molecular biology (Lima et al., 2019a). Ecological studies can be divided into two categories: structural ecology describes the ecosystem (species diversity, distribution, etc.) and functional ecology refers to the flow of energy and cycling of materials through structural components of the ecosystem (productivity, production, trophic web, carbon fixation, etc.) (Gómez et al., 2004; Villéger et al., 2008). There is also a great interest in investigating the coupling between function and diversity in the case of submerged AR.

These structures are usually expected to produce an overall increase in species richness by protecting some species, and also an increase and diversification of trophic contributions (Bodilis et al., 2011; Hixon and Beets, 1989; Piazza et al., 2005). The improvement in habitat is generally reflected in greater food availability and more shelter against predators, as well as new recruitment areas for juveniles of various species (benthic invertebrates or fish), which explains the increase in organism biomass associated with these structures after their installation (Perkol-Finkel et al., 2018; Sherman, 2002). The numerous reviews in the literature dealing with AR mainly concern management (Becker et al., 2018; Claudet and Pelletier, 2004; Lima et al., 2019a), recommendations and priorities (Bohnsack and Sutherland, 1985; Lima et al., 2019a), but also deal with social aspects (Carral et al., 2018; Lima et al., 2019a) as well as overall assessment with performance evaluation (Baine, 2001; Lee et al., 2018; Lima et al., 2019a).

In the present paper, a statistical approach is adopted combining the results of multiple scientific studies in order to improve the AR performance evaluation. This meta-analysis investigated the effectiveness of 162 AR by using several parameters including the shape and composition of materials used for their construction, the monitoring techniques, and the original purpose of the artificial reef in question. We define effectiveness as the performance of the structure in relation to the purpose of its emplacement or research objectives. Our analysis is based on a simplify Reef Performance Scale proposed by Baine (2001). This approach does not yield an absolute qualitative assessment but is based rather on the information and data provided by selected papers and reflects the interpretations of various different authors. The main objectives of this study are to bring impartial information on AR effectiveness according to their design, monitoring and purposes. Considering the large variety of AR studies, the lack of recent literature review and the necessity of an updated meta-analysis, the present study provides recommendations to improve the AR success rate by enhancing their performance assessment using appropriate monitoring techniques consistent with the initial purpose of the structure.

2. Methodology

This non-exhaustive analysis examines 126 papers dated from 1973 to 2019 covering 162 AR sites (Appendix B). When several AR sites are discussed in a given paper, each site is considered independently in our analysis. The bibliographic corpus was selected from 5771 publications listed in Web of Science from January to September 2019 using the following keywords: artificial reef and marine infrastructure. Relevant papers were selected based on three criteria: (1) scientific monitoring of the AR had to be included; (2) the AR had to have been intentionally deployed and (3) the structure had to be submerged in a marine or estuarine mesohaline environment, with a specified objective.

Each of the 126 papers was thoroughly analyzed to identify the specific AR design, local environment, location and monitoring techniques employed for the assessment as well as the initial objectives of the AR. This led to the establishment of 67 variables belonging to 12 categories, which were then separated into four groups: (1) environmental categories, (2) AR type, (3) monitoring categories and (4) AR effectiveness. Each of the 12 categories were independent and groups 1, 2 and 3 were strictly representative of the bibliographic corpus information. Some of these variables correspond to several sub-variables that can be grouped together into categories (Appendix C). Tables 1–3 present the 12 categories along with the 67 associated variables. Environmental categories correspond to the variables: geographic location, seabed type, salinity and AR depth of

Table 1
Environmental variables (four categories) with their code used in the statistical analyses.

Environmental categories							
Geographic location		Seabed substrate		Salinity		AR immerging depth	
Tropical	Climate_Tropical	Sandy	Seabed_Sandy	>30	Salinity_Inf30	Intertidal	Depth_Inter
Temperate	Climate_Temperate	Hard	Seabed_Hard	<30	Salinity_Sup30	0.1–10 m	Depth_10
Subarctic	Climate_Subartic	Muddy	Seabed_Muddy			11–20 m	Depth_20
		Corals	Seabed_Corals			21–50 m	Depth_50
		Seagrass	Seabed_Seagrass			>to 51 m	Depth_51
		Artificial	Seabed_Artificial				

Table 2
Artificial reef variables (four categories) with their code used in the statistical analyses.

Artificial reef variables							
AR facility volume		AR shape		AR material		AR purpose	
0–100 m^3	Volume_100	ARMS	AR_ARMS	ECOncrete®	MA_ECO	Fisheries enhancement	Obj_Fisheries
101–1000 m^3	Volume_1000	Bags	AR_bags	Shells	MA_Shells	Biocenosis protection	Obj_BiocenosisP
>to 1001 m^3	Volume_1001	Blocs	AR_blocs	Wood	MA_Wood	Biocenosis restoration	Obj_BiocenosisR
		Cages	AR_Cages	Plastics	MA_Plastics	Experimental	Obj_Experimental
		Cubics	AR_Cubics	Rocks	MA_Rocks		
		Pyramidal	AR_Pyram	Tires	MA_Tires		
		Vertical	AR_Vert	Asbestos	MA_abest		
		Multipods	AR_Multi	Ceramic	MA_Ceramic		
		Tires	AR_tires	Concrete	MA_Concrete		
		ReefBalls®	AR_ReefB	Metal	MA_Metal		
		Vehicle	AR_Vehi	Fiberglass	MA_Fiberglass		
		Plates	AR_Plates				
		Cylindrical	AR_Cyl				
		Other	AR_Other				

immersion (Table 1). AR categories correspond to AR facility volume, AR shape, AR material and AR purpose (Table 2). The AR purpose category is divided into four variables. Fisheries enhancement corresponds to the sole purpose of improving fishing. Biocenosis protection corresponds to the immersion of an AR to physically protect an existing ecosystem against a threat. Biocenosis restoration corresponds to the immersion of an AR to rebuild an ecosystem by creating a new habitat. Finally, experimental purpose corresponds to the immersion of the AR as part of a scientific experiment and biocenosis restoration means reconstructing an ecosystem, i.e., a habitat, to promote its colonization by the living organisms associated with the original habitat. In the case of an AR fitted more than the variable (e.g. concrete and metal), it is considered in all of the relevant variables.

The third group (Table 3) corresponds to AR monitoring variables including monitoring techniques, ecological monitoring and immersion time. The ecological monitoring category provides information about the ecological nature of the monitoring techniques used. Ecological monitoring may be structural or functional. It also includes biodiversity measurements and ecological process. Structural ecology mostly involves descriptive techniques; functional ecology refers to relations, dealing with the fluxes between different trophic compartments. Ecological process corresponds to production measurements, including trophic and non-trophic interactions.

Submersion time corresponds to the duration of immersion of the AR according to the monitoring period. “Short Time” corresponds to periods between a day and a month, “Intermediate Time” to periods of between a month and a year and “Long Time” to periods longer than a year.

AR effectiveness is evaluated according to the interpretations of each paper with respect to the stated objectives. This evaluation is based on the Reef Performance Scale drawn up by Baine (2001). The Reef Performance Scale is an indicator of reef performance in relation to its given purpose. Our intention is not to provide an absolute assessment of AR effectiveness but rather to reflect the author’s interpretation. Baine’s scale is composed of seven levels from −3 to +3, with negative levels corresponding to AR which fail in their objectives and which have a negative impact on the surrounding environment (−3), which yield no useful data (−2) or which produce questionable results (−1). Level 0 corresponds to AR with inconclusive performance showing negative and positive effects. Finally, positive levels correspond to AR which succeed in their objectives. Level +1 is attributed to AR with a limited success and which provide limited useful data; these AR require some changes and management to improve their effectiveness. Level +2 corresponds to AR that succeed partly in meeting their objectives and which require some minor changes of design or management. Level +3 corresponds to ARs that fully succeed in their objectives and which require no change. These AR provide useful data for the assessment of reef performance and management. Out of the 30 case studies exploited by Baine (2001), 29 yield an effectiveness distributed between 0 and +3.

Table 3
Monitoring variables (three categories) and artificial reef effectiveness variables, with codes used in the statistical analyses.

Monitoring variables						AR effectiveness variables	
Monitoring techniques		Ecological monitoring		Immerging time length		AR effectiveness	
Scrapings	TC_Scrap	Functional	Eco_Functional	Short (<1 months)	Time_Initial	Low	Eff_Weak
Spectrophotometry	TC_Spectro	Structural	Eco_Structural	Intermediate (<1 year)	Time_Intermediate	Moderate	Eff_Partial
CPCe software	TC_CPCE	Biodiversity measurements	Eco_Biodiv	Long (>1 year)	Time_Stable	High	Eff_Strong
Microscope observations	TC_Micro	Ecological process	Eco_Process				
Visual observations	TC_Visual						
SCUBA diving	TC_SCUBA						
Environmental parameters	TC_Env						
Pelagic measurements	TC_Fish						
Pictures	TC_Pic						

Our AR effectiveness evaluation is composed of three levels: low, moderate and high (Table 3). Low effectiveness corresponds to AR with extremely limited success or none. This level corresponds to level 0 on the Reef Performance Scale (Baine, 2001). These AR might have some negative impacts and require some management and design changes. Moderate effectiveness corresponds to AR with a limited success in their objectives, but which might have some other positive effects. This level corresponds to +1 on the Reef Performance Scale (Baine, 2001). These AR require some management and changes to increase their success. High effectiveness corresponds to AR that have succeeded in their objectives for a major part. This level corresponds to +2 and +3 on the Reef Performance Scale (Baine, 2001). These AR confer benefits on the surrounding environment and require little or no modifications to improve their effectiveness.

Statistical analyses were performed with R i386 3.5.1 (R Development Core Team, 2008), with FactoMineR (Lê et al., 2008) and ggplot2 (Wickham, 2009). The data frame is made up of a binary presence or absence (1 or 0) matrix with observations in rows and the sum of variables in columns. The matrix is presented in Appendix B. Ascending hierarchical classification (AHC) was performed on the total data base. The optimal number of clusters was calculated using the Gap statistical method. AHC provides information on the similarities and dissimilarities of selected papers. This technique is widely used in ecological sciences and data analysis (Azzag et al., 2006; Cullis et al., 2018; Dolan and Parker, 2005). Associated dendrograms are available in the Supplementary material. Correlation coefficients are calculated using Pearson's method to identify those variables which are correlated together. A correlation is considered significant when $P < 0.05$. These correlation coefficients are calculated between all variables from the total data set. Data analysis with coefficient correlations is commonly applied in the biological and ecological sciences (Obayashi and Kinoshita, 2009; Rupp et al., 2012). A graphic representation and the full set of results (R coefficients and p-values) is available in the Supplementary material.

3. Results

The selected AR show a worldwide distribution: 69 in Europe, 37 in Asia, 26 in North America, 10 in Central America, 5 in South America, 3 in Africa, 11 in Australia and 2 in the Pacific Ocean. However, this selection is not representative of the actual distribution of AR across the world.

3.1. *Graphic representation of global data and dominant variables*

Fig. 1 provides information on the main variables. The main shapes are cubic, cylindrical, plate, pyramidal and cage. The main construction material used is concrete. The main purposes of AR submersion are biocenosis restoration, fisheries enhancement and purely experimental (Fig. 1A). The main geographic locations are temperate and tropical. The selected depths for artificial structures are between 0.1 and 50 m. The main seabed substrate is sandy followed by muddy and hard bottoms (Fig. 1B). The main tools for monitoring are biodiversity assessment, SCUBA diving and visual observations with ecological structural monitoring (Fig. 1C).

3.2. *Multiple correspondence analysis (MCA) representations with clusters*

MCA (Fig. 2) was performed to identify those variables that could be used to distinguish the selected AR. The MCA represents all relevant variables that contribute more than 1% to the two first dimensions. Clusters groups (A to E) are represented as follows: group A is composed of 22 AR sites, B of 33, C of 11, D of 36 and E of 60. The two first dimensions explain 21.8% of the scatter plot. Dimensions 3 and 4 explain 7.7% and 7.3% of the data (Eigen values are available in Supplementary data). The weak cumulative variance of the two first MCA axes associated with the number of clusters reflects the disparity of the data due to the

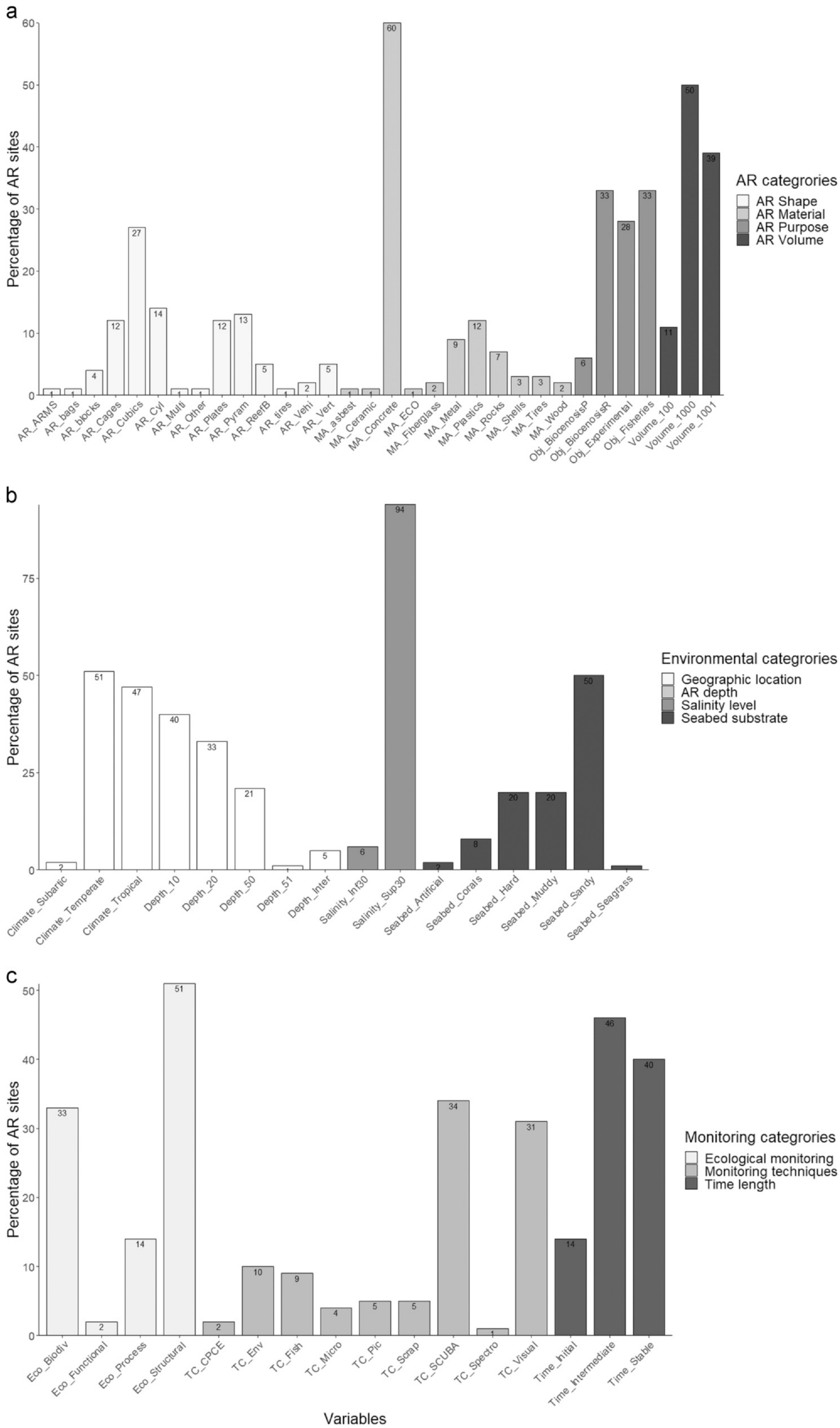

Fig. 1. Graphic representation of the percentage of artificial reef sites in terms of three categories of variables: AR type and purpose (1), environmental variables (2) and monitoring methods (3).

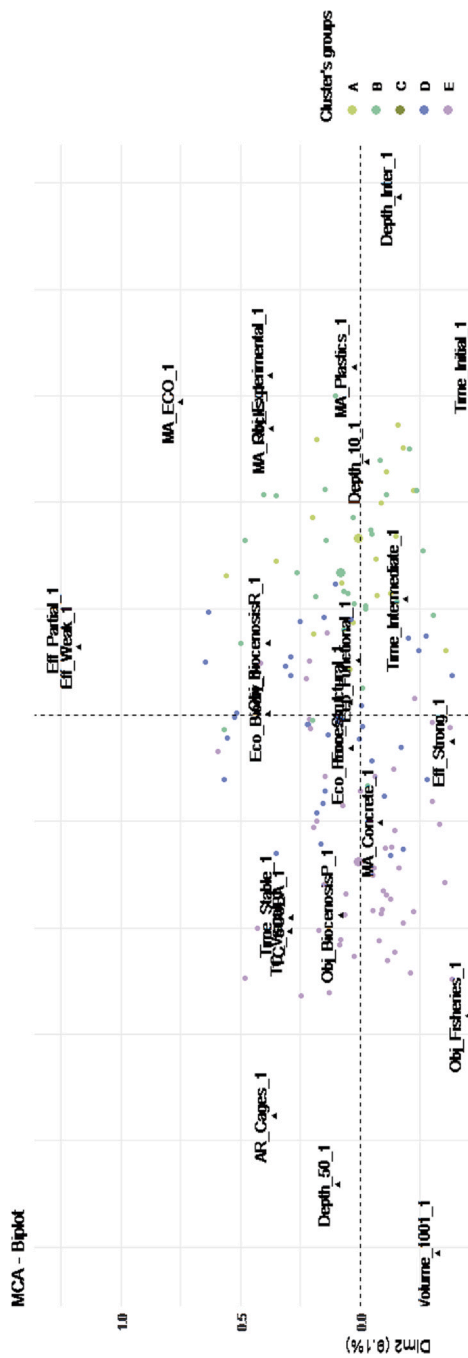

Fig. 2. Multiple correspondence analysis (MCA) of all the data with all the measured variables that contribute more than 1% to the two first dimensions. Clusters are represented (A to E) in different colors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

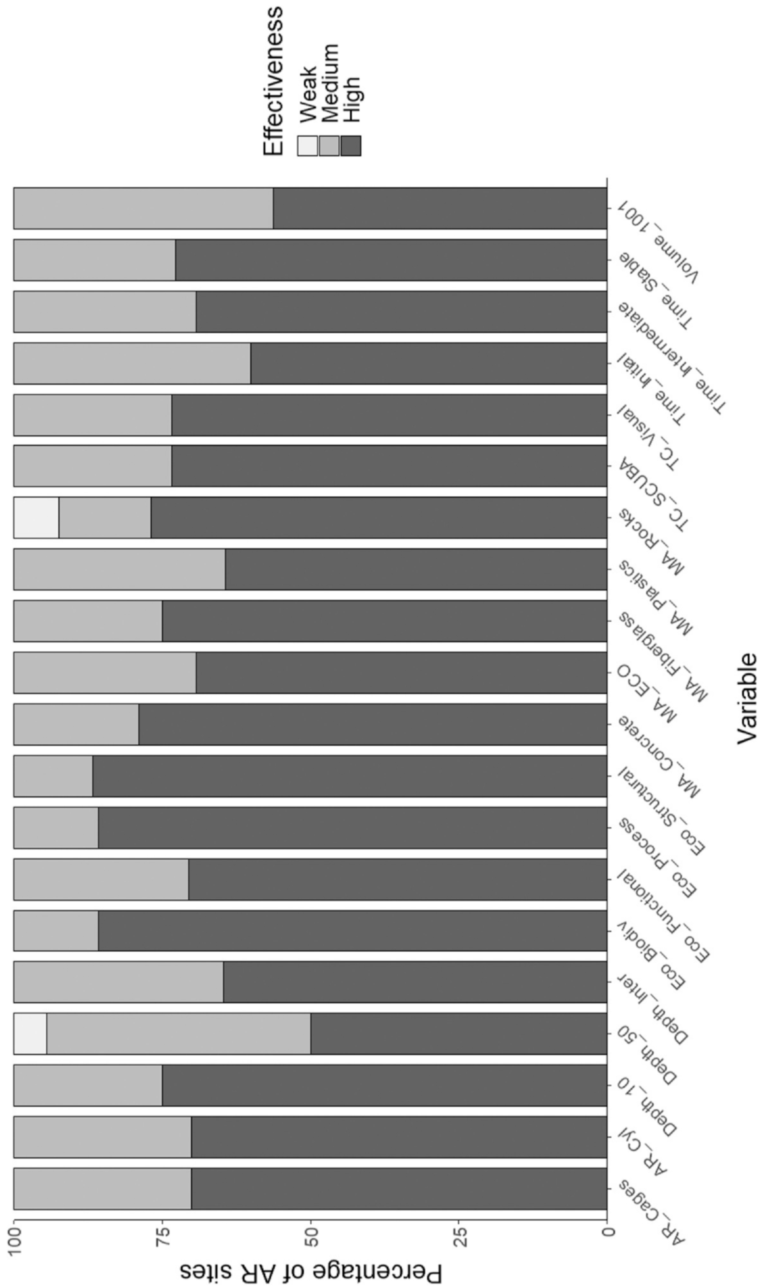

Fig. 3. Graphic representation of the percentage of AR sites in term of three effectiveness categories (weak, partial and strong) for each relevant variable (n = 20) selected for the MCA representation.

diversity of AR projects worldwide with different purposes, in different ecosystems, using various shapes, materials and monitoring methods (Fig. 3).

Clusters A and B seem close and mostly comprise of elements such as experimental purpose; structural and functional ecology analysis; plastics, rocks, and ECOncrete® materials; depth of submersion between 0 and 20 m; short and medium immersion periods. The group C dendrogram is composed of 11 AR studied by Kasim et al. (2013) in the tropical Indian Ocean. Cluster C describes the same variables as cluster D, situated between the dominant variable strong AR effectiveness and fisheries enhancement. Finally, cluster E is characterized by fisheries enhancement and biocenosis protection purposes, long immersion period, AR facility volume volumes higher than 1000 m^3, cages shape, concrete construction material, visual census, SCUBA diving and pelagic measurement monitoring techniques.

3.3. Effectiveness analysis of relevant variables

The proportion of AR sites in term of effectiveness categories (weak, partial and strong) was calculated for the relevant variables selected for the previous MCA analysis. Cages and cylindrical shapes were the most effective's ones (70% in strong effectiveness). Depth of submersion between 0 and 10 m (75% in strong effectiveness) or intertidal (64.7% in strong effectiveness) were the most efficient ones. Concrete was the most effective material (79% in strong effectiveness), in comparison, plastics and rocks material seemed less efficient with respectively 35.7% in medium effectiveness and 7.7% in weak effectiveness. Long immersion period was the most effective (72.7% in strong effectiveness) in comparison with short one (60% in strong effectiveness).

3.4. Evaluation of artificial reef purposes

Fig. 4 shows the percentage of assessed effectiveness for each AR purpose. For each of the four different AR purpose, the main assessed effectiveness was high (always more than 73% of the AR sites). Moderate effectiveness represented between 14.9% for fisheries enhancement AR and 23.4% for experimental AR. Low effectiveness represented between 1.4% for fisheries enhancement AR and 7.7% for biocenosis protection AR.

3.5. Variable correlations according to the purpose

3.5.1. Fisheries enhancement purpose

The objective of improving fisheries is correlated with a high level of efficiency (R = 0.25, $P = 0.038$) as well as visual census (R = 0.36, $P = 0.002$), SCUBA diving (R = 0.34, $P = 0.005$) and pelagic measurements (R = 0.42, $P < 0.001$). This objective is also correlated with depths of submersion between 10 and 20 m (R = 0.33, $P = 0.006$) and 21–50 m (R = 0.59, $P < 0.001$), sandy substratum seabed (R = 0.32, $P = 0.007$), salinity > 30 (R = 0.26, $P = 0.033$) and a temperate climate (R = 0.29, $P = 0.018$). Fisheries enhancement purpose is also correlated with several AR variables, such as cages (R = 0.49, $P < 0.001$), cylindrical shapes (R = 0.46, $P < 0.001$), pyramid shapes (R = 0.57, $P < 0.001$), cubic shapes (R = 0.74, $P < 0.001$) but also the concrete construction material (R = 0.58, $P < 0.001$).

3.5.2. Experimental purpose

The experimental purpose is correlated with microscopic analysis (R = 0.57, $P < 0.001$), CPCE software (R = 0.49, $P < 0.001$) and biodiversity analysis (R = 0.44, $P < 0.001$). This objective is also correlated with a structural ecology approach (R = 0.27, $P = 0.024$), submersion depths from 0 to 10 m in the intertidal zone (R = 0.51, $P < 0.001$ and R = 0.41, $P < 0.001$), artificial seabed (R = 0.35, $P = 0.004$) and short or medium immersion periods (R = 0.49, $P < 0.001$ and R = 0.32, $P = 0.008$). Experimental purpose is correlated with the following AR construction materials: plastic (R = 0.41, $P < 0.001$), ceramic (R = 0.28, $P < 0.022$), shells (R = 0.27, $P = 0.031$) and rocks (R = 0.44, $P < 0.001$); and with shapes made of bags (R = 0.24, $P = 0.048$), plates (R = 0.76, $P < 0.001$), and ARMS® (R = 0.43, $P < 0.001$). It is also correlated with the biocenosis restoration purpose (R = 0.25, $P = 0.029$).

3.5.3. Biocenosis protection purpose

The biocenosis protection purpose is correlated with a long immersion period (R = 0.34, $P = 0.005$), sandy and seagrass seabed substrates (R = 0.33, $P = 0.05$ and R = 0.44, $P < 0.001$) and submersion depths between 11 and 20 m (R = 0.25, $P = 0.041$). This purpose is correlated with AR volume > 1001 m^3 (R = 0.29, $P = 0.020$) and with ECOncrete® construction material (R = 0.29, $P = 0.023$). Finally, biocenosis protection is correlated with visual observations (R = 0.35, $P = 0.004$) and SCUBA diving (R = 0.29, $P = 0.017$).

3.5.4. Biocenosis restoration purpose

The biocenosis restoration purpose is correlated with lower efficiency (R = 0.23, $P = 0.06$) and salinity < 30 (R = 0.28, $P = 0.027$). It is correlated with biodiversity measurements (R = 0.24, $P = 0.041$). The biocenosis restoration purpose is correlated

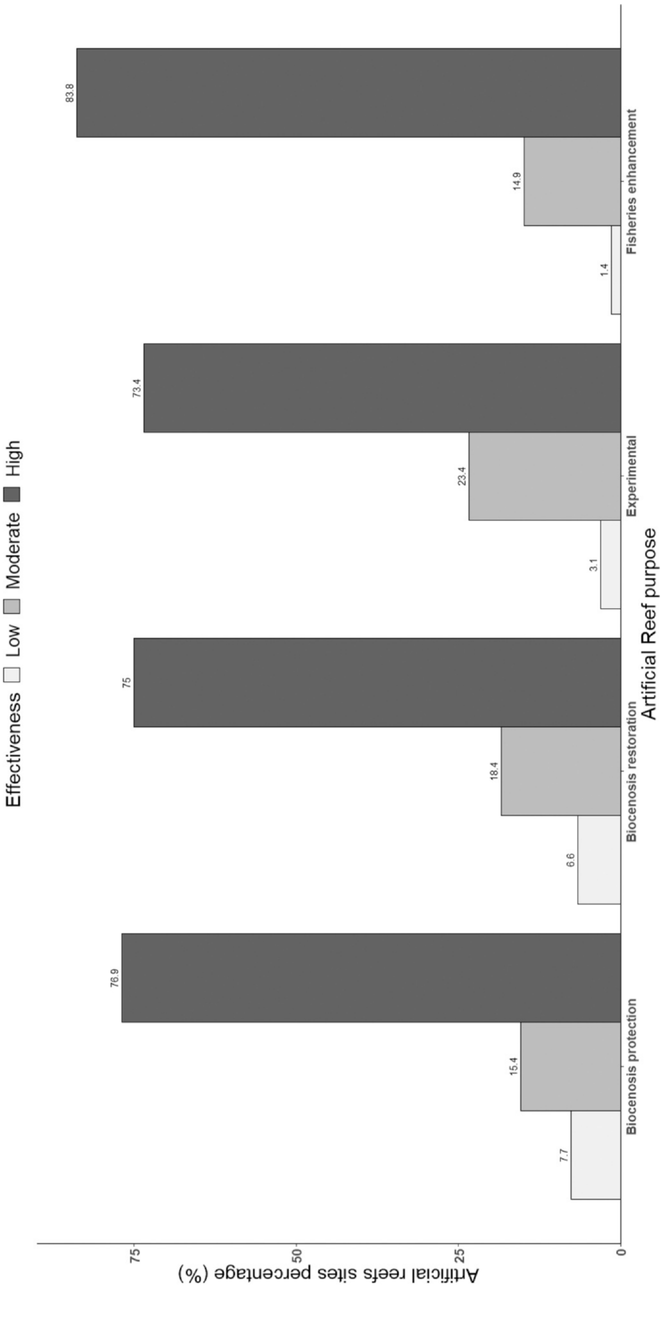

Fig. 4. Graphic representation of assessed effectiveness for each AR purpose.

with shapes made up of multipods (R = 0.25, P = 0.041) and ReefBalls® (R = 0.44, P < 0.001) and with tyres (R = 0.35, P = 0.040). Finally, the biocenosis restoration purpose is correlated with the experimental purpose (R = 0.27; P = 0.029).

4. Discussion

There is a great diversity of AR worldwide with a large range of different shapes, materials and purposes. In this study, we selected 162 AR from 126 scientific publications. A statistical approach on 67 common variables allowed us to describe the selected AR structures in terms of their design, location, objectives and the monitoring techniques used to assess their effectiveness.

4.1. Design, location and effectiveness of artificial reefs

Although AR are widely used around the world, their scientific monitoring is mainly performed in Europe (69 AR), Asia (37 AR) and North America (26 AR). However, the data set used in this paper does not represent the actual distribution of AR in the world because of the non-exhaustively of the analysis and the unequal nature of scientific monitoring of AR projects between regions. These structures are composed of different materials (n = 11), predominantly concrete (60%). There is also a wide diversity of shapes (n = 14), dominated by cubic structures (27%). Concrete AR are widely distributed across all continents. Our analysis shows a significant correlation between concrete material and high AR effectiveness due to the high fixation rate of marine organisms and the high level of colonization (Baine, 2001; Ido and Shimrit, 2015; Mos et al., 2019; Sempere-Valverde et al., 2018). Beside these performances, concrete AR were selected because they have a lower environmental impact than plastics such as PVC which are toxic and generate micro-plastic particles (Zhang et al., 2020). In this context, the development of biogenic materials such as ECOncrete®, with addition of marine products including oyster shells to replace part of the sand, represent a sustainable solution which strengthen the coherence of AR projects by limiting the environmental footprint (Lima et al., 2019a; Perkol-Finkel et al., 2018; Walles et al., 2016). In the same vein, the European RECIF project had proposed the incorporation of crushed seashells of the queen scallop *Aequipecten opercularis* (Linnaeus, 1758) into the substrate of concrete blocks through the development of innovative building materials for AR (Cuadrado Rica et al., 2016; Cuadrado-Rica et al., 2016).

Moreover, the design of AR has a significant impact on their effectiveness. According to our analysis, the most efficient shape is cylindrical. However, AR shape has a limited impact on efficiency in comparison to AR size. Our analysis points out that AR facility volume volumes higher than 1000 m^3 are significantly correlated with a high effectiveness. Large structures could create upwelling phenomenon and promote the primary production and, hence, the local fishery (Bortone et al., 2011). Furthermore, our meta-analysis shows that surface heterogeneity is an important condition affecting the AR efficiency. An increase of surface complexity promotes biodiversity and facilitates colonization (Boaventura et al., 2006; Hageman et al., 2013; Loke and Todd, 2016; Paalvast, 2015). Large holes addition to AR could markedly enhance the holding capacity of a reef for fish of reproductive ages (Bortone et al., 2011). Orientation as a function of currents and/or light are also key factors influencing colonization by ecosystem engineer species, as well as larval recruitment and benthic biodiversity (Boaventura et al., 2006; Loke and Todd, 2016).

Geographic location does not have a significant influence on AR efficiency in the papers selected for this study. However, AR shape and material are found to differ as a function of latitudes. Tropical climates are correlated with two different AR shapes (vertical and tyres) and four construction materials (ceramic, concrete, plastics and tyres). Temperate climate locations are only correlated with concrete material and two shapes (cubic and cages). This difference could be explained by a discrepancy of objectives of AR projects between low and higher latitudes. Our analysis shows that tropical climate is correlated with experimental purpose, which might lead to the large diversity of AR shapes and materials, while temperate climate is correlated with fisheries enhancement and to a lesser extent to biocenosis protection. It is interesting to note that most artificial structures in temperate climates mainly have an economic objective.

4.2. Assessment of artificial reef purpose

Because the reef effect induces fish aggregation and increases the capture rate (Becker et al., 2019; Bortone et al., 2011; Hackradt et al., 2011; Koeck et al., 2011), AR projects are found to be highly efficient in promoting fisheries in our analysis. Clear objectives contribute to a rational and scientific approach to AR evaluation. The fisheries enhancement purpose represents 33% of the purpose variable category. This variable is highly correlated with cluster E, which is the largest group (60 AR) and with cluster C. Group C is different because all the AR originate from the same study (Kasim et al., 2013). These latter authors submerged AR at 11 sites along the Indian coastline with a fisheries enhancement objective. They demonstrated the notable economic benefits of these structures for local fishermen compared with adjacent natural reefs. Many studies have reported that a large number of fisheries actors and the rising interest of the fishing industry in AR projects are relevant factors playing an essential role in the success and economic value of artificial reefs. The fisheries enhancement variable is correlated with a limited number of shapes, construction materials and monitoring techniques, highlighting the fact that AR projects targeting fisheries enhancement reach their objective of attracting fish. However, as reported in the literature, the apparent success of such structures might mask the negative effects on the ecosystem. Attraction local fish biomass without any increase of productivity in the area could lead to overfishing and/or an increase of accidental captures (Jensen et al., 2000; Smith et al., 2016; Whitmarsh et al., 2008).

The experimental purpose is correlated with four different monitoring techniques, five AR shapes and two AR construction materials. In contrast to the fisheries enhancement purpose, the effectiveness of experimental AR seems to be moderate in our analysis even if the correlation between each variable is not highly significant. The difference in effectiveness between these two purposes could be explained by the greater heterogeneity of monitoring techniques, shapes and materials used for experimental AR. For example, Paalvast (2015) used concrete slabs to assess the settlement of algae and macrofauna on a breakwater (Netherlands), while Brown (2005) used four different substrata (wood, rubber, steel and PVC) to record their influence on epifaunal assemblages in Loch Linnhe (Scotland, UK) and Fariñas-Franco et al. (2013) used scallop shells to assess the importance of habitat complexity in recruitment in Strangford Lough (Northern Ireland, UK). Most experimental AR are built to investigate the performance of different materials or shapes, thereby explaining the higher proportion of these variables compared to other purposes, and also the lower effectiveness of experimental reefs compared to other types of AR. We show that biocenosis restoration purpose is correlated with the experimental purpose where many types of shapes and construction materials are used (concrete, plastic, fibreglass, tyres, stone) (Clark and Edwards, 1999; Walker et al., 2002; Kotb, 2013). As previously mentioned, this diversity of AR types leads to a low effectiveness.

Submersion time and depth are key factors for the success of AR that influence the efficiency according to the purpose of deployment. Submersion time is an important variable that affects the effectiveness of AR. This variable is correlated with biocenosis restoration and fisheries enhancement purposes. On the contrary, short submersion time is correlated with experimental AR purpose, often because of a strict legislation (London Convention and Protocol, 2009). This highlights the fact that economic AR, such as those targeting fisheries enhancement, are submerged for very long or even unlimited periods (Bortone et al., 2011; Charbonnel and Bachet, 2010). Fish and benthic communities showed progressive evolution on several years after the immersion of AR highlighting the importance of long term surveys (Bortone et al., 2011; Relini et al., 2002). Short term survey may not be long enough to record the overall influence of an AR on its environment, the survey need to be conducted over several years (Seaman, 2000; Seaman and Sprague, 1991). Another key factor is the submersion depth, which plays an important role in maximizing the efficiency of the reef. In our analysis, submersion depths in the photic zone between 11 and 20 m led to the highest recorded effectiveness; this result might be explained by the fact that these depths correspond to the depths of AR targeting fisheries enhancement.

4.3. Assessment of monitoring techniques

The assessment of monitoring techniques considers the scientific protocols deployed and the survey duration. For example, for fisheries assessment, long-term monitoring is required to prevent any undesirable consequences such as overfishing (Ajemian et al., 2015; Smith et al., 2016). Otherwise, this approach involves protocols with trusted communication between the local fishermen and the AR project managers to maximize the efficiency and longevity of the monitoring and the structures (Keller et al., 2017; Lima et al., 2019b; Ramos et al., 2019). Pelagic measurements including gill and trammel nets to make catch per unit effort estimations are largely used to the fish abundance and biomass estimations, combining with visual observations these techniques provided a relatively accurate image of fish assemblages (Seaman and Sprague, 1991). Several AR projects did not have any real monitoring protocol or used only a small range of techniques to a limited extent (Gregg, 1995; Kasim et al., 2013); this point was already made by Koeck et al. (2011). This was the case in some AR projects dealing with protection areas or fish concentration, which were usually poorly documented. However, most of the AR projects cited in the present study were evaluated using the structural ecology approach which provides information such as biodiversity or species abundance for a variable number of ecosystem compartments. In many projects focused on fisheries, only a partial vision of the AR-associated ecosystem is considered (Cresson et al., 2014). Ecological process monitoring techniques (trophic fluxes, non-trophic interaction including ecosystem engineering, carbon and nitrogen cycles, productivity, etc.) are essential to understand the mechanisms and interactions between living organisms and their environment. This type of monitoring allows us to study functional ecology on AR sites. In our analysis, the functional ecology approach includes all papers that deal with trophic fluxes (Carvalho et al., 2013; Mazzei and Biber, 2015). For example, Cresson et al. (2014) pointed out the importance of integrating functional ecology techniques to allow a satisfactory evaluation of biomass production associated with AR in the bay of Marseilles. In their study, Cresson et al. (2014) used stable isotopic ratios to characterize the trophic network associated with the AR, thus providing an integrative view of trophic relationships. Surprisingly, in our analyses, the functional ecology approach appears to be correlated with low AR effectiveness. This result is probably due to the small number of the selected papers dealing with this topic (2%) as well as the caution shown by authors in their interpretations in comparison, for example, to fisheries or area protection assessment.

The lack of efficient monitoring techniques, or perhaps their suboptimal utilization, underlines the importance of choosing an appropriate complementary technique (i.e. functional and structural ecology approaches) for the evaluation of AR performance. As highlighted by this study, tropic food web, primary productivity and associated assemblages are also key indicators allowing a complete assessment of the AR function (Seaman, 2000). Seaman (2000) has published recommendations on AR evaluation, stressing the importance of defining the AR objectives and the success criteria used to optimize the monitoring techniques and evaluation plan. The choice of monitoring techniques to evaluate the structure performance must fit its primary objective. However, it is not sufficient to focus just on the primary objective. A study plan should integrated an evaluation before and after the AR deployment with an important frequency of sampling (Seaman, 2000; Seaman and Sprague, 1991). When it's possible, monitoring protocols should be standardized and overly complex study designs avoided (Bortone, 2006). As mentioned above, simply monitoring AR design to enhance fisheries or physically protect an area are frequently associated with incomplete monitoring protocols (Piazza et al., 2005). Even if a positive effect is recorded with respect to the original purpose of the AR, it is difficult to ensure sustainable management of the structures and, consequently, any long-lasting positive impact, without comprehensive monitoring techniques using the function ecology approach.

5. Conclusions

The binary nature (presence or absence) of the data frame might explain the massive loss of detailed information in the scientific literature. While the 67 studied variables are the most representative of the selected papers, there are many other aspects not included in this statistical analysis such as the surrounding environment or non-indigenous species. Our study nevertheless represents an objective view of the quantitative and qualitative aspects of artificial reefs. It reveals the wide variety of artificial reefs in the world. Independently of any purpose, the effectiveness of AR depends to a great extent on the properties of these structures.

Concrete with high roughness is by far the most widely used material and seems to be one of the most efficient. The rugosity of the substrate would increase the surface available for settlement and can consequently increase the biomass, the coverage percentage and the primary production of the structure. Further studies should investigate the micro-scale topography influence of the AR surface on the first colonization steps after its immersion. In addition, this material ensures high resistance and does not produce pollutants. The construction material seems to be more important than the shape of the structure, but our results nevertheless suggest that cylindrical or cubic designs are best.

The selection of monitoring techniques is an important factor for the assessment of AR effectiveness. That means selecting the appropriate monitoring techniques must be carefully thought out and include complementary methods. To limit potential negative impacts, and ensure sustainable management and a proper assessment, appropriate monitoring techniques including functional analysis may be necessary to obtain a full understanding of the AR and its impact.

Optimal monitoring should be seasonal and continue for at least 5 years. It is also important to assess different trophic groups to correctly evaluate the effect of the AR on the associated ecosystem and at least on the primary producers, primary consumers, benthic fauna and secondary consumers, and modeled the trophic network before and after the deployment of AR (Cresson et al., 2019). Strategically, the selection of the monitoring techniques should be correctly divided between structural and functional approach. Biological indicators like diversity and abundance should be measured by visual census, picture analysis and microscopic observations. Ecological processes (i.e. trophic webs, productivity, production, etc.) should be assessed by isotopic analysis, primary productivity and production measurements, and trophic food web functioning. In addition, environmental parameters such as temperature, nutrients, depth or light and surrounding ecosystem should also be assessed in order to evaluate the impact of AR on it.

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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2021.e01538.

Appendix B

See Table B1.

Table B1
Complete table of the references used in this study. Artificial reef numbers correspond to the values in the dendrograms and MCA plots.

Artificial reef number	Reference
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142	Angel, D.L., Spanier, E., 2002. An application of artificial reefs to reduce organic enrichment caused by net-cage fish farming: preliminary results. ICES J. Mar. Sci. 59, S324–S329.
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Table B1 (*continued*)

Artificial reef number	Reference
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Table B1 (*continued*)

Artificial reef number	Reference
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Appendix C

See Table C1.

Table C1
List of final variables used in the study with their respective compositions.

Final variable	Included variables					
AR material wood	Bamboo	Wood				
AR material plastics	Nylon	Plastic	PVC	Polyethylene	Plexiglas	Vinyl cloth
AR material rocks	Clay	Rocks	Limestone	Sandstone	Gabbro	Slate
AR shape cylindrical	Cones	Cylindrical	Pipes	Nozzles		
AR shape plates	Slabs	Plates				
AR shape other	Pan scourers	Shells				
Monitoring techniques pictures	Pictures	Quadrats	Detailed pictures	Video recording	Satellite observations	
Monitoring techniques biodiversity measurements	Cover percentage	Density	Diversity	Abundance	Richness	
Monitoring technique environmental measurements	Physico-chemicals parameters	Water parameters	Organic matter measurements			
Monitoring techniques primary production measurements	Pigments	Pulse Amplitude Modulated (PAM)				
Monitoring techniques pelagic measurements	Acoustic monitoring	Experimental fishing	Fish tagging			
Monitoring techniques ecological process	Survival rates	Biomass	Growth rate	Isotopes	Primary production	

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