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# ARTIFICIAL REEFS IN BRAZIL: PERSPECTIVES ON THE RESTORATION OF MARINE ECOSYSTEMS

## Recifes artificiais no Brasil: perspectivas sobre a restauração de ecossistemas marinhos

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## ABSTRACT

Artificial reefs (ARs) can restore degraded reef ecosystems when properly implemented. Despite growing interest, controversy exists due to the varied impacts associated with these structures. Each location worldwide has unique laws and regulations surrounding AR implementation. In this article, we critically assess and update the state-of-the-art on ARs in Brazil, exploring their history, key aspects, and scientific knowledge of their status and future perspectives. ARs have been used in Brazilian coast by government entities since the 1980s and by local communities aiming to boost fishing productivity since the 1990s. However, important aspects such as environmental monitoring, site assessment, material technologies, design, and socioeconomic considerations have not been extensively addressed. Consequently, inadequate planning has led to economic and socioenvironmental impacts like invasive species, pollution, and disruptions to community trophic structures, affecting the Brazilian coast economically, socially, and ecologically. While some progress has been made in legislation, further

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specifications and science-based tools are needed. Concerns have also emerged about the sinking of numerous vessels for tourism purposes. Thus, we present a decision-making tool for AR utilization, emphasizing scientific planning, assessments, long-term strategies, interdisciplinary studies, and public policies for management and monitoring, including existing ARs.

**Keywords:** artificial reef, Brazil, coastal management, restoration, fishing.

## *RESUMO*

*Os recifes artificiais (ARs) podem restaurar ecossistemas de recifes degradados quando implementados adequadamente. Apesar do interesse crescente, existe controvérsia devido aos variados impactos associados a essas estruturas. Cada local em todo o mundo possui leis e regulamentos exclusivos relativos à implementação de AR. Neste artigo, avaliamos criticamente e atualizamos o estado da arte sobre ARs no Brasil, explorando sua história, os aspectos-chave e o conhecimento científico sobre seu status e perspectivas futuras. Os ARs têm sido utilizados na costa brasileira por entidades governamentais desde a década de 1980 e por comunidades locais com o objetivo de aumentar a produtividade pesqueira desde a década de 1990. No entanto, aspectos importantes, como a monitorização ambiental, a avaliação do local, as tecnologias de materiais, a concepção e as considerações socioeconômicas, não foram extensivamente abordados. Consequentemente, o planejamento inadequado gerou impactos econômicos e socioambientais, como espécies invasoras, poluição e perturbações nas estruturas tróficas comunitárias, afetando a costa brasileira econômica, social e ecologicamente. Embora tenham sido feitos alguns progressos na legislação, são necessárias mais especificações e ferramentas baseadas na ciência. Também surgiram preocupações sobre o naufrágio de numerosos navios para fins turísticos. Assim, apresentamos uma ferramenta de tomada de decisão para utilização de AR, enfatizando planejamento científico, avaliações, estratégias de longo prazo, estudos interdisciplinares e políticas públicas para gestão e monitoramento, incluindo ARs existentes.*

***Palavras-chave:*** *recife artificial, Brasil, gestão costeira, restauração, pesca.*

## INTRODUCTION

Historical records indicate that artificial reefs (ARs) have been used as a strategy to enhance fish production for recreational and commercial purposes (West *et al.*, 1994). In the context of marine and coastal planning, ARs serve various purposes such as the restoration of marine and coastal ecosystems (Lindahl, 2003), mitigation or environmental compensation (Leeworthy; Maher & Stone, 2006), reuse of discarded materials like vessels (Church; Warren & Irion, 2009) and oil and gas platforms (Kaiser & Pulsipher, 2005), protection against coastal erosion, and as a measure to avoid bottom trawling (Miller, 2002; Svane & Petersen, 2001). Recent approaches suggest that well-designed ARs can also contribute to carbon immobilization and enhance the resilience of marine ecosystems against the impacts of climate change (Mathews *et al.*, 2021; Rossi & Rizzo, 2020). Furthermore, ARs can serve as tourist attractions that offer socio-environmental solutions and financial gains for coastal communities. To achieve this, long-term monitoring and spatial planning is essential to understand their development and the ecosystem services they provide to local communities (Rossi & Rizzo, 2020). Thus, several applications of ARs align with the objectives of the UN's Decade of Restoration, which aims to restore biodiversity, blue carbon, and associated biomass (Unep & FAO, 2022), and with the sustainable development goals 13 and 14 (climate action and life below water), emphasizing the importance of considering ARs as a restorative measure.

Over several decades, studies worldwide have focused on the utility, advantages, and disadvantages of ARs (Lima; Zalmon & Love, 2019; Paxton *et al.*, 2020; Stone, 1972). In Brazil, scientific research on the subject has mostly been presented in a scattered manner, including reports, meeting minutes, and scientific articles (Brotto & Araújo, 2001; Seixas; Barreto & Santos, 2013). Due to Brazil's limited upwelling zones and lower nutrient content in oceanic currents compared to countries like Peru and Chile (Tresierra & Culquichicón, 1993), the local governments have a strong interest in implementing ARs to increase fishing production. However, starting from the 1970s, Brazil experienced a decline in national fish production due to overfishing and depletion of stocks caused by unsustainable fishing practices (Brandini, 2013; Filho, 2011; Neto *et al.*, 2021; Zalmon *et al.*, 2002).

Until 2009, the absence of regulatory policies for AR deployments in Brazil led to the use of structures that did not replicate natural reef environments. For instance, clusters of tires (Conceição & Junior, 2001; Freitas & Petrere, 2001) and indiscriminate sinking of discarded vessels (Santos, 2006) continued to contribute to various negative impacts such as the establishment of invasive species (e.g., *Tubastraea* spp. and *Pterois* spp.), pollution, attraction and depletion of commercially important species, and other conflicts resulting in environmental and socioeconomic problems (Batista *et al.*, 2020; Simon; Pinheiro & Joyeux, 2011; Oliveira; Vasconcelos & Rey, 1993, Soares *et al.*, 2016; 2020). This highlights a significant conflict surrounding ARs: there are substantial discrepancies between theory and application (Lima; Zalmon & Love, 2019), leading to skepticism regarding their use among a significant part of Brazilian society, as well as in other parts of the world (Miranda *et al.*, 2020; Svane & Petersen, 2001).

In Brazil, Santos and Passavante (2007) conducted a review on the state-of-the-art of ARs in Brazil 15 years ago, examining their designs and uses. However, this article takes a critical perspective from the restoration of marine ecosystems and provides an updated and comprehensive overview of the most relevant information regarding ARs in Brazil. We explore the history of the main programs that have promoted their implementation and addresses key aspects through studies that contribute scientific knowledge on their current status and future prospects. Additionally, we offer a strategic decision-making tool for ARs implementation in the country.

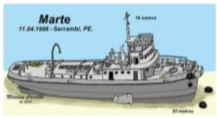
## History of ARs in Brazil

Records dating back to the 17th century mention the use of ARs called “marambaias” by traditional fishing communities in Brazil. These structures were constructed using leaves, branches, and stones, serving as fixed substrates to attract fish and increase habitat complexity (Santos & Passavante, 2007). Nowadays, “marambaias” are constructed using both natural and discarded materials, such as tires, empty oil barrels, and wood, primarily for lobster fishing purposes (Alencar *et al.*, 2021) (Table I).

In Brazil, ARs have been utilized as a coastal zone management tool by various institutions since 1980, initially implemented by the Superintendence of Fishing Development (Sudepe) to discourage trawling (Santos & Passavante, 2007). Since the 1990s up to the present, projects have been undertaken along the entire Brazilian coast, with the implementation of ARs developed through partnerships between Brazilian states, universities, governmental and non-governmental organizations (Table I).

The primary objective of these ARs programs was to enhance fishing productivity (Conceição & Junior, 2001; Conceição *et al.*, 2007). However, the initial deployments of ARs in the country also served a secondary purpose of discarding obsolete materials (Bastos, 2005; Conceição *et al.*, 2007; COPPE/UFRJ, 2020; Freitas & Petrere, 2001) (Table I). Similar initiatives, such as “Rigs-to-Reefs” (Kaiser & Pulsipher, 2005) or “Ship-to-Reefs” (Hynes; Peters & Rushworth, 2004) programs, were implemented in other countries. Despite cautionary calls from the scientific community to prioritize comprehensive research on the role of ARs in ecosystem function before improving regional fishing opportunities (Cowan *et al.*, 1999), this unplanned activity has become a global and local trend.

Table I – Main intervention related to ARs in Brazil throughout the time

| Year | Project (involved beings) | Type of AR/purpose | Location | Representation |
|---|---|---|---|---|
| Before 17th century | (Fishermen) | "Marambaias" | Brazil |  (Filho, 2011) |
| 1989-1991 | Tuna project (Cepene) | Attractor structures | Northeastern Brazil |  (Santos *et al.*, 2010) |
| 1993 | "Recifes Artificiais" Project (UFC-Labomar, fishermen) | Tires | Ceará |  (Conceição & Franklin-Junior, 2001) |
| 1996-1997 | Program "Artificial Reefs on the North Coast of Rio de Janeiro" (UNF) | Concrete tubes and blocks, tires, bricks and Reef balls® | Guaxindiba, São Francisco do Itabapoana, Rio de Janeiro |  (Lima, 2020) |
| 1997-1998 | Freitas and Petrere (2001) | Tires pyramids | Barra Bonita Reservoir, São Paulo |  (Freitas & Petrere, 2001) |
| | Project of Protection to Marine Resources – Promar (MMA) | Anti-trawling structures of steel (30) and concrete (100) | São Paulo |   (Bastos, 2005) |
| 1998-1999 | (Private initiative for tourism -without institution accompany) | Vessel ("Marte" tugboat) sinking | Recife, Pernambuco |   (Ribas, 2013) |
| | (Petrobras, UFC-Labomar and local communities) | Concrete containers "Casulos" | Guamaré, Rio Grande do Norte |  (Conceição & Nascimento, 2009) |
| 1999-2001 | Program "Recifes Artificiais Marinhos do Paraná – RAM/PR" (Ecoplan/UFPR, MarBrasil association) | Concrete structures (2000), bulk barges (> 2000) and Reef balls® | Itacolomis island –Currais Archipelago MPA and Curitiba, Paraná |  (Brandini, 2013) |
| 2002 | (IBAMA, CPRH, researchers and institutes) | 3 Vessel (tugboat) sinking | Recife, Pernambuco |  (Naufragios do Brasil, 2023) |

(continuation Table I)

| Year | Project (involved beings) | Type of AR/purpose | Location | Representation |
|---|---|---|---|---|
| 2003 | (Petrobras) | Oil pipes of concrete | Rio das Ostras, Rio de Janeiro |  (COPPE/UFRJ, 2020) |
| | Project "Artificial reefs of Espírito Santo" | Sinking of the ship Victory 8B | Guarapari, Espírito Santo |  (Photo from: Eduardo Nogueira in *Naufrágios do Brasil*, 2023) |
| | Project "Marambaia" | Sinking of containers | Paracuru, Ceará |  (Conceição *et al.*, 2007) |
| | Orion Project (Petrobras DPCM, Engepron) | Sinking of antique hydrographic vessel | Quissamã, Rio de Janeiro |  (Bastos, 2005) |
| 2010-2012 | Rebimar program | Concrete blocks with corrected pH (3,500) | Between Paraná and São Paulo coast | MarBrasil, 2023 |
| 2019-2020 | "Artificial Shipwreck Park" (IBAMA, MMA/ICMBio, UFPE, Ports and Navy | Sinking of 2 research vessels | APA Costa dos Corais, Tamandaré, Pernambuco |  (ICMBio, 2023) |
| | (Navy, Setur-BA) | Vessels "ferry-boat Juracy Magalhães" and "Anhatomirim" | Salvador, Bahia |  (G1, 2020) |

Among the initial implementation programs in the country, starting from 1993, ARs predominantly comprised modules of up to 2,000 tires deployed along the coast of Ceará. These tires were discarded during a major epidemic in the fight against the Dengue Virus, resulting in approximately 6,000 tires per AR system (Conceição & Franklin-Júnior, 2001). In 1998, the deliberate sinking of the tugboat "Marte" in Pernambuco state marked the beginning of a series of eight more vessel hulls intentionally sunk, involving governmental and academic institutions such as Ibama, research centers, and universities (Santos, 2006). The documentation of the biodiversity and visual appeal of these sinkings attracted fishermen, divers, and adventurers, contributing to the reputation of these ARs in the region (Santos, 2006). Consequently, State Decree No. 23.394/2001 was enacted to regulate activities around the ARs, prohibiting underwater fishing and fishing with hooks in shipwrecks within the Pernambuco state coastal zone (Brasil, 2001).

In 2009, the Marine Biodiversity Recovery Program (Rebimar) became the first licensed program for AR installation in Brazil. Between 2010 and 2012, this program placed 3,500 pH-corrected concrete blocks in the southeast region of the country. The objective was to restore marine biodiversity, regulate fishing activities, promote artisanal fishing, and discourage industrial trawling (Rebimar, 2023).

On the other hand, ARs should ideally mimic the structure and function of natural reef ecosystems (Perkol-Finkel *et al.*, 2006). Depending on their intended purpose, ARs can be constructed using various materials ranging from discarded items to sophisticated materials (Figure S1 – see supplemental material) (Svane & Petersen, 2001; Miller, 2002). In Brazil, ARs were often constructed from concrete and took the form of cubes, circles, or reef balls, with different sizes and masses. The choice of shape appears to follow global trends, and although there is no theoretical explanation for the decision-making process, the inclusion of holes as shelters for marine organisms is a common feature (Brandini, 2013; Conceição *et al.*, 2007). The implementation of ARs in Brazil varied in terms of quantity, depth, and distance from the coast, employing experimental design approaches (Brotto *et al.*, 2006; Jardeweski & Almeida, 2006; Krohling; Brotto & Zalmon, 2006; Santos; Cunha & Santos, 2010). Other materials such as ceramic slabs, bricks, tires, plastic, metal, and wood were less frequently used (Figure S1 - see supplemental material).

In terms of marine restoration, using hard materials like concrete makes sense as they enhance the survival of coral transplants (Ferse, 2010). Consequently, ARs made of hard materials, such as concrete, are commonly employed in restoration methods like coral transplantation, larval and juvenile resettlement, gardening, and nurseries (Bracho *et al.*, *in press*). To ensure the success of an AR project, specific features including materials, shapes, textures, and layout need to be carefully considered (Perkol-Finkel *et al.*, 2006). However, there are limited local studies that evaluate material properties related to seawater (Brandini & Silva, 2011), resistance (Portella *et al.*, 2013), and the potential for pollution in Brazilian marine ecosystems (Lourenço *et al.*, 2018).

Oppositely, there are instances of deployed ARs in Brazilian marine-coastal ecosystems that utilize highly toxic materials. Brotto, Krohling and Zalmon (2006a) applied anti-fouling paint to prevent the colonization of invertebrates, while Spotorno-Oliveira, Coutinho and Tâmega (2015) used experimental epoxy mass plates to test benthic organism colonization. The use of such materials can result in the bioaccumulation of heavy metals and other harmful elements, posing risks to the health of marine organisms associated with these structures and potentially impacting human consumption (Zihao *et al.*, 2022). Consequently, it is crucial to prioritize programs where ARs are viewed as genuine restoration measures, accompanied by research initiatives to assess their influence in this environment (Brotto & Araújo, 2001).

Until 2009, the Brazilian Normative Instruction nº 22 of Ibama (2009) defined ARs as structures intentionally arranged in the underwater environment, built or composed of inert and non-polluting materials of natural or anthropogenic origin. These structures significantly altered the relief of natural bottoms or influenced various processes, including physical, biological, geochemical, and socioeconomic aspects, in accordance with national, regional, and local interests (Ibama, 2009). However, this norm was subsequently revoked by Normative Instruction Ibama nº 28 (2020), which introduced a more flexible definition. Under the revised definition, ARs are now considered entirely submerged structures deliberately built or placed on the seabed to emulate the ecosystem functions of reefs and other natural substrates. The objectives of ARs include the protection of biodiversity, regeneration of degraded habitats, and enhancement of marine biological resources, among others.

Despite the updated definition, certain significant aspects from the previous version were omitted, such as the requirement for prior environmental planning before implementation and restrictions on pollutants. The current instruction (Normative Instruction n° 28) only prohibits excessive amounts of hazardous and potentially polluting materials. Moreover, protocols and information on environmental licensing for AR installations have become more flexible, particularly for projects located in protected areas. The responsibility for conducting studies that define the condition of the AR and the ecosystem to be implemented is not clearly established, nor is the responsibility for monitoring, which is left to the discretion of Ibama to designate the responsible parties. Additionally, the new legislation introduces measures to differentiate and manage structures that originate from projects initially licensed for purposes other than ARs, such as port facilities, oil and gas exploration and production, pipelines, and coastal protection. These structures can now be licensed as ARs as long as they fulfill at least one of the objectives defined in the instruction (Ibama, 2020).

The licensing process for ARs in Brazil commences with Decree nº 5,300 of December 7, 2004, which regulates Law nº 7,661 of May 16, 1988, establishing the National Coastal Management Plan (PNGC). The decree stipulates that the deployment of ARs in the coastal zone must adhere to environmental legislation and be subject to specific regulations. Furthermore, a bill (law project nº 3,292/2004) aimed at regulating the installation of artificial reefs along the Brazilian coast to protect and conserve biodiversity has been under discussion in the National Congress (Ibama, 2006).

This led to the creation of the initial Normative Instruction nº 125 on October 12, 2006, which sought to legalize, standardize, and synthesize the implementation, maintenance, and removal of ARs. However, this instruction was subsequently revoked in 2009 by other instruction pertaining to the use of ARs for fishing and recreational purposes. These, in turn, were later revoked by a new instruction in 2020.

This led to the establishment of the initial Normative Instruction nº 125 on October 12, 2006, which aimed to legalize, standardize, and streamline the implementation, maintenance, and removal of ARs. However, it was later revoked in 2009 by two instructions specifically addressing the use of ARs for fishing and recreational purposes. Subsequently, a new instruction was issued in 2020. Overall, the legal regulations concerning ARs in Brazil have undergone multiple changes, but they remain limited and increasingly less stringent in the country. The simplification and lack of specificity in legislation and policy pertaining to ARs in Brazil have created significant information gaps, allowing for the authorization of practices that contradict the fundamental principles of using ARs for the restoration of marine and coastal ecosystems in Brazil. Consequently, the indiscriminate use of large vessels and the disposal of materials, as well as the inadequate maintenance of harbors, ports, and oil platforms designated as ARs, have resulted in several negative impacts associated with these structures along the Brazilian coast.

The bioinvasion of sun coral (*Tubastraea* spp.) is a significant impact associated with these structures, affecting over half of the Brazilian maritime territory. It has led to a reduction in biodiversity, biomass, changes in species composition, and increased homogeneity of marine organisms from Ceará to Santa Catarina (Batista *et al.*, 2020; Capel *et al.*, 2019; Creed *et al.*, 2017; Mangelli & Creed, 2012; Soares; Davis & Carneiro, 2016). In response to this issue, various actions have been taken, including the organization of work groups, mitigation projects, environmental education initiatives, and the development of national plans involving scientific and civil society participation (Brasil, 2017; Brasil, 2018; Creed *et al.*, 2017; Meireles; Pimentel & Creed, 2015). These efforts aim to mitigate the impact caused by sun coral, including proposals for the removal of sunken structures (Batista *et al.*, 2020) that act as stepping-stones for invasive corals (Soares; Davis & Carneiro, 2016).

Another example of the impact associated with ARs is the bioinvasion of lionfish (*Pterois* spp.), observed along 2,766 km of coastline, twelve protected areas, and eight Brazilian states (Soares *et al.*, 2023). This species uses ARs as stepping-stones and poses a threat to tropical regions with high levels of endemism, rare and/or cryptic taxa, which are primary prey for lionfish (Soares *et al.*, 2022, 2023). In addition to sun coral and lionfish, other invasive species have taken advantage of ARs, such as oil rigs, ports, and experimental plates, to colonize and establish themselves along the Brazilian coast (Table SI – see supplemental material) (Almeida *et al.*, 2015; Almeida; Souza & Vieira, 2018; Anker *et al.*, 2013; Araújo *et al.* 2018; Bumbeer & Rocha, 2012; Creed & Paula, 2007; Farias *et al.*, 2020; Miranda *et al.*, 2018, Soares *et al.*, 2023; Spotorno-Oliveira; Coutinho & Tâmega, 2015). The dispersion mechanisms of these non-native species can involve encrustations on vessel structures, ballast water, and incrustations on oil platforms (Creed & Paula, 2007).

Furthermore, ARs can potentially cause other types of impacts, although this information remains largely unknown in the country. Information gaps exist regarding the impacts of pollution from the materials used, the attraction and depletion of commercial species, imbalances in the trophic network, and changes in hydrodynamics resulting from AR implementation. These issues directly affect the conservation of marine-coastal ecosystems and have implications for various aspects of human interaction with these ecosystems, including food and economic dependence, opportunities for fishing cultivation and production, tourism, cultural significance, spiritual value, and recreational use. Additionally, in terms of national territory management, ARs serve as a tool for controlling destructive fishing activities like trawling, providing physical protection to the coastal zone against climatic phenomena, and preventing coastal erosion when utilized as anti-drag measures (Goergen *et al.*, 2020).

## Research on ARs in Brazil

As a result of AR implementation programs in the country aimed at managing fishery resources, a significant body of research has emerged that evaluates the population and community dynamics of marine organisms associated with these structures, particularly focusing on fish species of commercial interest (Alencar *et al.*, 2003; Conceição *et al.*, 2007; Menegassi, 2018; Pizzato, 2004; Santos & Passavante, 2007; Santos; Cunha & Santos, 2010; Zalmon *et al.*, 2002).

These studies examine the relationship between fish richness and abundance and specific complexities and sizes of the structures (Brotto & Araújo, 2001; Brotto; Krohling & Zalmon, 2006b; Gatts *et al.*, 2014; Santos; Brotto & Zalmon, 2010; Rocha *et al.*, 2014; Santos *et al.*, 2011; Souza *et al.*, 2018). They also explore the proximity of structures to natural rocky ecosystems (Jardeweski & Almeida, 2006) and, more recently, the assemblages of fish larvae associated with ARs to understand whether ARs function as attractor or production structures (Alegretti *et al.*, 2021). Furthermore, ARs have been utilized in research that assesses the influence of environmental parameters on the recruitment of benthic organisms using concrete plates (Krohling; Brotto & Zalmon, 2006).

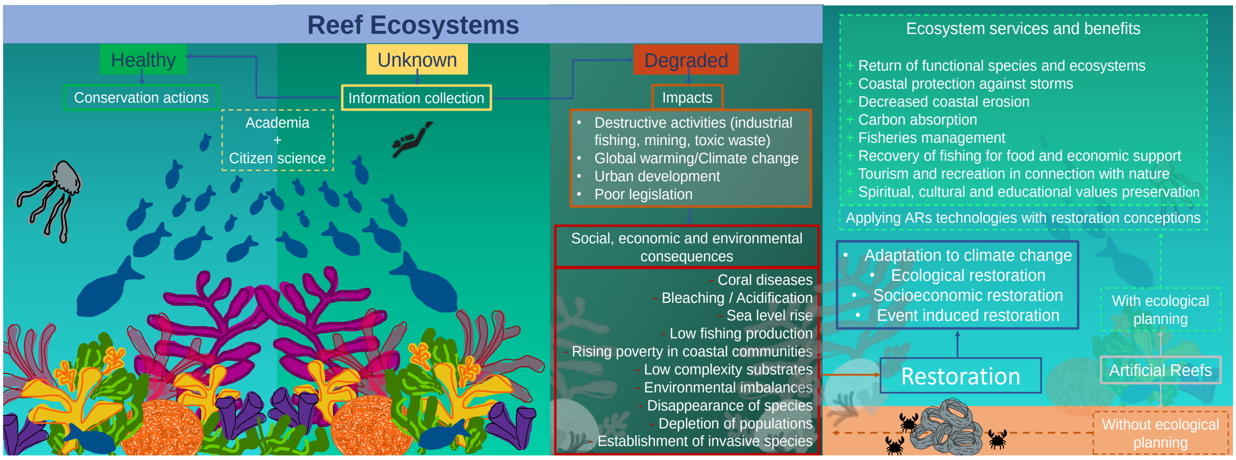
Most studies conducted in the country report successful AR implementations (Santos & Passavante, 2007). However, few of these studies have implemented appropriate monitoring protocols to demonstrate the effectiveness of ARs or used suitable control areas, such as natural reef ecosystems in good condition, as reference measures. Several studies have compared similar types or multiple ARs among themselves (Brandini & Silva, 2011; Brotto; Krohling & Zalmon, 2007; Souza *et al.*, 2018; Zalmon *et al.*, 2014), presented results from a single AR system over the years (Santos *et al.*, 2011), or compared ARs with non-equivalent ecosystems, such as sandy substrates (Rocha *et al.*, 2014; Zalmon *et al.*, 2002), without evaluating the effect of restoration. Consequently, the effectiveness of many AR implementations in Brazil in restoring marine ecosystems remains unknown.

The evaluation of an AR should determine whether it has fulfilled its intended purposes (Lindberg & Relini, 2000). To achieve this, there are quantitative methods available that allow testing whether an AR has produced the desired changes (e.g., abundance, richness, biomass). A suitable evaluation tool is the BACI-type analysis (Before-After/Control-Impact), which enables the temporal assessment of quantitative changes at a site before and following an event, such as the implementation of ARs (Chapman, 1999; Goergen *et al.*, 2020). Despite the importance of long-term monitoring ARs for their success, few studies have included reference sites for necessary comparisons (Alegretti *et al.*, 2021; Costa *et al.*, 2022; Jardeweski & Almeida, 2006). Observing the evolution of ARs, making adjustments, and preventing them from becoming potential risks or causing further degradation of the implemented habitat are crucial steps for their success and long-term management (Becker *et al.*, 2018).

Furthermore, long-term monitoring ARs is crucial for making informed decisions about their management and ensuring their long-term sustainability. While some ARs may serve as local ecological refuges (Freitas; Petrere & Abuabara, 2002), others function both as production and attraction structures, attracting individuals in early developmental stages, juveniles, and large predatory fish (Costa *et al.*, 2022). It is important to regulate AR attractors in terms of harvesting and fishing activities to prevent fish populations from becoming vulnerable to overexploitation and depletion. Moreover, the attraction exerted by ARs on large demersal predators can have negative impacts on nearby natural reefs, leading to negative changes in predation and competition interactions, as well as nutrient input (Simon; Pinheiro & Joyeux, 2011).

The lack of adequate planning and monitoring of ARs in Brazil highlights a serious problem. Without proper planning, monitoring, and long-term management, ARs can fail and contribute to the degradation of marine environments (Figure 1) (Bortone *et al.*, 2011; Chou, 1997; Goergen *et al.*, 2020; Paxton *et al.*, 2020; Pickering *et al.*, 1998). However, despite the difficulties associated with monitoring and managing ARs, such as labor availability, technical personnel, materials, and financing, it is essential to address these aspects in the planning phase to ensure long-term sustainability (Baine, 2001; Becker *et al.*, 2018; Chou, 1997). One potential solution to overcome these challenges is to involve both the civil and scientific communities in the implementation of ARs, fostering a sense of ownership and responsibility towards the environment from which these communities derive resources. This collaborative approach can help adjust and regulate various aspects of ARs to ensure their sustainability.

Figure 1 – Flowchart of considerations for using and managing ARs




Source: modified from Goergen *et al.* (2020).

In fact, according to Normative Instruction nº 22 of July 10, 2009, the implementation of ARs must consider the fishing communities that will be affected, with direct participation from fishermen. Fishing communities often have a deep understanding of local resources and may provide valuable insights for interventions that enhance fishing production (Lima *et al.*, 2018). In some cases, fishers with over 20 years of experience have contributed to selecting AR deployment sites based on their local ecological knowledge of the marine biota (Conceição & Franklin-Júnior, 2001; Lima *et al.*, 2018). Fishermen have also assisted in monitoring ARs, identifying their functions as breeding sites, increasing fish weights, attracting fish, and reducing industrial fishing activities. This involvement of the fishing community has generated a positive perception and acceptance of ARs (Lima *et al.*, 2018).

Fishing communities also play a crucial role in determining the structure and economic importance of the fish community in ARs. Studies have shown that the fish community in ARs, as determined by multimetric indices (ARMIs), exhibits significant increases over time compared to other sites (Lima *et al.*, 2020). However, there are other socio-environmental and economic aspects related to ARs that have received less research attention. For example, studies on the involvement of the scientific community in AR initiatives (Seixas; Barreto & Santos, 2013), ethnoecology, and the socio-economic aspects of artisanal fishing (Lima *et al.*, 2019) and tourism (Giglio; Luiz & Schiavetti, 2016) are important research areas that require further exploration. In particular, ARs have been considered as an alternative to alleviate the pressure on natural environments from tourism, where activities such as visitation, sport fishing, and diving are highly prevalent (Sutton & Bushnell, 2007). Although some divers may not perceive ARs as environments of similar value to natural ones (Giglio; Luiz & Schiavetti, 2016), shipwrecks, which are frequently visited, represent significant areas for tourism (Santos, 2006).

In general, when implementing ARs projects in coastal communities for recreational use, tourism, or the subsistence of these communities, it is crucial to engage in participatory planning involving multiple stakeholders. This includes members of the coastal civil community, fishers associations, government officials, merchants, universities, and researchers. By involving all stakeholders who will be directly and indirectly affected, a participatory plan can ensure the rights to space, the appreciation of local culture, conservation, and a fair distribution of resources (Pedrosa & Lessa, 2018). It is worth noting that research in this area has already identified a shortage of researchers and quality research on ARs in the country (Seixas; Barreto & Santos, 2013), which further emphasizes the importance of addressing this issue. Citizen science-based research is also an effective alternative that has been increasingly utilized in natural resource management and environmental protection. It facilitates public involvement and provides a means for environmental monitoring (McKinley *et al.*, 2017).

## Future perspectives of ARs use in Brazil

In Brazil, there has been a perception that artificial reefs (ARs) can be used as a disposal opportunity. Recently, there has been a plan to implement over 1,200 ARs in seven states of the country: Paraíba, Pernambuco, Alagoas, Bahia, Federal District, Rio de Janeiro, São Paulo, and Santa Catarina (G1, 2020). These planned ARs include marine protected areas that are currently in good conservation status. In March 2020, the National Plan for Artificial Reefs was presented, which aimed to sink 128 shipwrecks, including vessels, aircraft, and war tanks, with the apparent intention of promoting diving and sport fishing. The plan also included the sinking of ARs in the Fernando de Noronha Archipelago, which is one of the best-preserved, marine biodiversity hotspot, and well-managed marine protected areas in the South Atlantic. The archipelago is known for its high endemism and is composed of a National Marine Park and an Environmental Protection Area. However, this plan has not yet been officially implemented.

This controversial plan has raised concerns among the scientific community, as it proposes sinking dismantled ships, trains, and planes, primarily within marine protected areas. Considering the country's history of serious environmental impacts and the relaxation of legislation regarding ARs, this situation represents a possible environmental crisis that poses a threat to biodiversity and ecosystem functioning (Miranda *et al.*, 2020). Therefore, we urge a change in mindset regarding ARs in the country, encouraging the exploration of alternative methods for recycling obsolete large structures. It is suggested that larger ARs should serve as attractors rather than production habitats (Bohnsack *et al.*, 1994; Gatts *et al.*, 2014).

Furthermore, studies have shown that there is an ongoing development in understanding the attraction-production dilemma of artificial reefs. Some research has revealed that larger structures attract big predators, leading to a reduction in biomass after recruitment events, while smaller structures and cavities are associated with larvae and juvenile individuals, contributing to ecosystem production (Bonsack *et al.*, 1994; Roa-Ureta *et al.*, 2019; West *et al.*, 1994). As a result, engineered structures worldwide are being designed with greater three-dimensional complexity, aiming to closely mimic coral reef habitats (e.g., EcoReefs, BioRock, ReefBalls®) (Boström-Einarsson *et al.*, 2018). Additionally, advancements in technology have led to the development of intelligent or smart biomaterials that can perceive and respond to their surroundings (smart materials) and improve or optimize their response (intelligent materials) through various stimuli such as light, temperature, pH, electromagnetic fields, ultrasound, or cell/tissue-induced enzyme secretion and protein interactions (León *et al.*, 2023). These global technological advances offer potential applications and improvements for effective restoration actions in Brazilian marine ecosystems.

Instead, we emphasize the need for investment in new technology development and filling the gaps with ecologically based information to fulfill the comprehensive purpose of artificial reefs (Lima; Zalmon & Love, 2019). This purpose includes guaranteeing marine ecosystem restoration, recovering fish stocks, and providing economic, social, and cultural benefits. This becomes particularly relevant in the context of the Decade of Ecosystem Restoration (Unep & FAO, 2022). In light of this, we present a decision framework that promotes the better utilization of artificial reefs in marine and coastal ecosystems, drawing upon a compilation of classic and updated information on reef ecosystem restoration, as well as the planning and management of artificial reefs for restoration purposes (Figure 1) (Bortone *et al.*, 2011; Chou, 1997; Goergen *et al.*, 2020; Paxton *et al.*, 2020; Pickering *et al.*, 1998).

We also propose that artificial reefs of different natures should have specific planning and management tailored to each type of ecosystem and the specific impacts they aim to address. Structures that were not originally created with the specific objective of promoting the restoration of marine ecosystems, but are repurposed as artificial reefs (*e.g.*, ports, oil platforms, docks, vessels), should be subjected to more rigorous long-term monitoring and management. The materials, shapes, locations, and conditions of these structures can potentially facilitate impacts related to invasive species, pollution, and trophic changes in the marine community structure surrounding them.

On the other hand, artificial reefs created specifically for the colonization of marine organisms, such as experimental plastic plates and concrete structures, have also been found to harbor invasive species. However, this type of artificial reef offers the advantage of being manipulable, allowing for choices regarding location, structure, and material characteristics. These factors could help prevent impacts or make mitigation efforts more achievable. Therefore, studies are needed to determine whether artificial reefs can be installed at a sufficient distance from port areas to avoid the establishment of non-native species, while implementing the necessary monitoring and management measures highlighted throughout this article. Additionally, research on the ecological engineering of artificial reefs is crucial, including the assessment of toxicity levels in deployed materials, the use of alternative inert materials that promote the growth of marine bioengineering organisms, and the development of carbon-sequestering structures. These areas are currently prioritized in artificial reef research in the country (Becker *et al.*, 2018; Lima; Zalmon & Love, 2019).

## CONCLUSION

In Brazil, degraded reef ecosystems require tools that can facilitate: 1) active ecological restoration to rehabilitate biodiversity and structural complexity in the degraded environments, 2) mitigation of the impacts of climate change through carbon immobilization, and 3) the management of previously overexploited fish stocks. These aspects are crucial for reef ecosystems that directly support millions of people, and they can be achieved through well-planned implementations of ARs.

We also emphasize that the main issues surrounding ARs in Brazil, as well as in other countries worldwide, are related to their management and planning. In this article, we criticize the implementation of ARs in Brazil that lacked proper planning, as well as those that were superficially studied and driven by immediate or ill-defined interests of civil, commercial, or governmental sectors. We emphasize the notable shortcomings in scientific research, monitoring, management, and impact assessment of these projects. It is essential to address the knowledge gaps in this emerging field through comprehensive studies that encompass the socioeconomic sector, ARs design and materials, legislation and planning considerations, and the integration of mathematical models to assess ecological, economic, and social factors. Such an approach can effectively mitigate environmental impacts, as discussed in this article.

While ARs do not represent a sole solution for the degradation of marine ecosystems, they are a valuable and accessible tool for environmental compensation when irreversible impacts occur in coastal zones. ARs can be properly planned to enhance the production of larvae and juveniles of commercially valuable species, restock species of socio-environmental significance, support transplants or the growth of key species, and contribute to carbon absorption for marine ecosystem restoration. Therefore, we recommend prioritizing the monitoring, management, and regulation of existing ARs, conserving the associated marine and coastal ecosystems, and publishing research findings, as suggested in this article, to establish an information baseline that can inform decision-making processes.

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