UNIVERSIDADE FEDERAL DO CEARÁ
INSTITUTO DE CIÊNCIAS DO MAR
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS MARINHAS TROPICAIS

CAROLINA BRACHO VILLAVICENCIO

NOVOS MÉTODOS PARA RESTAURAÇÃO MARINHA ATRAVES DOS “SAR” (SYMBIOTIC ARTIFICIAL REEFS)

FORTALEZA
2025

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Tese apresentada ao Programa de Pós-Graduação em Ciências Marinhas Tropicais da Universidade Federal do Ceará, como parte dos requisitos para obtenção do título de Doutora em Ciências Marinhas Tropicais. Área de concentração: Ciência, Tecnologia e Gestão Costeira e Oceânica.

Orientadora: Profa. Dra. Helena Matthews-Cascon
Coorientador: Prof. Dr. Sergio Rossi Heras

FORTALEZA
2025

Universidade Federal do Ceará
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UNIVERSIDADE FEDERAL DO CEARÁ
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS MARINHAS TROPICAIS

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Novos métodos para restauração marinha através dos SAR (SYMBIOTIC ARTIFICIAL REEFS)
".

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Fortaleza, 20 de Agosto de 2025

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A Aylén.

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“A cada gota d'água que você bebe, a cada respiração que você respira, você está conectado ao Oceano. Não importa onde você viva na Terra, a maior parte do oxigênio da atmosfera é gerada pelo Oceano.”

(Sylvia Early).

RESUMO

Recifes artificiais (RAs) são uma ferramenta usada no nível mundial desde várias décadas para restaurar ativamente ecossistemas marinho-costeiros e recursos pesqueiros. Contudo, RAs tem sido implementados sem planejamento, causando diversos impactos ambientais e suspeita do seu uso em programas de restauração. Esta tese teve como objetivo determinar quais as características ótimas para que os RAs sejam bem sucedidos na restauração de ecossistemas marinhos e costeiros. Isto se condiz principalmente com os ODS 13 (ação contra a mudança global do clima) e 14 (vida na água). Assim, o estudo foi dividido em três partes. O primeiro capítulo aborda uma discussão sobre os RAs no Brasil, explorando a sua história, conhecimento científico chave e perspectivas futuras, aportando assim desde uma perspectiva ecológica uma ferramenta de tomada de decisão no uso de RAs para evitar diversos impactos ambientais já ocorridos no país (i.e., introdução de espécies exóticas, uso de materiais poluentes, etc.). No segundo capítulo foi realizada uma revisão sistemática de literatura (RSL) sobre o estado das artes dos RAs no mundo entre 1990-2020 incluindo uma metanálise sobre a efetividade dos RAs em se assemelhar a recifes naturais (RNs), com o índice de similaridade de Bray-Curtis como medida de sucesso de restauração de ecossistemas marinhos e costeiros. Importantes lacunas de conhecimento sobre aspectos socioeconômicos; design, materiais e disposição nos habitats selecionados; aspectos jurídicos, de gestão e de planejamento considerando o monitoramento de longo prazo são ressaltadas. Com relação à eficácia, poucos artigos (n=13) permitiram comparações apropriadas entre RAs e RNs, destacando a necessidade de aplicar sítios de referência adequados nestas implementações. A meta-análise mostrou que os RAs não são semelhantes aos RNs de referência (p=0,03 e p=0,05 para modelos efeito comum e aleatório, respectivamente). Um alto índice de heterogeneidade (88%) indica que essa relação pode ser influenciada por outros fatores além da natureza do recife. No entanto, alguns RAs bem sucedidos em se assemelhar a RNs brindaram direções mais acertadas neste sentido. No terceiro capítulo foi realizado um estudo experimental na cidade de Porto Cesário, Itália, entre outubro/2019 e setembro/2021. Foi testada a eficácia de materiais de origem orgânica conhecidos por disponibilizar nutrientes, degradar poluentes e reduzir o risco de patógenos em ecossistemas terrestres. Placas experimentais de biochar, biofermento e concreto (controle) foram fotografadas em diferentes tempos durante o período de estudo. Foi estimada a cobertura de grupos taxonômicos usando o software Photoquad e analisadas com PERMANOVA univariada e multivariada sob os fatores material e tempo. Foram detectadas diferenças significativas entre material, tempo e sua interação, mostrando uma sucessão ecológica com mudanças na composição comunitária através dos períodos de colonização. Biochar alcançou uma maior cobertura de organismos marinhos em menor tempo de colonização, comparado com biofermento e o controle, o qual é requerido em programas de restauração, assim como mostrou-se como material ótimo para submersão. Ecossistemas recifais degradados tem oportunidades para ser restaurados por meio de RAs, sempre que um planejamento científico e logico com especificidade espaço-temporal seja aplicado.

Palavras-chave: Recifes Artificiais; Restauração Ativa; Ecossistemas Marinhos.

ABSTRACT

Artificial reefs (ARs) are a tool used for several decades to actively restore marine-coastal ecosystems and fisheries resources. However, RAs have been implemented without planning, causing several environmental impacts and suspicion of their use in restoration programs. This thesis aimed to determine the optimal characteristics for ARs to be successful in restoring marine and coastal ecosystems. This mainly relates to SDGs 13 (climate action) and 14 (life below water). Thus, the study was divided into three chapters. The first chapter addresses a discussion on ARs in Brazil, exploring their history, key scientific knowledge and future perspectives, thus providing from an ecological perspective a decision-making tool on the use of ARs to avoid several environmental impacts that have already occurred in the country (i.e., introduction of exotic species, use of polluting materials, etc.). In the second chapter, a systematic literature review (SLR) was carried out on the state of the art of ARs in the world between xx-xx, including a meta-analysis on the effectiveness of ARs in resembling natural reefs (NRs), with the Bray-Curtis similarity index as a measure of success in restoring marine and coastal ecosystems. Important information gaps are highlighted regarding socioeconomic aspects; design, materials and layout in the selected habitats; legal, management and planning aspects considering long-term monitoring. Regarding efficacy, few articles (n=13) allowed appropriate comparisons between ARs and NRs, highlighting the need to apply adequate reference sites in these implementations. The meta-analysis showed that ARs are not similar to reference NRs (p=0.03 and p=0.05 for common and random effect models, respectively). A high level of heterogeneity (88%) indicates that this relationship may be influenced by factors other than the nature of the reef. However, some ARs that were successful in resembling NRs provided more accurate directions in this regard. In the third chapter, an experimental study was carried out in the city of Porto Cesario, Italy, between October 2019 and September 2021. The effectiveness of organic materials known to provide nutrients, degrade pollutants and reduce the risk of pathogens in terrestrial ecosystems was tested. Experimental plates of biochar, bioferment and concrete (control) were photographed at different times during the study period. The coverage of taxonomic groups was estimated using Photoquad software and analyzed with univariate and multivariate PERMANOVA using material and time as factors. Significant differences were detected between material, time and their interaction, showing an ecological succession with changes in community composition through the colonization periods. Biochar achieved a higher coverage of marine organisms in a shorter colonization time, compared to bioferment and the control, which is required in restoration programs, as well as being an optimal material for submersion. Degraded reef ecosystems have opportunities to be restored through ARs, whenever a scientific and logical planning with space-time specificity is applied.

Keywords: Artificial Reefs; Active Restoration; Marine Ecosystems.

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LISTA DE ABREVIATURAS E SIGLAS

APA – Area de Proteção Ambiental
AR – Artificial Reefs
ARMIs – lima 2020
BACI – Before – After – Control – Impact Method
BRUV - Baited Remote Underwater Video
CEPENE - Centro Nacional de Pesquisa e Conservação da Biodiversidade Marinha do Nordeste
CPRH – Agência Estadual de Medio Ambiente do Pernambuco
COPPE/UFRJ - Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia, da Universidade Federal do Rio de Janeiro
FADs – Fish Aggregating Devices
IBAMA - Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis
ICMBio - Instituto Chico Mendes de Conservação da Biodiversidade
Labomar- Instituto de Ciências do Mar
MMA – Ministério do Meio Ambiente
MPA – *Marine Protected Area*
ODS - Objetivos de Desenvolvimento Sustentável
PCA - Principal Component Analysis
PERMANOVA – Permutational Analysis of Variance
PETROBRAS - Petróleo Brasileiro S.A.
PICO – Population – Intervention – Control – Outcome
PNGC – Plano Nacional de Gestão Costeira
PRISMA - Preferred Reporting Items for Systematic reviews and Meta-Analyses
RAs - Recifes Artificiais
RAM/PR – Recifes Artificiais Marinhos do Paraná
REBIMAR - Programa de Recuperação da Biodiversidade Marinha
RNs – Recifes Naturais
ROV - Remotely Operated Vehicles
RSL – Revisão Sistemática de Literatura
SAR -Symbiotic Artificial Reefs
SDG - Sustainable Development Goals
SLR – Systematic Literature Review

SUDEPE - Superintendência do Desenvolvimento da Pesca
UFC – Universidade Federal do Ceará
UFPE – Universidade Federal do Pernambuco
UFPR – Universidade Federal do Paraná
WOS – Web of Science

SUMÁRIO

1 INTRODUÇÃO GERAL

A conservação dos ecossistemas marinhos e costeiros é de extrema importância pois toda a vida na superfície depende da vida nos oceanos. A vida marinha fornece metade do nosso oxigênio e grande parte da nossa alimentação, além de regular o clima, fornece abrigo em uma imensa diversidade de habitats e formas de vida, assim como são responsáveis por fornecer recursos e serviços ambientais e econômicos imprescindíveis à sobrevivência humana, como fornecimento de alimento e habitat, especialmente de comunidades costeiras (NAS, 2019).

No ano 2010, o primeiro censo da vida marinha mostrou que a vida no planeta oceano é mais rica, mais conectada e mais alterada do que era esperado (AUSUBEL; CRIST; WAGGONER, 2010). Contudo, o aquecimento global, a acidificação dos oceanos, o aumento das doses de UV, o aumento do nível do mar, a eutrofização antropogênica, a poluição, a pesca predatória e o desenvolvimento da costa tem levado ao aumento da disseminação de doenças em corais, ao aumento da frequência e da intensidade de eventos devastadores de branqueamento e finalmente ao declínio irreversível de aproximadamente um 70% dos recifes do mundo (DUBINSKY; STAMBLER, 2011).

Somado a isto, recifes de corais possuem o esqueleto mais massivo, contudo precisam de uma média de 1 ano para crescer 1 centímetro, e é por conta deste crescimento lento, precisam aproximadamente 100.000 a 30 milhões de anos para se formar completamente (BUDDEMEIER; KINZIE, 1976; OCHOA-SERENA *et al.* 2025; NOAA, 2026; WEINSTEIN *et al.*, 2016). Neste sentido, é sabido que as medidas de regulação não são mais suficientes para permitir uma recuperação natural (HUTCHINGS; BAUM, 2005; ROSSI, 2013; WWF, 2015). Em resposta, a declaração da Década da Restauração de Ecossistemas pelas Nações Unidas demonstra a necessidade urgente no nível global em criar novos métodos por meio de melhores práticas para obter o máximo ganho na restauração destes ecossistemas (ARIAS-GONZÁLEZ *et al.*, 2022).

Antigamente, as práticas de restauração consistiam em remover uma perturbação e permitir que o ecossistema se recuperasse por meio de processos ecológicos naturais; porém, comumente a restauração requer múltiplos esforços, uma vez que múltiplas perturbações têm empurrado os ecossistemas para além de sua capacidade de se recuperar espontaneamente (FALK *et al.*, 2006). Nesse sentido, a conservação *per se* não é mais suficiente com o nível e a frequência da perturbação humana, levando-os a um ponto em que as medidas de restauração passiva devem ser complementadas pela restauração ativa para proteger os recifes globais (WESTOBY; BECKEN; LARIA, 2020). Isto, somada à estreita vinculação de centenas de milhões de pessoas e organismos que dependem dos recifes para alimentação ou subsistência, os milhares de comunidades que dependem dos recifes para proteção contra as ondas, as pessoas cujas práticas culturais estão ligadas aos recursos dos recifes e as muitas economias que dependem dos recifes para a pesca ou turismo, fazem que a saúde e a manutenção deste importante ecossistema global sejam cruciais (NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, 2019).

A restauração dos ecossistemas marinhos, incluindo métodos passivos e ativos, é infalível para promover o recrutamento natural e a sobrevivência das espécies de interesse, o retorno da estrutura e função do ecossistema e a melhoria dos processos abióticos que moldam a comunidade (GANN *et al.*, 2019). Neste sentido, cada vez são mais necessários os esforços para aprimorar métodos de restauração ativa de ecossistemas marinhos e costeiros, visto o ritmo de degradação e o declínio global dos recifes, em decorrência dos efeitos das mudanças climáticas.

Com isto, diversas abordagens de restauração ativa de ecossistemas de recifes de coral têm sido usadas, como o transplante ou repovoamento por fragmentação de corais, jardineira ou *nubbins* (LINDAHL, 2003; OREN; BENAYAHU, 1997); alterações genéticas para aumentar a resiliência (NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, 2019); RAs multifuncionais (CARMO; NEVES; VOORDE, 2011; LOKESHA; SUNDAR; SANNASIRAJ, 2013), entre outras. Contudo, recifes artificiais (RAs) podem ser usados para combinar várias destas abordagens, o que poderia ser um aspecto chave para aprimorar projetos de restauração de ecossistemas recifais.

Os RAs são estruturas tridimensionais colocadas nos fundos marinhos que tem entre outras finalidades a de restaurar ecossistemas marinhos e costeiros, particularmente ecossistemas recifais, os quais encontram-se entre os mais impactados no nível mundial (SEAMAN; LINDBERG, 2009). Paradoxalmente, RAs podem ser feitos desde materiais de desperdício afundados no mar, construções costeiras que podem ser consideradas RAs "incidentais", assim como podem ser construídos de maneira específica para certas finalidades. Entre estas podem ser mencionadas a restauração de ecossistemas marinhos e costeiros, melhoria da qualidade da água, ferramenta contra furacões, ferramenta para melhorar atividades de surf, como ferramenta anti-arrasto, como atrator para aumentar a biomassa e riqueza de espécies para pesca e turismo (MILLER, 2002; SVANE; PETERSEN, 2001). Essas últimas seriam as formas mais comuns no uso dos RAs, onde usualmente não são planificados, construídos, implementados, nem monitorados de maneira ambientalmente adequada.

Desta maneira, RAs tem ocasionado impactos como a instalação de espécies exóticas (BRINK; HUTTING, 2017), poluição por tóxicos (BROWN, 2005; HARTWELL *et al.*, 1998), mudanças na composição comunitária local ou dilema atração-produção (BORTONE, 1998; BRICKHILL; LEE; CONNOLLY, 2017; RULE; SMITH, 2007; ZALMON *et al.*, 2014), entre outros que finalmente podem levar a conflitos sociais, ambientais e econômicos em longo prazo e que podem ser irreversíveis.

Rossi e Rizzo (2020) estabelecem algumas condições mais específicas que os RAs deveriam cumprir, como imitar o afloramento natural de fundos rochosos presentes nas áreas-alvo, possuir características estruturais focadas no assentamento de corais, gorgônias e esponjas, apresentar cavidades de diferentes tamanhos e formas para aumentar a presença de espécies vágeis (i.e. peixes, moluscos e crustáceos), assim como podem ser desenhados para capturar CO_2, por meio da porosidade superficial das suas próprias estruturas de concreto, durante o processo conhecido como carbonatação.

Com isto, estudos mais recentes sobre RAs estão mais relacionados à reabilitação dos ecossistemas marinhos (LEE; OTAKE; KIM, 2018; LIMA; ZALMON; LOVE, 2019; MILLER, 2002). Entre outros estudos, Prabowo *et al.* (2022) testaram o transplante de corais duros em recifes artificiais e indicam que o nicho disponível para outras espécies da fauna marinha, criado pelas estruturas artificiais, pode preservar os fragmentos de coral, especialmente na fase inicial. Assim como outro estudo recomenda o uso de estruturas duras para sustentar os fragmentos de transplante de coral, devido à baixa efetividade de materiais de curta durabilidade como o bambu (FERSE, 2010). No entanto, persistem importantes vazios de informação sobre técnicas mais elaboradas como o uso de materiais inertes alternativos, a avaliação e mitigação do impacto ambiental com uso de controles e a avaliação sobre aspectos socioeconômicos, sendo atualmente as áreas prioritárias na pesquisa sobre RAs (BECKER *et al.*, 2018; LIMA; ZALMON; LOVE, 2019).

É bem sabido que as características mais importantes a serem consideradas na construção de RAs em sistemas de recifes de corais tropicais são referentes à orientação espacial, a complexidade e a forma do substrato (PERKOL-FINKEL; SHASHAR; BENAYAHU, 2006). Assim como existem vários programas informáticos e matemáticos que servem para modelar essas estruturas (LAN; CHEN; HSUI, 2004; LAN; HSUI, 2006). Contudo, outras características específicas como materiais, formas, texturas e disposição, implementação dentro da água, assim como informações que resultem do uso do RA dentro da água, são necessárias para levar a cabo esse tipo de restauração ativa de maneira acertada.

Desta maneira, se faz necessário criar (planejar, desenhar, construir, instalar e monitorar) RAs que visem restaurar ecossistemas marinhos e costeiros de maneira adequada e replicável para qualquer ecossistema de recifes degradado.

No Brasil, os RAs têm sido utilizados como ferramenta de manejo da zona costeira por diversas instituições devido sua versatilidade, sendo implementado no país desde o 1980 pela Superintendência de Desenvolvimento da Pesca (SUDEPE), buscando evitar a pesca de arrasto (SANTOS; PASSAVANTE, 2007). Isto ressalta o Brasil como um dos países do Atlântico Sul com um grande interesse na implementação de recifes artificiais (RAs), devido a uma necessidade de compensar o déficit de "baixa produtividade pesqueira", por ter poucas zonas de ressurgências em comparação com outros países como Peru e Chile, e à queda na produção pesqueira após o ano 1986 como resultado de práticas pesqueiras predatórias que levaram a sobrepesca e depleção de estoques (ZALMON *et al*., 2002, FILHO, 2011, NETO *et al*., 2021).

Os RAs podem ser considerados também como dispositivos de agregação de peixes (FADs), usados para agregar espécies de peixes pelágicos próximos à costa, incrementando a capacidade de carga regional e permitindo maior acesso por pescadores em comunidades costeiras (ROGERS *et al*., 2014, ROA-URETA *et al*., 2019). Apesar disso, a pesca de arrasto, a sobrepesca e cultivos são comumente assinalados como impactos associados aos RAs. Isto, devido a que o aumento da produção em biomassa pode levar ao aumento da capturabilidade dos stocks correndo o risco de superexploração, o qual deve ser tratado com medidas de regulação de pescarias (GROSSMAN *et al*., 1997, ROA-URETA *et al*., 2019).

Por outro lado, a implementação de RAs vem com um amplo conjunto de questões logísticas, políticas e sociais pois pode incorrer em custos elevados e é logisticamente desafiador (ROGERS *et al.*, 2014). A tomada de decisões em conjunto, considerando aspectos econômicos e culturais, e preferências é de grande importância para que estes projetos se levem a cabo com sucesso. Projetos de implantação de RAs interdisciplinares pode contribuir na simplificação da logística, permissões, fiscalização, financiamento e administração, monitoramento como a aplicação da ciência cidadã, e na educação e treinamento que promovam identidade y sentido de pertença às pessoas relacionadas com os RAs (FLORISSON *et al*., 2018, GOERGEN *et al*., 2020).

As restaurações baseadas em ciência seguem (1) metas explicitamente declaradas, (2) um projeto de restauração formado pelo conhecimento ecológico e (3) avaliação quantitativa das respostas do sistema empregando coleta de dados pré e pós-restauração. Porém um aspecto negativo da restauração ecológica, como é comumente praticada hoje, é que os resultados da maioria dos esforços não são facilmente acessíveis. Com poucas exceções, a maioria das medidas de restauração realizadas não são testadas como efetivas, na ausência de controles, monitoramento em longo prazo e reportes de esforços posteriores, o que representa o elemento-ciência mais crítico que, com o tempo, levaria a uma melhor compreensão da natureza desafio (FALK *et al*., 2006).

Por isso é importante aprimorar técnicas e métodos de restauração de ecossistemas marinho-costeiros degradados, que permitam a recuperação e manejo de ecossistemas antigamente sobre explorados e/ou impactados. Esses aspectos dependem de ecossistemas recifais em bom estado de conservação, dos quais milhões de pessoas dependem de maneira direta.

1.1 Hipótese Científica

Os recifes artificiais são semelhantes aos recifes naturais como uma resposta bem-sucedida na restauração de ecossistemas marinhos e costeiros e servem como novos métodos eficazes de restauração ativa.

1.2 Objetivos

São objetivos da presente pesquisa:

- **Objetivo Geral**

Avaliar os fatores que modelam o sucesso de recifes artificiais na restauração de ecossistemas marinhos e costeiros.

- **Objetivos Específicos**

✓ Realizar uma revisão do estado das artes dos RAs existentes no Brasil e no mundo com fines de restauração marinha

✓ Estimar a efetividade dos RAs na restauração de ecossistemas marinhos e costeiros no nível global.

- ✓ Testar diferentes técnicas de construção de materiais para colonização ativa ou passiva de RAs.
- ✓ Analisar os fatores que determinam que RAs sejam exitosos na restauração de ecossistemas marinhos e costeiros.

CAPÍTULO I

RECIFES ARTIFICIAIS NO BRASIL: PERSPECTIVAS SOBRE A RESTAURAÇÃO DE ECOSSISTEMAS MARINHOS

2 CAPÍTULO I – RECIFES ARTIFICIAIS NO BRASIL: PERSPECTIVAS SOBRE A RESTAURAÇÃO DE ECOSSISTEMAS MARINHOS[1]

ARTIFICIAL REEFS IN BRAZIL: PERSPECTIVES ON THE RESTORATION OF MARINE ECOSYSTEMS[1]

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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

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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 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 (RAs) 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 RAs. Neste artigo, avaliamos criticamente e atualizamos o estado da arte sobre RAs no Brasil, explorando sua história, os aspectos-chave e o conhecimento científico sobre seu status e perspectivas futuras. Os RAs 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 RAs, enfatizando planejamento científico, avaliações, estratégias de longo prazo, estudos interdisciplinares e políticas públicas para gestão e monitoramento, incluindo RAs existentes.

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

2.1 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).

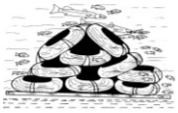
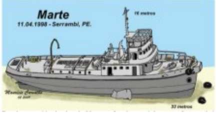
In Brazil, Santos & Passavante (2007) conducted a review on the state-of-the-art of ARs 15 years ago, examining their designs and uses. However, this article takes a critical perspective from the restoration of marine ecosystems and provides an updated and comprehensive overview of the most relevant 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.

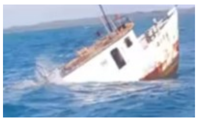
2.2 History of ARs in Brazil

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 1).

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 1).

Table 2-1. Main intervention related to ARs in Brazil throughout the time.

Year	Project (involved beings)	Type of AR/purpose	Location	Representation
Before1 7th 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"	Concrete tubes and blocks, tires, bricks and Reef balls®	Guaxindiba, São Francisco do Itabapoana, Rio de Janeiro	 (Lima, 2020)
1997-1998	Freitas & 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)
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, Espirito Santo	 (Photo from: Eduardo Nogueira in Naufragios 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

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 1). 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.

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) (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).

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 use 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 S1) (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).

2.3 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.

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, fisher's 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).

2.4 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).

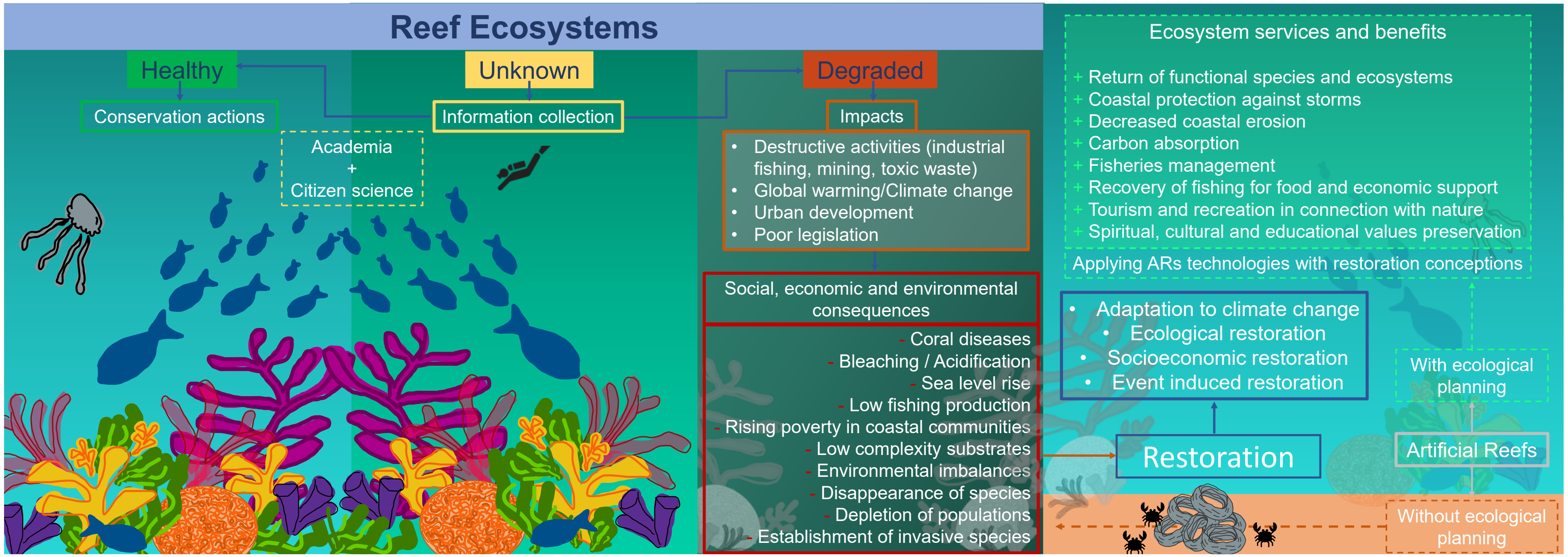
2.5 Conclusion

In Brazil, degraded reef ecosystems require tools that can facilitate: i) active ecological restoration to rehabilitate biodiversity and structural complexity in the degraded environments, ii) mitigation of the impacts of climate change through carbon immobilization, and iii) 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.

Figure 2-1 - Flowchart of considerations for using and managing ARs. (Modified from Goergen et al., 2020).



CAPÍTULO II

RECIFES ARTIFICIAIS AO REDOR DO MUNDO: UMA REVISÃO DO ESTADO DA ARTE E UMA META-ANÁLISE DE SUA EFICÁCIA PARA A RESTAURAÇÃO DE ECOSSISTEMAS MARINHOS

3 CAPÍTULO II – RECIFES ARTIFICIAIS AO REDOR DO MUNDO: UMA REVISÃO DO ESTADO DA ARTE E UMA META-ANÁLISE DE SUA EFICÁCIA PARA A RESTAURAÇÃO DE ECOSSISTEMAS MARINHOS

ARTIFICIAL REEFS AROUND THE WORLD: A REVIEW OF THE STATE OF THE ART AND A META-ANALYSIS OF ITS EFFECTIVENESS FOR THE RESTORATION OF MARINE ECOSYSTEMS [2]

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Abstract: Over the past decade, there has been increasing interest in marine restoration, requiring a consideration of various approaches for optimal success. Artificial reefs (ARs) have been employed for marine restoration and fisheries management, but their effectiveness in restoring ecosystems lacks well-defined ecological criteria and empirical evidence. A systematic review of the literature on ARs articles between 1990–2020, a meta-analysis of their effectiveness based on the similarity of species composition with reference natural reefs (NRs), as well as bias risk analyses were carried out. Research on ARs primarily focused production of marine communities (n = 168). There are important information gaps regarding socioeconomic aspects; design, materials, and disposal in the selected habitats; legal, management, and planning aspects considering long-term monitoring. Regarding effectiveness, few articles (n = 13) allowed comparisons between ARs and NRs, highlighting the need to apply proper reference sites in AR implementations. Meta-analysis showed that

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[2] Bracho-Villavicencio, C.; Matthews-Cascon, H.; Rossi, S. Artificial Reefs around the World: A Review of the State of the Art and a Meta-Analysis of Its Effectiveness for the Restoration of Marine Ecosystems. Environments, v. 10, n. 7:121, 2023. https://doi.org/10.3390/environments10070121

ARs are not similar to reference NRs (p = 0.03, common effect and p = 0.05 random effect models). However, a high index of heterogeneity (88%) suggests that this relation may be influenced by factors other than the reef type. Thus, further analysis can disguise variables conditioning this AR–NR similarity as a measure of restoration for degraded marine ecosystems.

3.1 Introduction

The loss of biodiversity, complexity, and long-living biomass of organisms has been evidenced in marine systems during the last two decades, but has been stressed at an alarming rate of change especially during the last three-four years (WORM et al., 2006) The systematic destruction of complexity due to direct and indirect factors (ROSSI, 2013) brought entire nations and communities to take seriously the regenerative programs at large scale, such as the targets of the Restoration Decade promoted by the UN to enhance the recovery of biodiversity, blue carbon and associated biomass (UNEP; FAO, 2023). As we know, restoration programs are not new, but the upscaling and its feasibility on the long term has become a target that needs a good selection of methods, money, and political commitment (UNEP; CBD; COP, 2012).

Artificial reefs (ARs) are intentionally placed benthic structures intended to protect, enhance or restore components of marine ecosystems (SEAMAN; LINDBERG, 2009), while they can concentrate populations of living marine resources (UNEP, 2009). They have historically been implemented as a strategy to increase the production of species of recreational and commercial interest, receiving more attention since the 1980s (WEST; BUCKLEY; DOTY, 1994).

However, ARs may be also considered an active restoration tool for degraded marine ecosystems that have lost habitat heterogeneity, biomass, diversity, richness, and abundance of marine organisms due to various impacts such as mining, oil and gas extraction, trawling, overfishing and pressure for tourism (GOERGEN, et al., 2020; ROSSI; RIZZO, 2020). In addition, there are incidental or accidental ARs such as anti-drag tools (HACKRADT; FÉLIX-HACKRADT; GARCÍA-CHARTON, 2011), ARs for coastal erosion protection (CLARK; EDWARDS, 1999) tourism pressure mitigation on corals (BROCK, 1994), etc.

Altogether, they can be complementary tools to speed up programs of marine ecosystem restoration (ROSSI; RIZZO, 2020). Nevertheless, ARs were often based on structures that were not designed to meet the specific needs of the biota (ROSSI; RIZZO, 2020). Therefore, several problems have been associated with AR deployments such as attraction and depletion of species stocks with socioeconomic conflicts (GROSSMAN et al.,1997; SMITH et al., 2016)), pollution, and toxicity (ZHANG et al., 2020), changes in species composition with the possible introduction and dispersion of exotic species (MANGELLI; CREED, 2012), and changes in the hydrodynamics of the site (DA SILVA et al., 2020).

In this sense, a great conflict about ARs is evident, there are great contrasts between the theory and its application (LIMA; ZALMON; LOVE, 2019), which gives a questionable position to the use of ARs as a restoration measure by some scientific groups (TZVETKOV et al., 2015). However, it is known that, when implemented correctly, ARs represent a tool that assists in the active restoration of highly degraded reef ecosystems (PAXTON et al., 2020). All this leads us to question ourselves about what causes a successful AR deployment to achieve the necessary restoration of marine ecosystems.

A restoration project aims to re-establish a functioning ecosystem that emulates the reference ecosystem at a comparable ecological age (GANN et al., 2019). When a system is restored, it may be applying silviculture methods (HAMEL et al., 2021), but the idea is not to completely recover the ancient habitat (which is impossible), but to give enough complexity to the habitat to enhance the biodiversity and biomass lost; thus, restoration must have a very long-term vision (UNEP; CBD; COP, 2012). It has to be highlighted, however, that many of the actual plans are not based on an ecosystem engineering approach (RINKEVICH, 2020). A proper assessment of a restoration program should preferably include a BACI (before/after–control/impact) type analysis in which control sites and restored/degraded sites should be compared before and after an impact, in order to verify a change in the intervention site (GOERGEN, et al., 2020). While it is often unpredictable to know if an impacted site has been monitored and has baseline data that allows for a before-and-after comparison, a comparison of control and impacted sites is more often available when evaluating the success of a restoration program.

Furthermore, studies that have hypothesized the success of ARs based on changes in abundance, biomass, diversity, and species richness (AMBROSE; ANDERSON, 1990) could disguise a failed restoration, as their metrics usually identify variations of these metrics but cannot reflect changes in the composition of species, ignoring relevant problems related to ARs such as changes in community structure and invasive species introduction

(MIRANDA et al., 2020). Thus, we would know that a restoration project is successful if the reef's ecosystems intervened by ARs achieved a similar state of the reference "healthy" natural reefs (NRs) in terms of species composition, an approach recently applied through meta-analysis in terrestrial ecosystems, known as the species composition–ecosystem function relationship (CROUZEILLES, et al., 2016; CARRICK e FORSYTHE, 2020).

There are also important gaps regarding ARs characteristics and their implementation, which can be filled by reviewing results from published data and analyzing them for an integral evaluation of the social, economic, and environmental aspects ((ROSSI; RIZZO, 2020; LIMA; ZALMON; LOVE, 2019; SEIXAS et al., 2013).

Although there are some recent systematic reviews on ARs, they focus on the restoration of a limited geographic region (MCLEAN et al., 2015), or they review qualitative measures of effectiveness based on self-reports and other characteristics of AR implementations (VIVIER et al., 2021). Thus, there is no global statement on the application of ARs, or a measurement of effectivity can be biased, once it was not based on quantitative and verifiable results. The aim of the present study is to address a global measurement of AR restoration success in coastal and marine ecosystems, using quantitative contrasted data on species composition between ARs and their reference NRs. In addition, we have compiled a general historical description of the ARs over the past thirty years around the world.

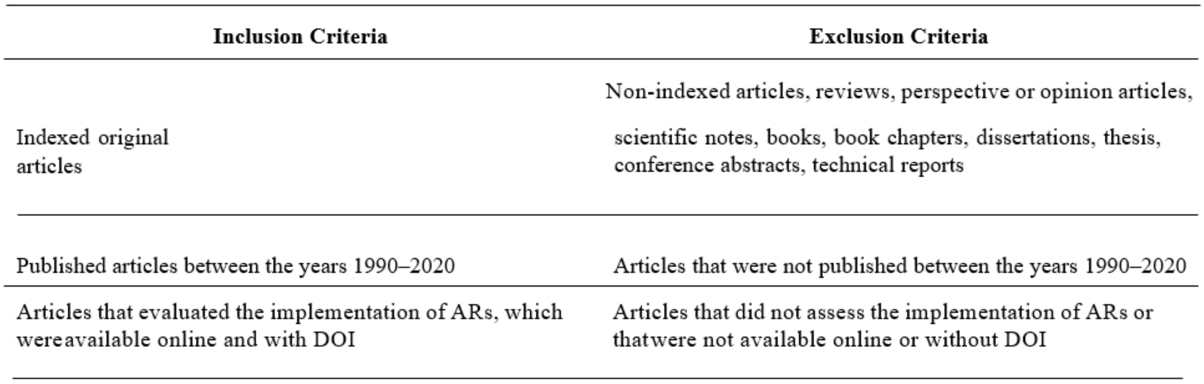
3.2 Materials and Methods

3.2.1 Overview of ARs Deployments around the World

A systematic literature review (SLR) was carried out following the PRISMA Protocol (MOHER et al., 2009) on indexed research articles from 1990 to 2020. The literature search was performed in Scopus® and Web of Science® (WOS) databases using the term "artificial reef" as keywords in the title of the article of any language on 1st March 2020.

We compiled 1265 documents (Figure S1), then studies were selected based on exclusion criteria adapted from (MOHER et al., 2009) (Table 3-1). For the first exclusion criterion, books, theses, dissertations, technical reports, reviews, and opinion articles were excluded, as information in this type of literature is not granted by per-review validation. Second, duplicate indexed articles were excluded and considered as a single document. Third, articles were excluded if the full document was not available online or, after reading the abstract, if the article did not address the implementation of ARs as its main subject.

Table 3-1. Inclusion and exclusion criteria taken into account for the systematic literature review.



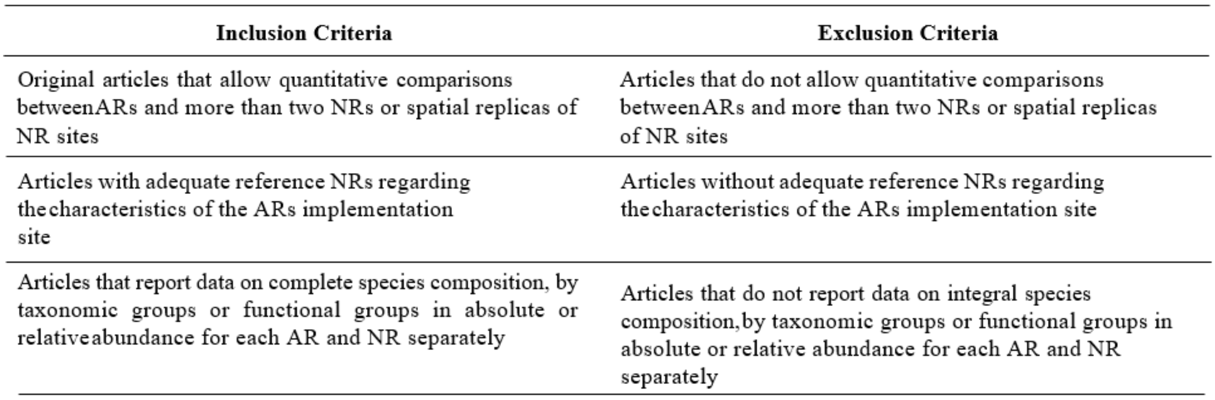
Inclusion Criteria	Exclusion Criteria
Indexed original articles	Non-indexed articles, reviews, perspective or opinion articles, scientific notes, books, book chapters, dissertations, thesis, conference abstracts, technical reports
Published articles between the years 1990–2020	Articles that were not published between the years 1990–2020
Articles that evaluated the implementation of ARs, which wereavailable online and with DOI	Articles that did not assess the implementation of ARs or thatwere not available online or without DOI

Information was extracted from each reference including author's name and year of publication; study title; main theme of the study; newspaper name; financing information; country of publication; and the number of times it was cited. In addition, to describe general aspects of ARs around the world, the articles were classified by: (a) type of AR: primary purpose of structure was or was not an AR, such as accidentally sunk vessels, ports, oil platforms, jetties, wharves, breakwaters; (b) purpose of the AR: purpose of creation reported; (c) material used for AR construction; (d) shape of the AR, (e) type of study: observational or experimental; (f) type of ecosystem: marine, freshwater or estuarine ecosystems; (g) type of substrate: environment on which the AR was installed; (h) ecosystem degradation reported; (i) type of impact; (j) active restoration action taken, when reported: coral transplantation, larval resettlement, gardening, etc.; (k) depth of implantation; (l) area of AR system (km^2); (m) AR module area (m^2) and (l) module weight (kg); (n) distance from the coast (km); (o) exploratory variable evaluated; (p) time of AR implantation (years); (q) time of AR monitoring (months); (r) sampling method; (s) involvement of the community: civil, commercial, scientific and/or governmental entity; (t) within a protected area; (u) restricted fishing; (v) control sites: NRs, non-reef sites or the same site prior to implementation; (w) funding; and (x) country of implementation of the AR.

3.2.2 Restoration Effectiveness in ARs Deployments

Articles that were included for the description of global AR deployment were examined by applying additional exclusion criteria: Articles where AR sites were not compared with reference healthy NRs as appropriate control or reference sites, as well as articles that did not report data by species for ARs and NRs sites separately, and those that did not have an appropriate number of replicates of ARs and NRs sites, were excluded (Table 3-2).

Table 3-2. Inclusion and exclusion criteria taken into account for the meta-analysis.



Inclusion Criteria	**Exclusion Criteria**
Original articles that allow quantitative comparisons betweenARs and more than two NRs or spatial replicas of NR sites	Articles that do not allow quantitative comparisons betweenARs and more than two NRs or spatial replicas of NR sites
Articles with adequate reference NRs regarding thecharacteristics of the ARs implementation site	Articles without adequate reference NRs regarding thecharacteristics of the ARs implementation site
Articles that report data on complete species composition, by taxonomic groups or functional groups in absolute or relativeabundance for each AR and NR separately	Articles that do not report data on integral species composition,by taxonomic groups or functional groups in absolute or relative abundance for each AR and NR separately

In addition, due to the low number of articles that fulfill our criteria, we ran a new SLR following the PRISMA protocol for SLR and a meta-analysis, and population, intervention, control, and outcome (PICO) strategy was performed. We applied the PICO strategy using the string search in the Scopus database on May 2023 as follows: (TITLE (reef) OR TITLE (reefs) AND TITLE (natural) AND TITLE (artificial) AND TITLE-ABS-KEY (species)). The search resulted in 53 articles (Figure S2), to which the same exclusion criteria were applied for screening (Table 3-2).

Metrics for species composition used to calculate the Bray–Curtis similarity index were absolute or relative density, absolute or relative abundance, and proportional frequency of occurrence, among others (FIELD; CLARKE; WARWICK, 1982). Afterward, species composition lists were transcribed for AR and NR sites from studies that met the conditions (Table 3-2). We used the Bray–Curtis index to compare reported species composition similarity between ARs and NRs, due to it having several numerical qualities that make it suitable for comparing species or functional groups composition across ecological communities (FIELD; CLARKE; WARWICK, 1982).

The similarity indices were calculated by making all possible comparisons between all NRs sites within a study as a control. Comparisons between each AR site and NRs were also calculated for each study as intervened. The mean and standard deviation of the similarity indices were calculated for control (similarity between NRs) and for intervened sites (similarity between RNs and ARs). Meta-analysis and bias analysis as funnel plot and

Egger's test were performed in order to ensure the robustness of the meta-analysis using the RStudio software with the "meta" package.

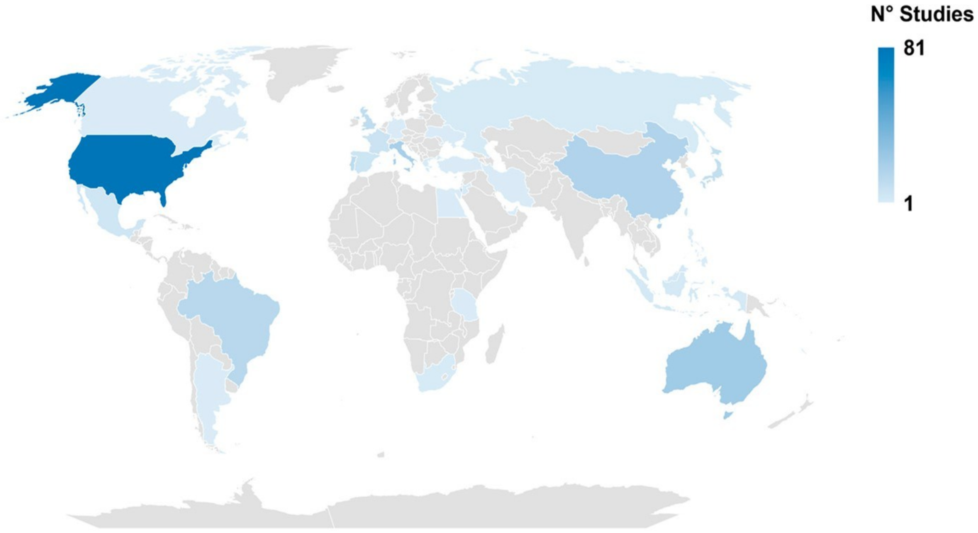
Effect measure values (mean differences) around zero were desired as a successful outcome of the restoration, that is, ARs species compositions achieved were to be similar to those of reference NRs. Negative values should mean that ARs did not achieve the same species composition of reference NRs. Positive values should mean that ARs hold more species than reference NRs, which is probably associated with invasive species presence (CROUZEILLES et al., 2016; CARRICK e FORSYTHE, 2020).

3.3 Results

3.3.1 Research on ARs between 1990 - 2020

From 502 articles screened, 281 articles showed that there was interest in ARs world- wide during the period 1990–2020 around the world, with a particular spike in 1994 and two increases in the years of 1998 and 2002 (Figure S3). Among the pioneer countries, Japan shows up in the implementation of ARs, along with the United States and Italy. In general, the country that led the studies on ARs in the world between 1990–2020 was the United States (*n* = 78), followed by Australia (*n* = 23), Italy (*n* = 24), Israel (*n* = 18), and China (*n* = 17) (Figure 3-1). While the number of surveys is not an identical reflection of the number of AR installations in the world, it does represent the interest of countries in evaluating ARs.

Figure 3-1. Distribution of AR surveys around the world included in the SLR between 1990–2020.



Most of the research (60%, *n* = 168) on ARs included in this review was focused on biomass production (Figure S4), including the association of biological and ecological aspects of species of commercial and food interest with ARs, such as changes in biomass, abundance, richness, species diversity, the effect of ARs on patterns of use, occupation, and the behavior of fish populations and communities, as well as topics related with aquaculture and the attraction–production dilemma.

The production topic was followed by the topics of mitigation/restoration, including transplantation of corals and other invertebrates, larval resettlement of fish and corals, mitigation of habitat loss, by invasive species, by pollution of materials and mining; and effectivity/management with 12%, respectively (*n* = 33). Next, topics of monitoring and impacts represented 4.6% and 5%, respectively (*n* = 13 and 14, Figure S4). Additionally, the type of research that predominated was experimental, particularly during the period of 1990–2010, giving way in the last decade to observational research (Figure S5). The latter was often the report of continued long-term monitoring of implementations cited in previous years within the same period 1990–2020.

Research on ARs over the years 1990–2020 has focused on assessments of marine population and community structure. During the 1990s–2000s, 65% of the studies focused on production in terms of abundance, biomass, and richness of commercial species increases, while 10.6% of the studies evaluated impacts, 8.2% focused on themes of restoration and mitigation, and 7% of the articles evaluated effectiveness and management (Figure 3 - 2). In the following period 2001–2010, interest in production decreased to 60.8%, leading to more interest in studies of mitigation/restoration (12.4%) and effectivity and management (10.3%).

During the 2001–2010 period, studies about impacts decreased to 4%, and a new topic related to the disposition and orientation of ARs was studied. More recently, 2011–2020 period, interest in production-focused studies dropped slightly (54.5%), while interest in effectiveness and management studies grew by 17.2%, as did efforts to restore and mitigation of marine ecosystems (14.1%). There has also been an increase in studies related to the development of monitoring methods; however, it is noteworthy a drop in studies in which ARs are related to environmental impacts, as well the low numbers of studies focused on socioeconomic aspects, abiotic changes, the development of new material technologies.

While production was the most popular topic, this was mainly evaluated using ichthyofauna as the explanatory variable (60%) (Figure 3-2). Studies of ichthyofauna (*n* = 101) were followed by studies that evaluated the fauna in general (*n* = 52), including studies that evaluated infauna, epifauna, and endofauna, as well as microfauna, meiofauna, and macrofauna (Figure 3-3). Twenty-one studies evaluated cnidarians, where corals were the main explanatory variable. Other variables less studied in association with ARs were changes of abiotic factors, socioeconomic aspects, aspects of the ARs, impact indicators such as microplastic and heavy metals, and biotic variables such as aquatic flora, crustaceans, malacofauna, ascidians, plankton, bryozoans, echinoderms, and fungus (Figure 3-3). This highlights the need to diversify research and integrate key aspects in the assessment and management of ARs for restoration programs.

Figure 3-2. Main research topics found in studies of artificial reefs during the last three decades.

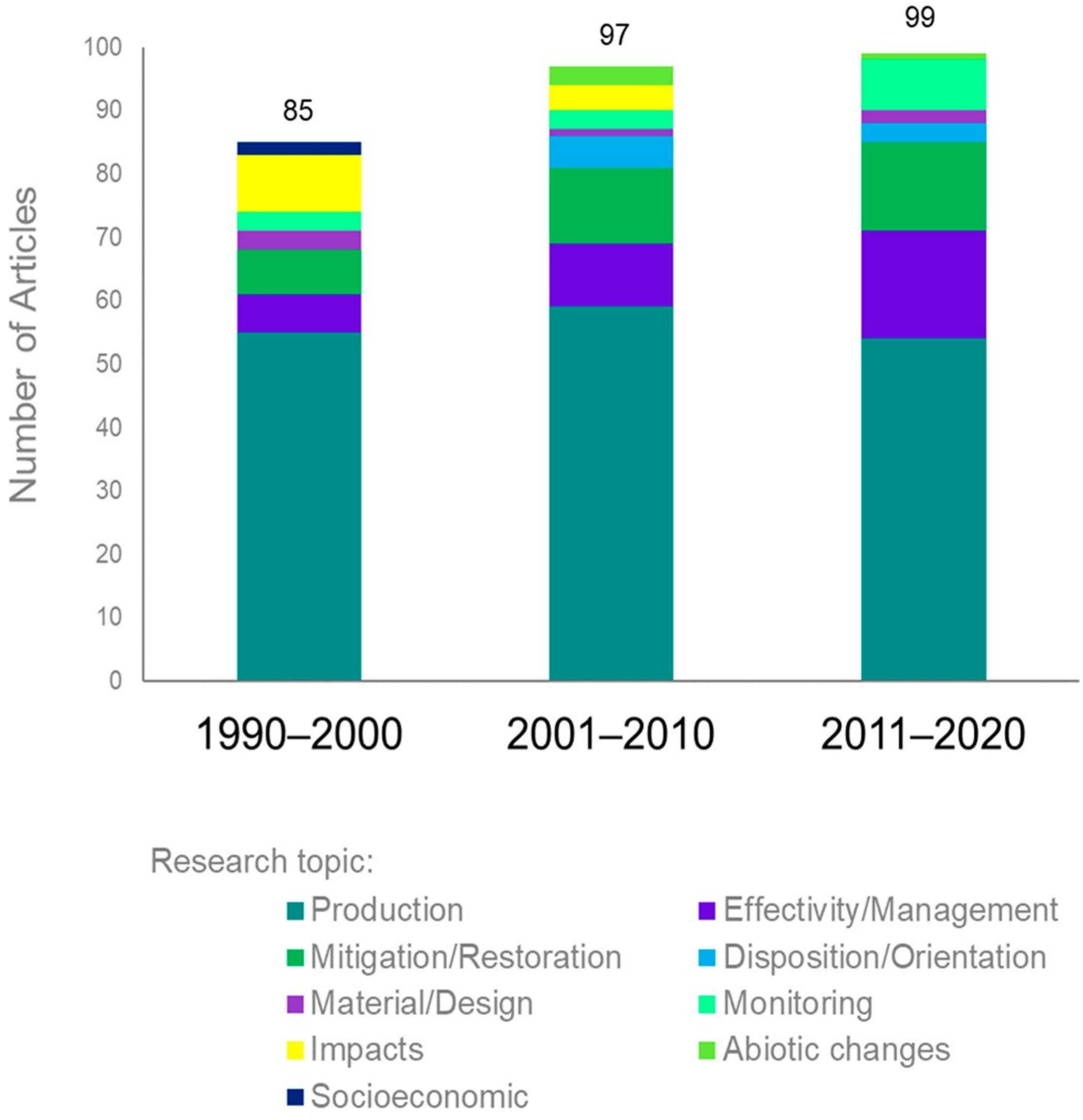
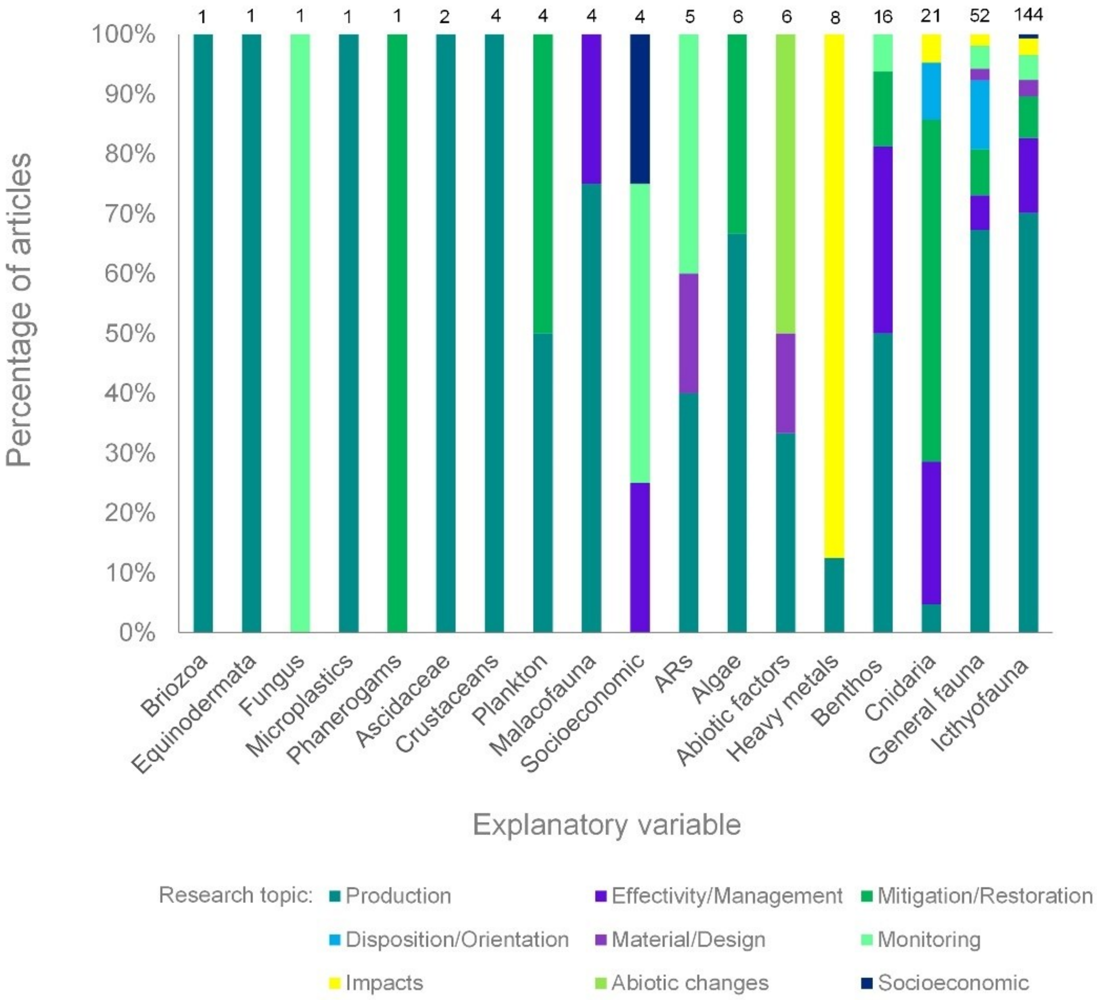
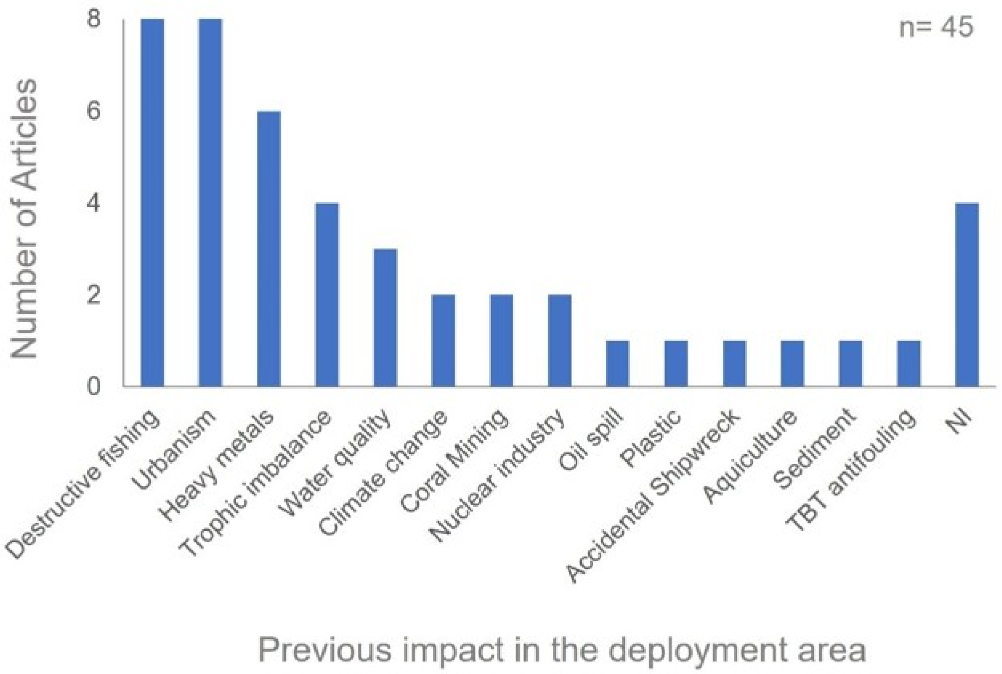


Figure 3-3. Exploratory variables used in studies regarding artificial reefs between 1990–2020.



On the other hand, if ARs will be installed as a restoration measure, it should be declared first which type of previous impact the ARs will restore in the deployment area. However, there is a high number of studies that did not report a previous impact in the deployment area (84%, $n = 236$). Between the 16% of articles describing the impact of the site ($n = 45$), most were related to the fishing sector (17.8%), mentioning trawling, crops, overfishing, and the urban and economic development sector (17.8%). Heavy metals were reported as pollutants from the construction materials of ARs (13.3%), as well as articles evaluating the risk of trophic imbalance, including the introduction of invasive species (9%). Noteworthy is the low frequency of reports of other impacts, no less important for the conservation of reef ecosystems, such as climate change, oil spills, coral mining, plastic pollution, and accidental/incidental sinking of vessels (Figure 3-4).

Figure 3-4. Reported impacts in studies related to ARs during the period of 1990–2020. NI = Studies that declared the site as impacted, but did not specify the impact type or cause of impact.



In addition, the time of deployment of ARs or "AR age", as well as the duration of the monitoring in the studies are important aspects as they can help to understand the evolution of the ecosystems where the ARs are implanted. Most studies had monitoring for up to 2 years, with an important number of articles where ARs were monitored between 1 and 12 months. Monitoring intervals of up to 4 years, 8 years, or more, were less frequent (Figure 3-5). In addition, 22 articles did not inform the monitoring time. Furthermore, most of the studies did not report the ARs age (n = 78). The age of the ARs varied between new structures of 1 month and old structures of more than 100 years, and the latter were mainly shipwrecks (Figure 3-5). There was a considerable number of ARs up to 42 years old; however, older ARs were less frequent in this review.

In addition, the preferred sampling method for monitoring ARs was the visual census (34.5%), followed by manual collection (17.4%), and photos or videos (8%, Figure S6). Methods with more advanced technologies were less frequent, but present from the late 1990s onwards, such as telemetry using ecosonar (n = 16, 5.7%) and remotely operated vehicles (ROV) or baited remote underwater video (BRUV) (n = 15, 5.3%). The collection through gillnet fishing was equally frequent with 14 articles. It is worth mentioning that few articles applied more than one sampling method, and there were 10 articles that omitted information about the data collection method (Figure S6).

Regarding monitoring of ARs, there was also a low consideration of control sites as a reference in the evaluation of ARs (23.5%), that is, almost 80% of the articles (*n* = 213) did not apply at least one control or reference site when monitoring the ARs progress (Figure 3-6). Of those articles that used control sites, 31 used non-reef ecosystems as reference sites, 26 articles applied RNs as reference sites, and 6 used NR and other non-reef ecosystems as reference sites. Another way to assess a change in an ecosystem is to obtain a record prior to the intervention of AR as a control, which was the case of a few articles (*n* = 7).

Most articles applied a single reference site (*n* = 34), and fewer articles used 2 (*n* = 13) or more than 3 reference sites (*n* = 21, Figure 3-6). In addition, only 16 articles reported to study ARs within protected areas, and 6 articles signaled the restriction of fishing in ARs, while 13 evaluated ARs with use for fishing and 268 did not inform the fishing status.

Figure 3-5. Time of deployment and monitoring of ARs in studies between 1990–2020.

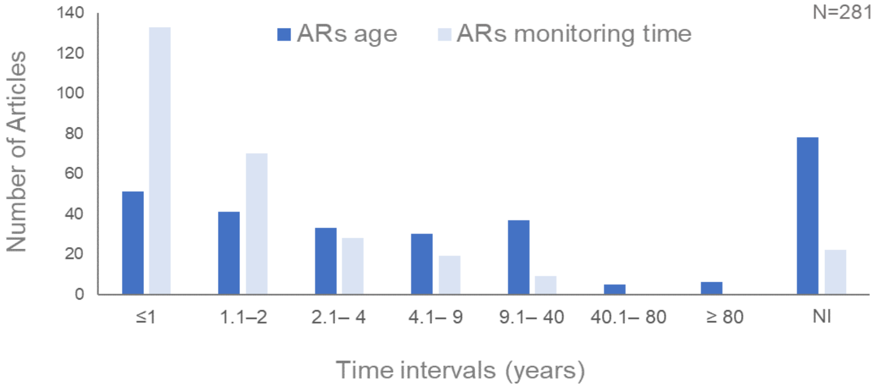
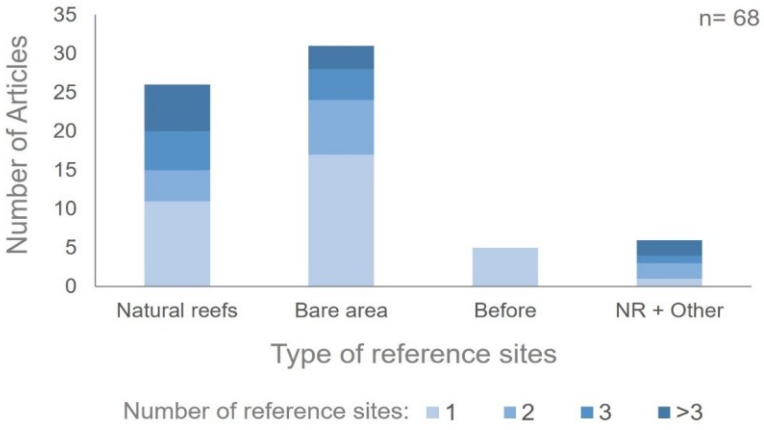


Figure 3-6. Types and number of reference sites taken into account in studies of ARs between 1990–2020



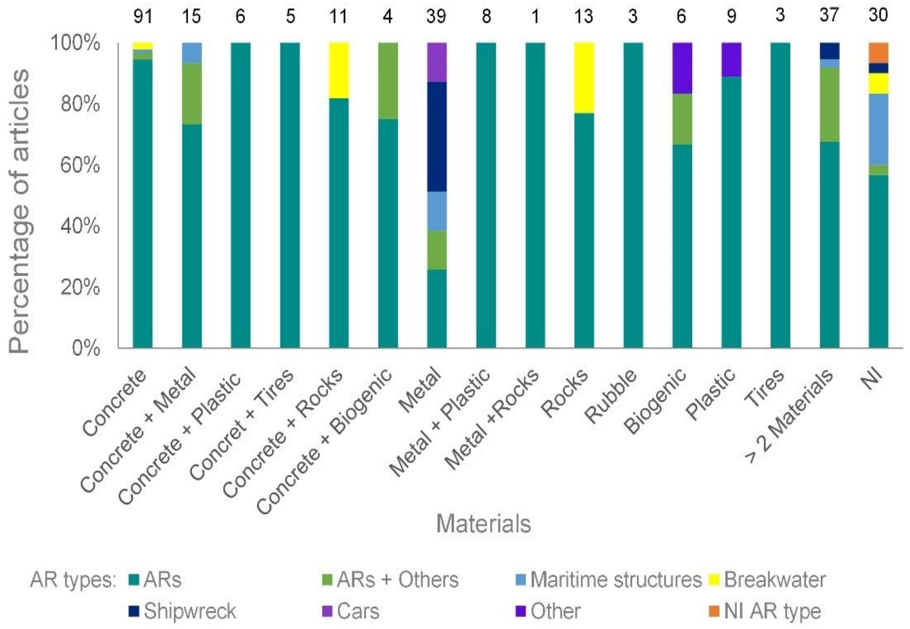
Apart from the authors of the articles evaluated, other members of different communities were involved in the work effort for the development of most of the studies (74.3%) in which was recognized the participation of one or more personalities. In addition, there were few reports of implementations in which the civil community was involved (0.5%), with few exceptions of articles that assessed socioeconomic aspects through interviews with fishermen or administrators of ARs. On the other hand, in addition to the scientific community, commerce/industry and government agencies were among the most involved (9 and 3%, respectively). Other partnerships involving two or more societies represented 32.4% of studies, thus, demonstrating the need for interdisciplinary and logistical support in this type of enterprise (Figure S7).

Likewise, a large number of funded articles (79%), compared to research that did not report funding (21%), demonstrates the almost mandatory requirement for financial support where one or more governmental, scientific, and commercial agencies have invested in research on ARs (Figure S8).

3.3.1.1 Characteristics of ARs in the World

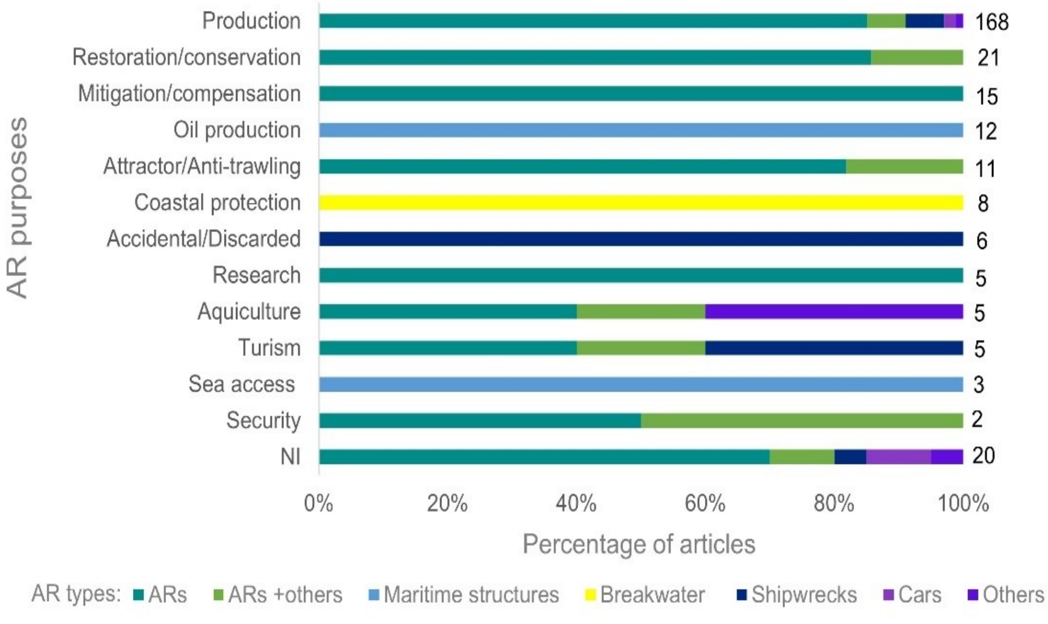
Structures purposely built for the enhancement of marine ecosystems, here called ARs, were most cited (*n* = 209). The largest proportion of these types of ARs was constructed of concrete, rocks, metal, and concrete with metal, and a combination of various materials, although a considerable number did not specify the material used for the ARs studied (*n* = 17). Few articles reported the use of biogenic materials (*n* = 5), such as shells, corals, among others. Structures not intentionally constructed for marine ecosystems enhancement were metallic or wooden vessels sunk deliberately or accidentally, as well as ports, jetties, piers, oil platforms, cars, breakwaters, and dams, which were less frequently reported and whose materials were not always defined (*n* = 13, Figure 3-7).

Figure 3-7. Types and materials of ARs used in studies during the period of 1990–2020.



Although many articles did not directly or indirectly report the purpose for which the AR was created, studies related to ecological or fishery research, evaluating the effect of ARs in promoting, increasing or changing the abundance, diversity or richness of species associated with structures, predominated (*n* = 168, Figure 3-8). These were classified as ARs for production purposes (60%), followed by ARs for restoration or conservation (7.5%), and by ARs for mitigation or compensation (5.3%, Figure 8).

Figure 3-8. Purposes for which ARs were constructed during the period of 1990–2020.

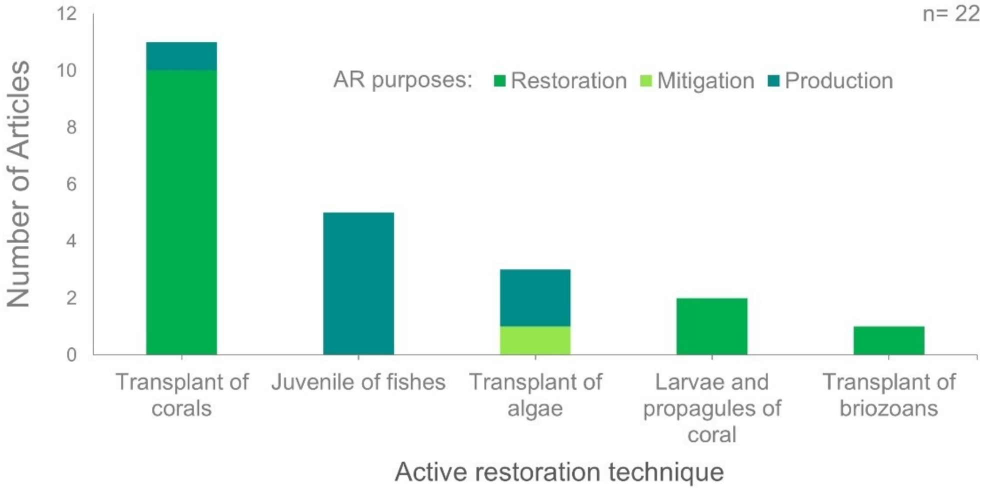


There are some types of ARs that have not been initially created for it. For example, certain structures such as oil platforms, jetties, ports, piers, breakwaters, etc., despite their creation purpose, inevitably excerpt as incidental ARs, as they provide a new immerse surface that serves for marine fauna and flora to colonize. There were also other types of structures, such as vessels whose purpose of creation was transport, however purposely or accidentally sunken, in which the increase in biomass and diversity was sought for commercial, food, or recreational purposes. Thus, structures whose creation was accidental, or for coastal protection, maritime uses, cultivation of organisms, security, conservation, and scientific research, were less frequent (Figure 3-8).

Among the studies that had declared the ARs purpose of restoration and mitigation, some applied supplementary techniques for active restoration such as transplantation of coral, algae, and other taxa, larval and juvenile resettlement, among others (7.8%, *n* = 22, Figure 3-9).

The marine environment was almost exclusive in the use of ARs (*n* = 241); however, there were a few studies citing deployments in estuaries (*n* = 13) and rivers (*n* = 3), and 2 studies as laboratory experiments. The type of bottom, where the structures were installed, was predominantly sand (*n* = 62), muddy sand (*n* = 29), phanerogams (*n* = 13), reef (*n* = 11), or rocky (*n* = 10, Table S1).

Figure 3-9. Active restore support actions during the period of 1990–2020.

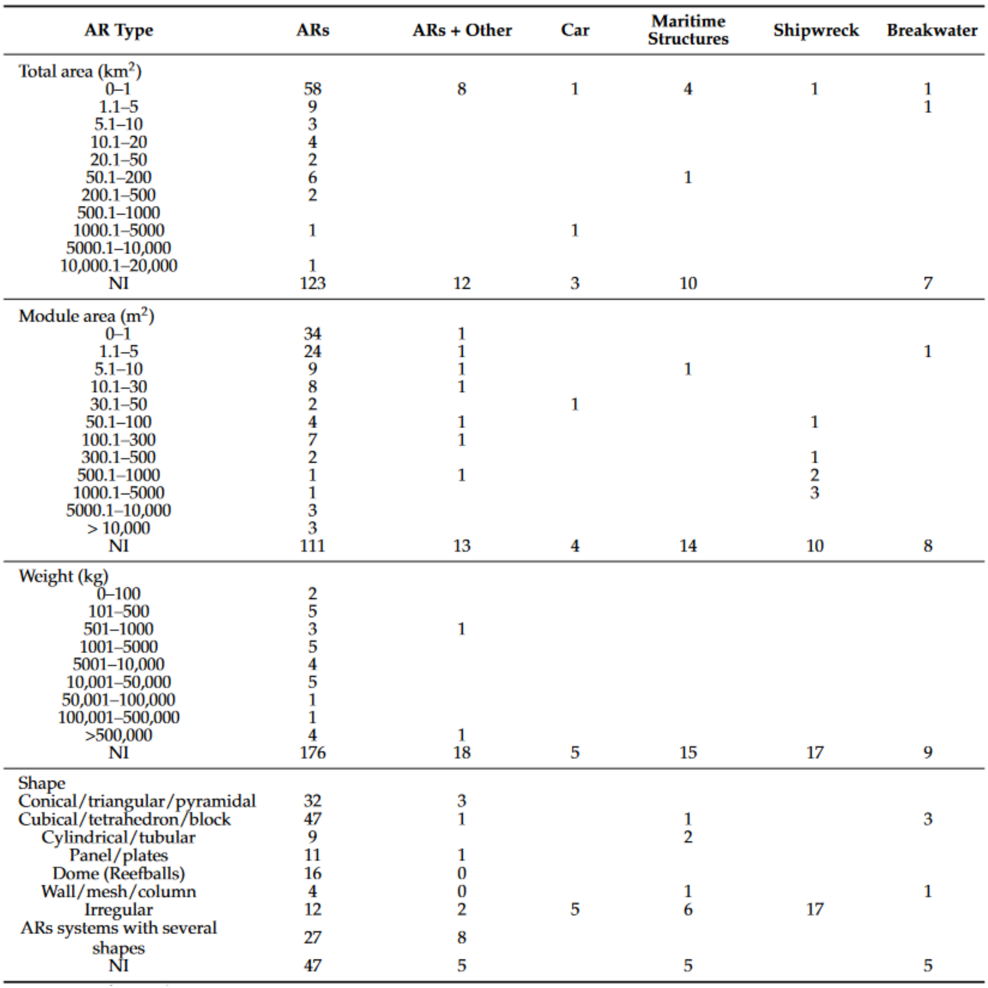


Furthermore, most articles that reported distance from the coast (43%, *n* = 121) show that most structures were located no more than 5 km offshore (*n* = 77), followed by articles whose ARs were between 5 and 10 km (*n* = 19), by those between 11–50 km (*n*

= 17), and those located more than 50 km offshore (*n* = 8). However, there were 160 articles in which this information was not provided. Likewise, the implementation depths also varied between the first 10 m (*n* = 79), as far as 20 m (*n* = 95), 30 m (*n* = 48), 40 m (*n* = 13), and deeper depths up to the 130 m (*n* = 7), and 39 articles did not report the depth where ARs were deployed.

In addition, the size of AR systems, as well as the size of each module, varied and depended on the purpose of their use. Large-scale AR systems were infrequent and usually consisted of various types of ARs including those built with primary and secondary purposes (systems with ARs of various materials, vessels, bridge debris, and cars) as disposal material and/or with a special purpose to promote the production of marine organisms. Medium-scale ARs were also used for production, usually built primarily for that. However, small-scale ARs were mostly used for restoration, mitigation, or scientific purposes.

Table 3-3. Physical characteristics of ARs in studies during the period of 1990–2020.



AR Type	ARs	ARs + Other	Car	Maritime Structures	Shipwreck	Breakwater
Total area (km^2)						
0–1	58	8	1	4	1	1
1.1–5	9					1
5.1–10	3					
10.1–20	4					
20.1–50	2					
50.1–200	6			1		
200.1–500	2					
500.1–1000						
1000.1–5000	1		1			
5000.1–10,000						
10,000.1–20,000	1					
NI	123	12	3	10		7
Module area (m^2)						
0–1	34	1				
1.1–5	24	1				1
5.1–10	9	1		1		
10.1–30	8	1				
30.1–50	2		1			
50.1–100	4	1			1	
100.1–300	7	1				
300.1–500	2				1	
500.1–1000	1	1			2	
1000.1–5000	1				3	
5000.1–10,000	3					
> 10,000	3					
NI	111	13	4	14	10	8
Weight (kg)						
0–100	2					
101–500	5					
501–1000	3	1				
1001–5000	5					
5001–10,000	4					
10,001–50,000	5					
50,001–100,000	1					
100,001–500,000	1					
>500,000	4	1				
NI	176	18	5	15	17	9
Shape						
Conical/triangular/pyramidal	32	3				
Cubical/tetrahedron/block	47	1		1		3
Cylindrical/tubular	9			2		
Panel/plates	11	1				
Dome (Reefballs)	16	0				
Wall/mesh/column	4	0		1		1
Irregular	12	2	5	6	17	
ARs systems with several shapes	27	8				
NI	47	5		5		5

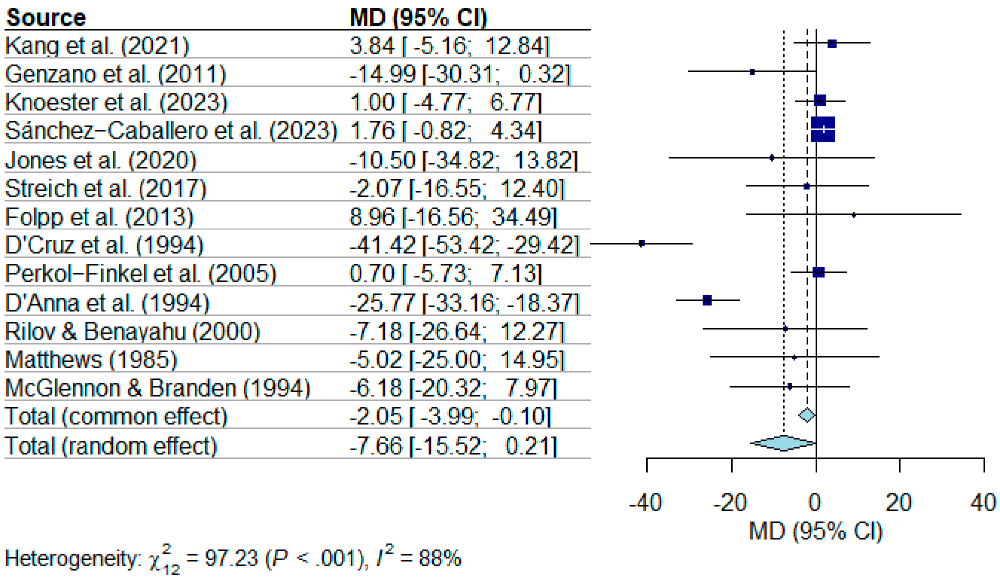
NI – Not Informed

Thus, most AR systems did not exceed the square kilometer, and most modules did not exceed the square meter. However, there were important gaps in this information as many studies did not report it (40%). On the other hand, the shapes of these ARs varied, counting domes (Reefballs), pyramids, tetrahedrons, cubes, blocks, boxes, cones, cylinders, columns, walls, meshes, and panels or plates, with pyramidal and cubic configurations being the most popular between the studies reviewed (Table 3-3).

3.3.2 Effectiveness of ARs Based on Similarity with NRs

Artificial reefs did not achieve the state of NRs, along the 13 studies that fulfilled the inclusion criteria. The species similarity values between ARs and NRs sites were significantly lower than similarity values between reference NRs sites (Figure 3-10).

Figure 3-10. Forest plot of effect size (mean difference) for species similarity between ARs and NRs



Source	MD (95% CI)
Kang et al. (2021)	3.84 [-5.16; 12.84]
Genzano et al. (2011)	-14.99 [-30.31; 0.32]
Knoester et al. (2023)	1.00 [-4.77; 6.77]
Sánchez–Caballero et al. (2023)	1.76 [-0.82; 4.34]
Jones et al. (2020)	-10.50 [-34.82; 13.82]
Streich et al. (2017)	-2.07 [-16.55; 12.40]
Folpp et al. (2013)	8.96 [-16.56; 34.49]
D'Cruz et al. (1994)	-41.42 [-53.42; -29.42]
Perkol–Finkel et al. (2005)	0.70 [-5.73; 7.13]
D'Anna et al. (1994)	-25.77 [-33.16; -18.37]
Rilov & Benayahu (2000)	-7.18 [-26.64; 12.27]
Matthews (1985)	-5.02 [-25.00; 14.95]
McGlennon & Branden (1994)	-6.18 [-20.32; 7.97]
Total (common effect)	-2.05 [-3.99; -0.10]
Total (random effect)	-7.66 [-15.52; 0.21]

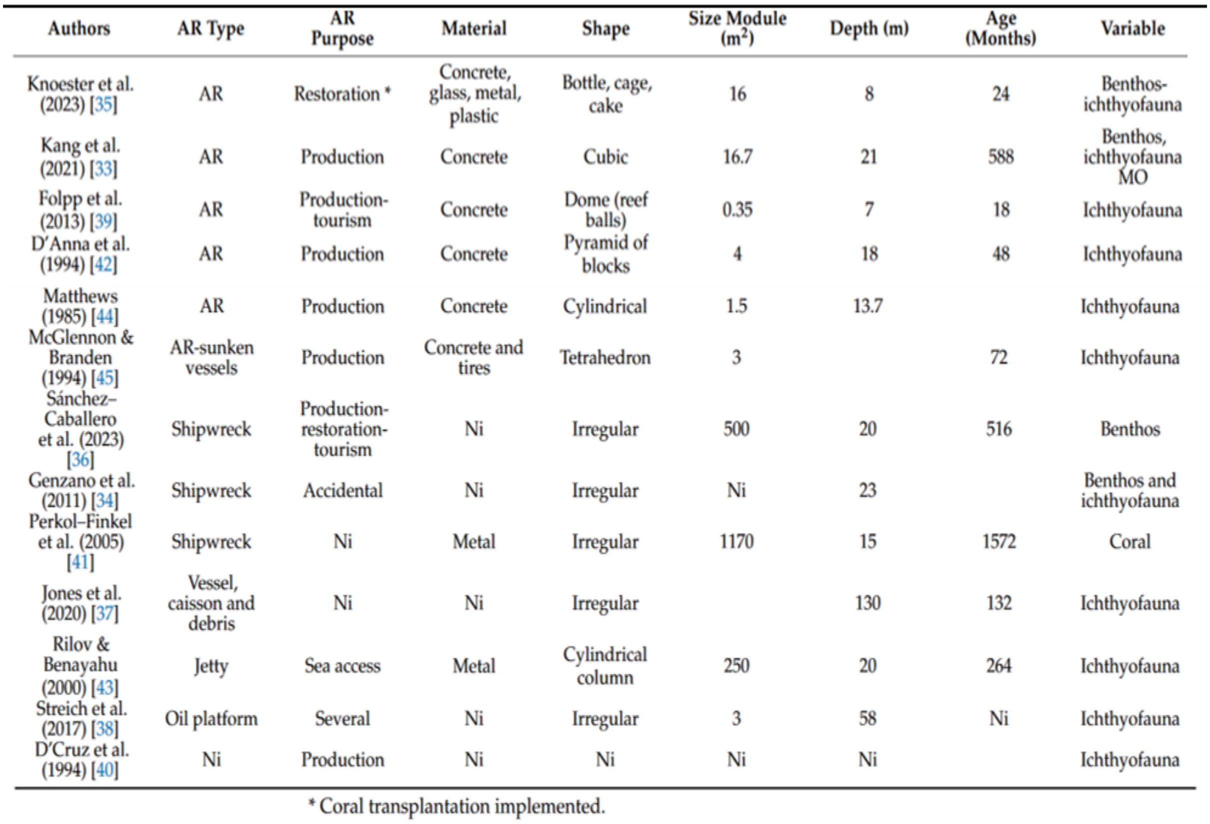
Heterogeneity: $\chi^2_{12} = 97.23$ ($P < .001$), $I^2 = 88\%$

Effect sizes and their 95% confidence intervals are provided for each study. Dark blue square sizes represent the weight of the effect size of each study, and the line width of squares corresponds to the 95% confidence interval limits for the effect size. Light blue diamonds represent the total effect size for species composition for the common effect model (smaller) and random effect model (bigger). Positive effect sizes indicate that species composition is higher on natural than artificial reefs, and a negative value means the opposite. Confidence intervals that overlap the zero line indicate that species composition is not significantly different on ARs vs. NRs.

Despite the total effect measure almost reaching the null effect line (light blue diamonds, Figure 3-10), as few articles supported similar metrics describing species composition between artificial and natural reefs with a considerable weight (KNOESTER et al., 2023; SÁNCHEZ-CABALLERO et al., 2023); D'CRUZ et al.,1994), both common and random effect models showed significant differences (total common effect $p = 0.03$, total random effect $p = 0.05$). This result has proven to be robust enough as the funnel plot shows a consistency in values between articles (Figure S9). Furthermore, aside from detecting a significant heterogeneity ($p < 0.001$, $I^2 = 88\%$), the Egger test confirmed the robustness of the analysis ($p = 0.149$).

Characteristics of ARs in studies included for the meta-analysis also varied in features, as well as deployment characteristics and situations (Table 3-4).

Table 3-4. Conditions of AR deployments in studies included for the meta-analysis on restoration effectiveness.



Authors	AR Type	AR Purpose	Material	Shape	Size Module (m^2)	Depth (m)	Age (Months)	Variable
Knoester et al. (2023) [35]	AR	Restoration *	Concrete, glass, metal, plastic	Bottle, cage, cake	16	8	24	Benthos-ichthyofauna
Kang et al. (2021) [33]	AR	Production	Concrete	Cubic	16.7	21	588	Benthos, ichthyofauna MO
Folpp et al. (2013) [39]	AR	Production-tourism	Concrete	Dome (reef balls)	0.35	7	18	Ichthyofauna
D'Anna et al. (1994) [42]	AR	Production	Concrete	Pyramid of blocks	4	18	48	Ichthyofauna
Matthews (1985) [44]	AR	Production	Concrete	Cylindrical	1.5	13.7		Ichthyofauna
McGlennon & Branden (1994) [45]	AR-sunken vessels	Production	Concrete and tires	Tetrahedron	3		72	Ichthyofauna
Sánchez–Caballero et al. (2023) [36]	Shipwreck	Production-restoration-tourism	Ni	Irregular	500	20	516	Benthos
Genzano et al. (2011) [34]	Shipwreck	Accidental	Ni	Irregular	Ni	23		Benthos and ichthyofauna
Perkol–Finkel et al. (2005) [41]	Shipwreck	Ni	Metal	Irregular	1170	15	1572	Coral
Jones et al. (2020) [37]	Vessel, caisson and debris	Ni	Ni	Irregular		130	132	Ichthyofauna
Rilov & Benayahu (2000) [43]	Jetty	Sea access	Metal	Cylindrical column	250	20	264	Ichthyofauna
Streich et al. (2017) [38]	Oil platform	Several	Ni	Irregular	3	58	Ni	Ichthyofauna
D'Cruz et al. (1994) [40]	Ni	Production	Ni	Ni	Ni	Ni		Ichthyofauna

* Coral transplantation implemented.

3.4 Discussion

3.4.1 Research on ARs in the World in the Last Thirty Years

Artificial reefs have received global attention, particularly with the purpose of increasing the hard surface to be colonized and the associated to the reef biomass of a marine ecosystem, regardless of their conservation status (LIMA; ZALMON; LOVE, 2019). However, geographic regions, such as the equatorial and tropical zone, which have been most affected by the effects of climate change with coral bleaching (HARRISON et al., 2019), showed lower development of this kind of studies.

There was an explosion of ARs especially during the 1990s, where many formats, distributions and materials were tested (BAINE, 2001). The idea during these decades was that ARs may be promoters of hard bottom spaces, and that vagile fauna was especially attracted by such structures (BECKER et al., 2018). However, it was not clear at all if these structures were only attractors or if the vagile organisms could close part or the entire life cycle in the surrounding areas, and the sessile biomass, algae, and especially mega zoobenthos were not clear targets then (BAINE, 2001; ROA-URETA et al., 2019).

Although recent advances have been made in studies of ARs, there are still gaps regarding more elaborate techniques, important to cover the full purpose of ARs (LIMA, ZALMON, LOVE, 2019). It is necessary to develop studies that evaluate the socioeconomic sector, the reef design, materials and disposition, legislation, and planning aspects to consider the management and mitigation of impacts related to ARs, active restoration techniques with long-term monitoring of functional groups and to apply mathematical models that allow the evaluation of ecological, economic and social aspects for ecosystem restoration (ROSSI, RIZZO, 2020; LIMA, ZALMON, LOVE, 2019; BECKER et al., 2018).

Recently the focus on artificial reefs has been driven to enhance the blue carbon and facilitate habitat restoration (ROSSI, 2022). It is clear that ARs per se are not enough, as we need to design not only the morphology, texture, and material of the structures, but also their real functionality in terms of population connectivity, species growth enhancement, or complexity as a true marine forest (UNEP, CBD, COP, 2009; ROSSI, RIZZO, 2020).

Examples of proper AR assessments are infrequent compared to the level of reef development, because monitoring is often an afterthought in AR projects; thus, most reports are not very accurate in terms of evaluating these ARs (SEAMAN, 2000). Only 50% of ARs are successful, and the rest have no, little, or limited success (BAINE, 2001). Monitoring ARs to quantify the effects of their implementation is essential to assess their effectiveness, or to adjust them to achieve their objectives. Quantitative monitoring of biological, socioeconomic, and ecological aspects has already been shown to benefit other types of approaches such as aquaculture-based fisheries (BAINE, 2001). Such information is lacking in most of the analyzed studies.

To measure the success of ARs there must be an estimate that serves as a reference to prove the change caused by the AR in the habitat to restore. For example, control or reference sites are necessary taking into account the situation before and after the intervention. Thus, a BACI (before–after/control–impact) approach would be preferable for ecological monitoring to perceive ecological changes (GOERGEN et al., 2020). Furthermore, effective ARs should be similar to natural reference reefs in functional diversity and ecological processes (i.e., recruitment, species-habitat interactions, trophic interactions), which must also be researched through experimental approaches in order to advance these goals (MILLER, 2002).

The lack of reference data highlights a need for consensus in the application of valid methods to demonstrate the effectiveness and evolution of ARs. Management of ARs must include adequate planning on the use and configuration of materials, site selection, and regulatory control of fisheries. Without long-term planning and management, ARs fail and represent yet another impact that contributes to the further degradation of marine environments (GOERGEN et al., 2020; PICKERING et al., 1998). In addition, sessile organisms, such as gorgonians, corals, algae, bryozoans, etc., which are easier to follow, were not considered in such monitoring programs, although they have an essential role as three-dimensional alive structures that enhance biodiversity and associated biomass (ROSSI et al., 2016).

Furthermore, in the attraction–production dilemma, bigger ARs concentrate biomass leading to an increase in the catchability of stocks. Therefore, trawling, overfishing, and crops were mostly identified as impacts associated with ARs. Local fishermen know this fact, and in many interventions, they were pro-positive (BRACHO-VILLAVICENCIO et al. 2023). Few articles reported the regulation of fisheries at ARs and there is a clear lack of information regarding the real impact on local fisheries. In this sense, fisheries must be regulated at different scales, including semi-industrial and industrial fisheries, particularly in relation to herbivorous species, whose presence directly impacts other trophic levels

(ROA-URETA et al., 2019; ROGERS et al., 2015).

The implementation of ARs comes with a wide range of logistical, political, and social issues as it can incur high costs and is logistically challenging (ROGERS et al., 2015). Joint decision-making, considering economic, cultural aspects, and preferences is essential for the success of these projects. Interdisciplinary programs can contribute to the simplification of logistics, permits, inspection, financing and administration, monitoring, education, and professional training, promoting an identity and sense of belonging to people around (GOERGEN et al., 2020; FLORISSON et al., 2018).

3.4.2 Structural Characteristics of ARs

Among the most important characteristics to be considered in the construction of Ars in tropical coral reef systems are related to the spatial orientation, complexity, and shape of the substrate (PERKOL-FINKEL et al., 2006). Few studies considered testing depths (RULE, SMITH, 2007), vertical or horizontal orientations (SAMMARCO et al., 2014), floating or fixed dispositions (PERKOL-FINKEL et al., 2008), or distances between NRs and ARs (ZALMON et al., 2014) on faunal colonization, aspects that could determine the first stages of settlement, colonization, and successional processes in the ARs. Controlling the above-mentioned aspects combined with a site selection for installation must mitigate the problem of species introduction. Non-native species are commonly associated with ports and oil platforms, as their dispersal mechanisms can be through the fouling attached to ships, ballast water, and fouling on oil platforms (CREED, PAULA, 2007). Therefore, the disposal of the ARs must avoid the sea currents that come from this type of installation, since they probably come loaded with larvae of foreign species, and the presence of the AR would facilitate this type of environmental impact.

Moreover, ARs can be made from waste materials to specific structures since, originally, almost any hard substrate that had been submerged in the sea could be called an AR (MILLER, 2002). Consequently, much of the accumulated knowledge about ARs has been empirically constructed, with materials that may not currently be considered the best option in environmental terms (ROSSI, RIZZO, 2020), such as tires, leftover material from civil construction, remains of vessels, entire ships, and oil platforms, decommissioned and sunk without proper maintenance, etc.

Some programs such as “rigs-to-reefs” gained value in some countries, due to the reef communities that were established over time when these accidental or incidental structures were submerged, which originally were oil platforms, discarded ships, etc. Potential negative impacts of this program include physical damage to existing benthic habitats within the “fall zone”, unwanted changes in marine food webs, facilitation of species invasions, and release of contaminants as platforms erode (MACREADIE et al. 2011). Thus, a great concern arises among scientists about an undiscriminating way of using ARs implementations. As well as us, some scientists emphasize the study and deepening of the knowledge of the ARs already installed and the development of technologies that allow for marine ecosystems to be restored, avoiding new impacts, before continuing to implement non-functional and even more impacting ARs (MIRANDA et al., 2020; ROGERS et al., 2015).

Artificial reefs do not represent the only solution for damage to marine and coastal ecosystems. They are one of several management tools available, which, when properly managed, promote the improvement of habitats and biological productivity (PAXTON et al., 2020; PICKERING et al., 1998). The use of concrete ARs in coral transplants (POLAK, NASHAR, 2012) and plastic sheets in the resettlement of coral larvae (SUZUKI et al., 2011), are a clear example of the use of these structures as active restoration tools. In places of great recreational activity, ARs appear as an alternative to diminishing human pressure in natural environments where visitation, sport fishing, and diving cause potential damage to RNs (ROSSI, RIZZO, 2020; SUTTON, BUSHNELL, 2007). It is clear that the paradigm of these structures has to change to be much more efficient and in line with the real habitat needs in the zones where they may be implemented.

New studies are now bringing other potential textures, materials, and morphologies that emulate natural substrates (ROSSI, RIZZO, 2020), enhancing the settlement of vagile or sessile organisms depending on the silviculture paths that want to be promoted (HOROSZOWSKI-FRIDMAN, RINCKECICH (2016). There were some attempts to improve materials for impact mitigation, testing different mixtures of materials for concrete, either in cost reduction (SHU-TE et al., 1995; PONTI et al., 2015), and mitigation of heavy metals when waste materials reused (COLLINS et al., 1994).

Some techniques manage to reproduce the specific material the properties of reef ecosystems from low voltage mineral deposition technology (LVMD) (MARGHERITINI et al., 2021). Although applying it at a large scale may be more difficult than other methods (RINKEVICH, 2020), the need for techniques to mitigate the effects of climate change, such as sea level rise coastal protection, increasing carbon sequestration capacity, etc. (ROSSI, RIZZO, 2020; ROSSI, 2022), are needs becoming more evident in today’s world. ARs could act as facilitators of organisms that work as carbon immobilization species, as the sessile fauna that grows on their structures (sponges, corals, macroalgae, among others) sequester part of the CO_2 to build their hard three-dimensional organic or calcium carbonate ($CaCO_3$) structures, making them key ecosystems for mitigating the effects of climate change (ROSSI, RIZZO, 2020; ROSSI et al. 2016; SHAVER, SILLIMAN, 2017).

Some more specific conditions that ARs should fulfill include imitating the natural out- crop of rocky bottoms present in the target areas, having structural characteristics focused on the settlement of corals, gorgonians, and sponges, having cavities of different sizes and shapes to increase the presence of motile species (i.e., fish, mollusks and crustaceans), as well as being designed to capture CO_2, through the surface porosity of their own concrete structures, during the process known as carbonation (ROSSI, RIZZO, 2020).

Other approaches have been applied in the restoration of coral reef ecosystems, such as transplantation or repopulation by fragmenting corals or nubbins (OREN, BENAYAHU, 1997); positive interactions between species (SHAVER, SILLIMAN, 2017); floating reefs (PERKOL-FINKEL et al., 2008); acoustic enrichment (GORDON et al., 2019), integrated multitrophic aquaculture (XU et al., 2017; GIANGRANDE et al., 2021), among others.

All this suggests that the combination of active restoration methods including ARs can be the way to recover reef ecosystems that come to resemble conserved natural reefs, which can be called symbiotic artificial reefs (SAR). The implementation of artificial reefs to restore marine ecosystems can be well done, investing resources in studies specifically aimed at determining the appropriate characteristics of ARs for each location (SEAMAN, 2007). ARs should be considered strategically based on scientific assessments of specific location and resource needs to maximize the benefits of improving these habitats (PAXTON, et al., 2020), with an emphasis on their use in the restoration of marine and coastal ecosystems (ROSSI, RIZZO, 2020).

3.4.3 Effectiveness of Artificial Reefs

Several authors have observed similarities between RNs and ARs in terms of abundance, biomass, and species richness, with some inconsistencies at geographical levels (PAXTON, et al., 2020; HUNTER, SAYER, 2009). Nevertheless, as mentioned before, the species composition index would be preferable to avoid biased conclusions on effectivity. Assessments of the effect of in- stalling ARs for restoration with veridically comparable and adequate reference sites are limited. Few studies have applied ARs for the restoration of highly degraded-declared ecosystems, while monitored by compared with NRs or equivalents (i.e., rocky ecosystems), in a good state of conservation, so that they serve as a comparison with the implementation site/restoration. However, most ARs deployments had little or limited ecological data available, which difficult for an integrated stock assessment (ROA-URETA et al., 2019).

Although there is a great lack of data availability, we tested that ARs harbor fewer species than NRs. On one hand, ARs did not resemble the reference NRs, that is, they did not achieve the restoration state, although studies included in the meta-analysis had a mean age of 30 years since deployment (n = 9), so it would be expected that ARs had reached a steady state at that point. On the other hand, ARs had fewer species than NRs of reference means less probability of the presence of invasive species, as they are globally related to AR structures (MIRANDA et al., 2020; CREED, PAULA, 2007), which represents a relevant problem in order to avoid trophic imbalance in already degraded ecosystems.

Among the studies that contributed in a greater measure to a null effect size or restoration state (KNOESTER et al., 2023; SÁNCHEZ-CABALLERO et al., 2023; PERKOL-FINKEL et al., 2005), two of them evaluated shipwrecks ARs of 500 and 1170 m^2 of area, at 20 and 15 m of depth in substrates with rock or reef with sand. They were also two of the older ARs with 43 and 131 years of deployment at the study execution time, and 10 and 1 month of monitoring, being the taxa analyzed benthos and coral species. Additionally, these studies reported impacts in the deployment area related with climate change effects and anthropogenic impacts, mostly related with trawling fishing and other destructive fishing methods, and with trophic imbalance. Furthermore, the study with more weight regarding replicates and sampling effort (PERKOL-FINKEL, BENAYAHU, 2005) compared ARs and NRs regarding coral species, thus species composition similarity is more achievable comparing species of a unique taxon than several (i.e., benthos).

However, in Knoester et al. (2023), ARs sites achieved restoration success in a shorter time, compared to their reference NRs (mean difference near the line of null effect, MD = 1, Figure 10). Using ARs intentionally made of concrete, with a combination of other materials such as glass, metal, and plastic, and applying an additional active restoration technique, such as coral transplantation (KNOESTER et al., 2023), this study made a big difference in terms of the state of restoration of the ecosystem and the speed of it, comparing to those studies that did not apply it, since it achieved the reference NRs state at two years of monitoring (KNOESTER et al., 2023). Thus, the development of intentionally made ARs that achieve a restoration state comparable with natural reefs of reference in a few years is desirable for restoration program implementations, instead of accidental or incidental ARs that make it in several decades.

Furthermore, the restoration success of degraded ecosystems will have local needs related to the ecosystem itself, the impact type and cause of the impact, potential key species available to restore the degraded ecosystem, conflicts of use, etc., this is, ARs deployments must be site specific for each case. In addition, a high index of heterogeneity (88%) suggests that this relation may be influenced by factors other than the reef type. Thus, we suggest further analysis to investigate variables conditioning this AR–NR similarity as a measure of restoration for degraded marine ecosystems. Moreover, further studies must evaluate ecosystems' responses to ARs deployment from a restoration perspective, while concealing social and economic frameworks.

We call the attention of researchers in this area to carry out adequate experimental studies and allow the accessibility of data to evaluate and improve the efficiency of ARs in the restoration of degraded marine and coastal ecosystems. This is important as marine ecosystems harbor an immense diversity of habitats and life forms, as well as they are responsible for providing resources and environmental and economic services essential to human survival, such as food and habitat supply, especially for coastal communities (NAS, 2019). Efforts to conserve these ecosystems are insufficient measures that must be complemented with an understanding of ecological processes to carry out actions of restoration, given the extent and rapid rate of human impacts (ROSSI, RIZZO, 2020). For example, ARs serve as corridors for marine organisms moving poleward and deep ward due to global warming effects in a possible tropicalization process across marine-coastal ecosystems while they can enhance local abundance and biomass of species at range edges (PAXTON et al., 2019).

Restoration of marine ecosystems, including active methods, is foolproof to promote the natural recruitment and survival of species of interest, the return of ecosystem structure and function, and the improvement of abiotic processes that shape the community, given the high degree of current degradation, especially in reef ecosystems as a result of climate change (GANN et al., 2019). The application of new methods of ARs implementation in coastal and offshore areas may be as well the key to fostering habitat restoration, but it has to be made with an articulate, realistic, and upscaled plan that individuates strengths and weaknesses of such protocols, making an accurate study of local regeneration needs and limitations.

CAPÍTULO III

COLONIZAÇÃO BÊNTÔNICA EM NOVOS MATERIAIS PARA RESTAURAÇÃO DE ECOSSISTEMAS MARINHOS EM PORTO CESÁREO, ITÁLIA

4 CAPÍTULO III – COLONIZAÇÃO BÊNTÔNICA EM NOVOS MATERIAIS PARA RESTAURAÇÃO DE ECOSSISTEMAS MARINHOS EM PORTO CESÁREO, ITÁLIA

BENTHIC COLONIZATION ON NEW MATERIALS FOR MARINE ECOSYSTEM RESTORATION IN PORTO CESAREO, ITALY[3]

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Abstract

Artificial structures seeking to mimic natural hard substrates can be employed as a tool for the restoration of marine ecosystems, although we need further studies to evaluate different materials for the habitats to be restored. Biochar and bioferment are materials of organic origin, known for make nutrients available, while degrading pollutants, and reducing the risk of pathogens in terrestrial ecosystems. We tested the efficacy of these materials with restoration purposes through experimental tiles consisting in Biochar (B), Bioferment (F), and tiles made of concrete which were used as controls (Ct) for the colonization of marine organisms in the marine protected area of Porto Cesareo, Southern Italy. Tiles were monitored

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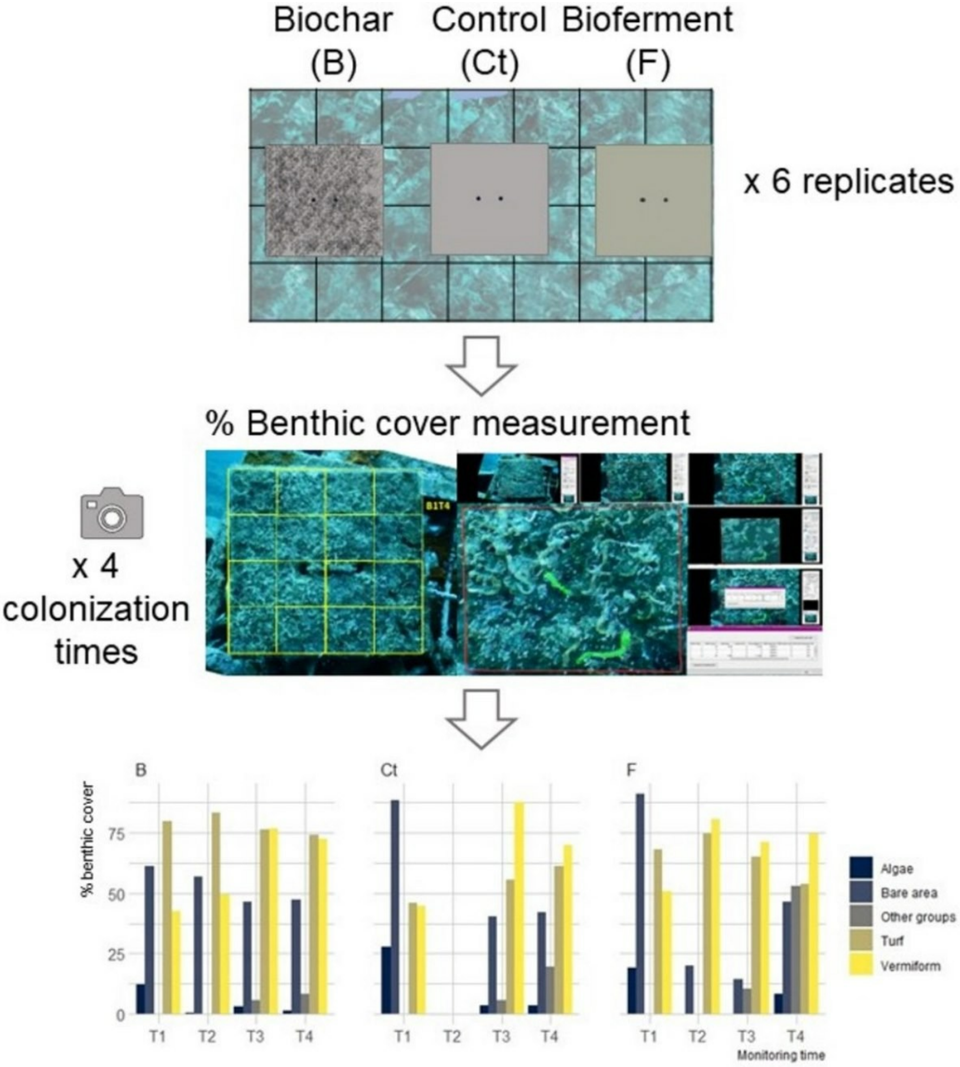
[3] Bracho-Villavicencio, C.; Matthews-Cascon, H.; García-Durán, M.; Vélez, X.; Lago, N.; Busquier, L.; Rossi, S. Benthic Colonization on New Materials for Marine Ecosystem Restoration in Porto Cesareo, Italy. Journal of Marine Science and Engineering, v. 12, n. 1:169. https://doi.org/10.3390/jmse12010169

throughout photographs from October 2019 to September 2021, and the colonization process analyzed using the software Photoquad. Univariate and multivariate permuted analyses of variance (PERMANOVA) were performed using the function Adonis2 from package vegan. During the first period, biochar treatment presented higher total benthic cover (81.23±2.76, median±SE), differing from bioferment and control tiles (45.65±5.43 and 47.95±3.69, respectively). Significant interaction between treatments and times, suggest changes in community structure related to materials and time. Furthermore, underwater instability of bioferment on the tiles could explain the similarity with control tiles in marine organisms cover. Hence, biochar shows to be a material with optimal stability in seawater, while demonstrating greater capacity for marine organisms colonization in less time compared to other materials, which is a pursued target in marine restoration programs.

Graphical Abstract



4.1 Introduction

With around 40% of the world's population living in coastal zones, marine ecosystems are responsible for providing environmental, cultural and economic goods and services that are essential for human survival (UN 2017). Nevertheless, the indiscriminate and increasing use of natural resources, together with the increase in human population density, affect coastal and marine ecosystems with the loss of habitats and species richness (Rossi 2013, Portugal et al. 2016). Porto Cesareo is a multiple-use marine protected area (MPA), which includes areas of relevant conservation value, however the enhancement of human activities has led to the degradation of the quality of the environmental (Semprucci et al. 2018), thus improvement of tools that allow the restoration of marine and coastal ecosystems needs to be addressed in order to mitigate these impacts.

Artificial structures can be employed as a tool for the restoration of marine ecosystems, seeking to mimic natural hard substrates and creating underwater gardens covered with typical species found within confined environments, such as filter feeder polychaetas, sponges, and ascidians (Rossi and Rizzo 2020, Giangrade et al. 2021). Still, the interest in artificial reefs also leads to possible negative impacts by the use of unsuitable materials (Giangrande et al. 2021).

In general, it is assumed that the type of material will determine the development of the benthic community (Burt et al. 2009). In this sense, the selection of materials for artificial structures for marine ecosystems restoration must involve environmental and ethical considerations (Leonard et al. 2022), as well as ecological requirements of the biological community, alongside economic, logistic and engineering factors (Dodds et al. 2022). Although guidelines have been developed to support the placement of artificial reefs in European seas (Giangrande et al. 2021), further studies are needed to evaluate the specificity of material needs for each locality to be restored.

On this basis, Biochar is a material that valorizes biomass residues (i.e., solid product of biomass pyrolysis) while it has environmental benefits, such as climate change mitigation for its potential for carbon sequestration and the reduction nutrient leaching (Campion et al. 2023). Biochar is commonly used as a bioremediatory component in agriculture soils, and recently as an admixture to cement, used in construction with excellent mechanical, electrical, thermal, and chemical stability (Laili et al. 2016, Cui et al. 2022). This material has been applied mainly in terrestrial ecosystem remediation, immobilizing of solidified radioactive waste when submerged (Laili et al. 2016), immobilizing heavy metals for soil remediation (Ji et al. 2022) and in construction for absorbing electromagnetic waves (Khushnood et al. 2015). Few studies have evaluated the performance of biochar material on marine sediments remediation (Dong et al. 2017, Hung et al. 2020, Wang et al. 2022, Kumar et al. 2023). However, biochar has not been tested on the colonization of marine organisms, particularly, with restoration purposes during early first stages of succession, which can reflect the ecosystem dynamics and anticipated changes over time (Gann et al. 2019), and due to the interest in the velocity of the restoration action on the degraded ecosystem.

Furthermore, it is known that microorganisms in ferments can help with the degradation process of solid organic waste (Rafikova et al. 2021), as well with the degradation of pollutants in terrestrial and marine environments (Colwell & Walker 1977, Udebuani et al. 2012). The process implies three principal benefits: i) the elements decomposition of the organic matter used for fermentation turning them into available nutrients, ii) the remediation of the substrate, and iii) the reduction of pathogenic microbiota and phytotoxicity by the action of some bacteria in ferments (Rafikova et al. 2021). In addition, animal manure, among which cow manure, make available large amounts of solid organic waste due to a great demand of livestock production that provides food for the human population, working as raw material for the production of bioferments (Rafikova et al. 2021). Thus, bioferment production from cow manure could assist for several purposes from recycling organic solid waste (Yang et al. 2023), to bioremediation through disintegration of hydrocarbon and plastic pollutants (Colwell & Walker 1977, Rafikova et al. 2021, Cifuentes and Basak, 2021), production of bio-hydrogen (Hosseinkhani et al. 2014), and as antimicrobial component (Kumar et al. 2020).

In this study, we hypothesize that the qualities of biochar and bioferment materials may assist in marine organism colonization in terms of diversity and abundance as it should make available nutrients, while degrading possible toxicities of materials used for artificial structures such as concrete, and reducing the risk of pathogens for marine organisms. Hence, different materials might influence the structure of marine organisms colonizing. In order to test this, we assessed benthic community development on biochar and bioferment materials, compared with concrete material as control, with restoration purposes in Porto Cesareo.

4.2 Methodology

4.2.1 Study area

The Porto Cesareo is a MPA established in 1997 (40◦15′ N–18◦53′ E). It is located along the Ionian Sea coast (Apulia, Southern Italy), between Torre Colimena and Torre dell'Inserraglio, facing the village of Porto Cesareo. It extends for about 18,000 m along the Porto Cesareo coastline and 6,000 m along the Nardò coastline, occupying 17,156 ha at sea (Sandulli et al. 2011). The area has moderate human impact due to a relevant increase of human population since 1991 and to the high touristic pressure (Semprucci et al. 2018).

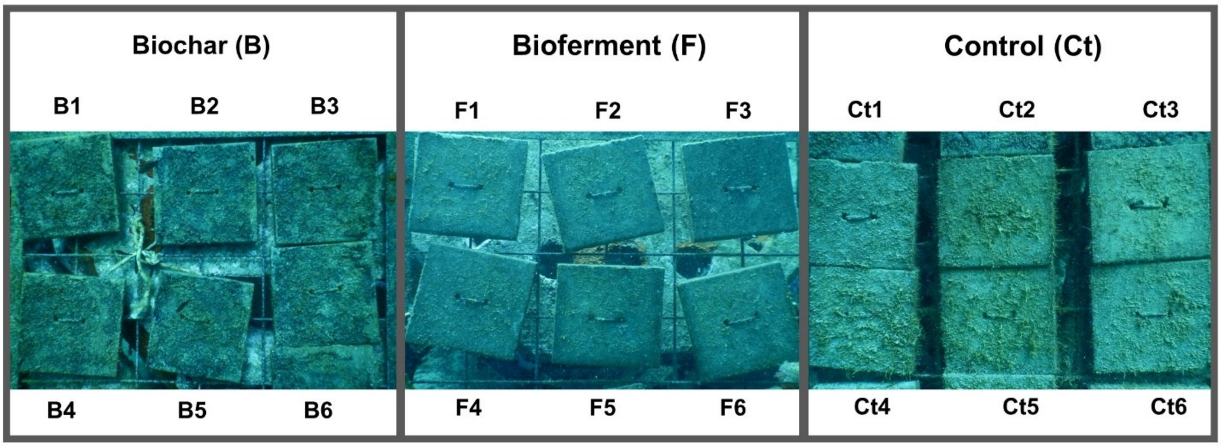
The substrate of the study area is mainly composed by coarse sand, although it has coralligenous formations with algal dominance (Correira et al. 2004, Semprucci et al. 2018). The temperature ranges from 15 to 30 °C, with a peak of high temperatures between May and July and lower temperatures between December and March (Pisticelli et al. 2011). Although been a marine protected area, the study area is dominated by colonizers life strategy organisms with low meiobenthic taxa richness (copepods and annelids), which indicate an immature stage of the community, commonly due to intervened or impacted ecosystems (Bongers et al. 1995, Semprucci et al. 2018).

4.2.2 Experimental design and Construction

The construction of the tiles for the Biochar treatment involved mixing biochar with commercial cement (Portland cement) and sand at a ratio of 1:1:4. The composition was mixed, blended, and controlled at 25° for 3 days, then molded and dried. The Bioferment treatment consisted of a liquid mixture, resulting in a process of decomposition and fermentation in the absence of oxygen (anaerobic) from organic vegetable and animal residues (straw and crop residues). Contains nutrients of high nutritional value (ammonia, nitrogen, hormones, vitamins, and amino acids). Its production is a relatively simple and low-cost process, as the preparation inputs are local, although its elaboration takes a period of two to three months. It was applied in layers after the activation of the Bioferment mixture, which consists of mixing the Bioferment liquid for 30 min and applying it to concrete tiles before their submersion.

We tested the efficacy of different material types for the colonization of marine organisms. Experimental tiles of 20 cm × 20 cm, consisting of Biochar treatment (identified as B), Bioferment treatment (identified as F), and control tiles (identified as Ct), were submerged for macrofauna colonization. Six replicates (six tiles) of each material, from now on mentioned as treatments and control tiles, were deployed attached to a frame in an artificial reef (Figure 1) located in Zone A of the integral reserve (zone A corresponds to the maritime space parallel to the coast between the geographic points 40°14′39.59″ N, 17°53′26.41″ E, and 40°14′8.99″ N, 17°54′13.21″ E). On vertical surfaces, abiotic factors may be more important for structuring community settlement (Duran et al. 2018). Hence, all tiles were deployed in similar conditions: at 20 m depth, in vertical orientation, and at the same angle to the currents. The tiles of each treatment were deployed close to each other to facilitate identification during sampling.

Figure 4-1. Experimental design of different material tiles. Codes corresponds to replicates for each material type.



4.2.3 Data collection and processing

Tiles were monitored throughout photographs from October 2019 in 4-5 months period, except the last sampling (September 2021), which was 14 months after due to COVID-19. The photographs were taken by expert divers, taking into account the same distance and angle for each sampling photograph. Control tiles were not photographed during the second monitoring time due to logistic issues.

To measure the percentage cover of major taxon groups, the images of colonized tiles were subdivided in 16 equal parts, and four subdivisions were randomly selected for each sampling time. Two tiles of the treatment of Bioferment (F) were lost at the second time of monitoring. A total of 240 replicates of photographs of colonized tiles were analyzed using the software *Photoquad* (Trygonis & Sini 2012). The measure of benthic groups cover in subdivisions was made using a layer-based analysis with a grid of 144 cells of 12 pixels, combined with a multiscale image segmentation with visual correction (Figure S1).

The main benthic groups, including macroinvertebrates and macroalgae, were analyzed in terms of percentage of cover and Shannon diversity index for each material among the four monitoring times. Less frequent benthic groups were summarized as “other groups” and included members of porifera, cnidaria, and other colonial species that were not possible to visually identify from images (Figure S2).

4.2.4 Data analysis

To test differences in the cover and diversity of major benthic groups among the materials, monitoring times and their interaction, univariate and multivariate permuted analyses of variance (PERMANOVA) of 999 permutations, with Euclidean and Bray Curtis distance matrices, respectively, were performed using the function Adonis2 from package vegan. Factors included in the analysis were treatments of materials and control with 3 levels of variation (B, F and Ct) and monitoring times with four levels of variation at 4th, 8th, 13th and 27th months of colonization time (T1, T2, T3 and T4 monitoring times). To assess significant differences from PERMANOVA test, the heterogeneity of data dispersion was tested on major taxon cover for each factor, using betadisper function from vegan package, and pairwise comparisons, using *mvpaircomp* function from biotools package. Pearson correlations for benthic groups were also assessed using rcorr function from Hmisc package. All analysis were performed using R Studio Software.

4.3 Results

Several taxon groups were recognized including assemblages of microbes and Algae (turf) and Polychaeta (Sabellidae) between the dominant benthic groups in tiles; followed by green algae (*Acetabularia* sp.) and brown algae (*Padina* sp.), and less frequent groups such as sponges, ascidians, mollusks, cnidarian, and other colonial species that were not possible to identify visually, gathered in “other groups”. In total 4 main benthic groups remained for data analysis (i.e., turf, polychaeta, algae and other groups).

Polychaeta and turf groups had a marked presence in all treatments and control tiles throughout the study period. However, treatment tiles varied qualitatively from simpler to more complex surfaces of tiles, especially in Biochar treatment during the 13th and 27th months of colonization, compared with the rest of the tiles (Figure S2). Green algae were present during the first and last period of colonization.

The multivariate PERMANOVA test on the benthic groups cover showed significant differences among material treatments, monitoring times and their interaction (Table 1). Suggesting a temporal variation of benthic group cover according to material types.

Table 4-1. Multivariated PERMANOVA on the cover of all main benthic groups

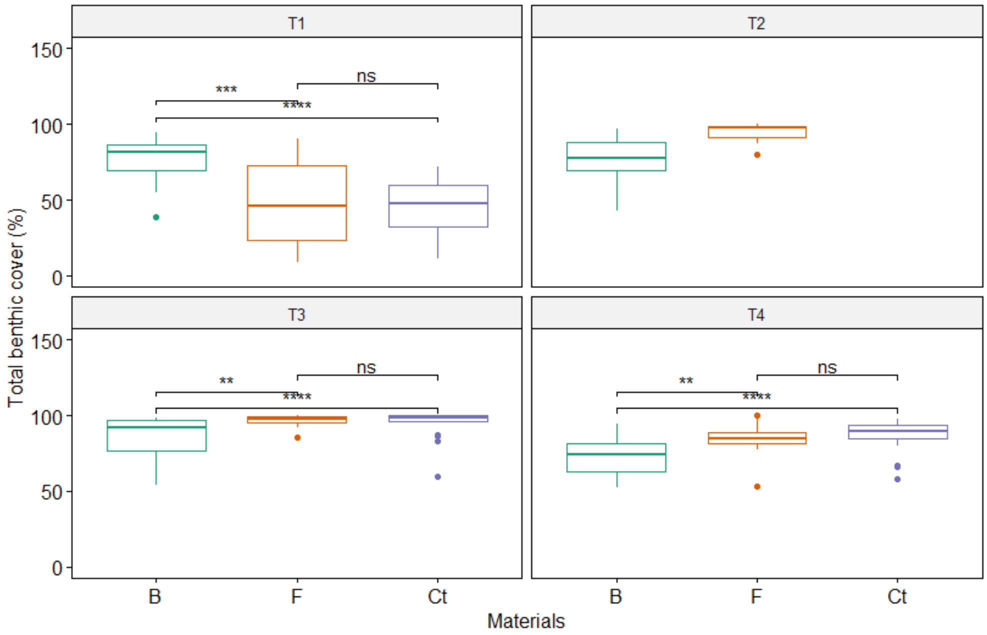
Source of variation	Df	SS	R^2	F	Pr(>F)	
Treatment	2	0.7966	0.04214	9.9689	0.001	***
Time	3	6.5522	0.3466	54.6622	0.001	***
Treatment:time	5	2.4055	0.12725	12.0408	0.001	***
Residual	229	9.1498	0.48401			
Total	239	18.9041	1			

However, 48% of the variation was not explained by the experiment, and the data of both treatment and time factors are significantly heterogeneous regarding the dispersion of the data ($p<0.05$, Figure 4-3). Therefore, significant differences in Permanova tests must be taken with caution. A principal component analysis (PCA) shows the heterogeneous dispersion of the data among the materials and times (Figure 4-3). All treatments overlap among them; however, Biochar treatment data is grouped in the center of the graphic, while Bioferment and control data are scattered and peripherally distributed (Figure S2. A-B).

In the same line, we can see the dispersion of the monitoring time data, showing the T1 tending to the left of the graphic and T2, T3 and T4 overlapped to the right, suggesting that there is a clear temporal variation of benthic colonization that could be more related to a local environmental variation (Figure S2.C-D).

Treatment differences are given by Biochar treatment which differed from Bioferment and control tiles in terms of total benthic cover throughout the study period ($p<0.05$, Figure 4-2). Furthermore, Biochar treatment presented the highest total benthic cover during the first period (81.23 ± 2.76, median ± SE) (Figure 4-2), while Bioferment and control tiles were colonized in 45.65 ± 5.43 and 47.95 ± 3.69 percent during the same period, respectively.

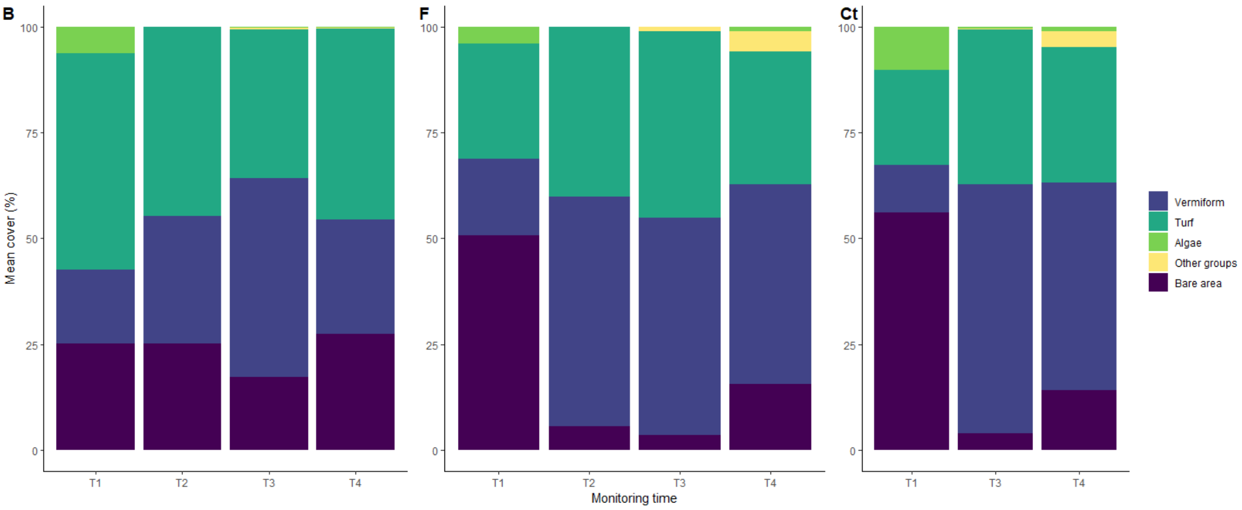
Figure 4-2. Total coverage of benthic main groups among the material treatments. B= Biochart, F= Bioferment, and Ct= Concrete as a control.



However, the total benthic cover increased afterwards for Bioferment and control tiles, and maintained higher during the rest of the study. These materials showed the same pattern, as there is no evidence of differences between Bioferment and control tiles in terms of total benthic cover (Figure 4-2).

On the other hand, the significant interaction between treatments and time, suggest changes in community structure related to certain materials depending on the colonization time. This can be observed in Bioferment treatment and control tiles, which vary from a low cover in the first monitoring time to a higher coverage of benthic organisms in the rest of the study and showing a similar pattern of colonization, which has the Polychaeta group as a dominant component of the community structure after the first period of colonization from there on. In contrast, Biochar treatment showed a rapid settlement of benthic organisms with a high coverage, in which turf and Polychaeta were both important components of the species composition of tiles throughout the study period (Figure 4-3).

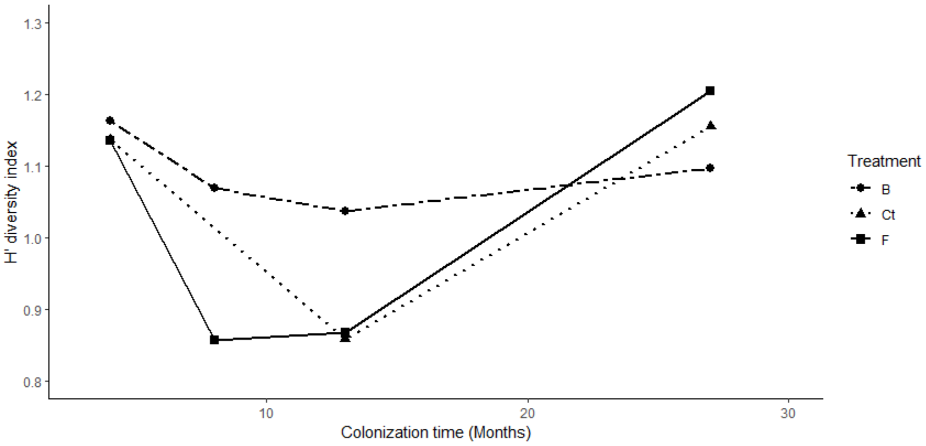
*Figure 4-3. Temporal variation of benthic groups covers among treatments. *There was not data available for control tiles during the second monitoring sampling.*



Moreover, independent analyses showed significant variation among treatments, time and their interaction in each benthic group. Although, the main source of variation was related mostly with the time in all cases ($p<0,05$, Table S1), which could be associated to temporal variation due to local environmental conditions changes.

Furthermore, Shannon diversity index of main benthic groups did not differ among treatments, but it did differ between the times of monitoring (Figure 4-4). During the first and last period of colonization diversity values were higher, whereas it was lower during the second and third period of colonization for almost all the treatments. Thus, diversity of main benthic groups shows a U-shaped trend, which was less marked for Biochar treatment (Figure 4-4).

Figure 4-4. Temporal variation of Shannon diversity index of main benthic groups among treatments.



4.4 Discussion

The assessment of successional stages is necessary to understand long-term ecological dynamics, predict changes in the ecological community and to assess the benefit for restoration programs, instead of a static evaluation that could mask a failed restoration (Boerema et al. 2016). Furthermore, the moniting sessile or sedentary benthic organisms in hard bottom brings more posibilities of evolution and speciation due to the spatial heterogeneity and stability, compared to water column and soft bottoms (García-Gómez et al. 2005). In particular which are more succeptible to impacts because of their low capacity to escape, turn them into a more obvious and accessible way to monitor marine environmental changes (García-Gómez et al. 2005).

In the present study, the observations of benthic community on tiles showed significant differences between materials and periods considered. Biochar presented a significantly higher benthic cover than the Bioferment treatment and control tiles, while this coverage rate was reversed over time, with the two last treatments not significantly different throughout the study period. In this sense, Biochar differences were maintained throughout the study period.

The succession of benthic organisms in Bioferment treatment and control tiles was given through a shift in taxon group cover at the eighth month (second period of colonization), with a rapid increase in Polychaeta group cover remaining the dominant group in both treatments until the final period of colonization. For Bioferment treatment, Polychaeta cover increased 4.6 times in four months, from 10.54 ± 0.63 (median ± standard error % cover) for the first period of colonization to 48.4 ± 1.13% and 49.68 ± 0.65% for the second and third periods, respectively, and to 43.82 ± 0.85% for the fourth period. Similarly, in control tiles, the Polychaeta cover increased more than seven times in 4 months, changing from 7.98 ± 0.44% to 58.16 ± 0.48% for the third period (control tiles were not sampled during the second period, T2) and to 51.01 ± 0.49%. In this sense, Bioferment treatment and control tiles presented a higher total benthic cover at the end of the study compared with Biochar treatment.

Conversely, Biochar treatment did not increase the total benthic cover during the second period of colonization, nor experimented the shift of taxon groups cover. Although Polychaeta cover increased for all tiles, it not surpassed the turf community cover in the case of biochar treatment. In this sense, while biochar treatment did not achieved a higher total benthic cover in the final period, this treatment displayed a buffer effect on taxon groups cover shifts through the successional process. Following the polychaeta group cover, it only increased 2 times in a 4-months period, from 16.3±0.45% for the first period to 31.87±0.57% and 41.39±0.77% for the second and third period, respectively, and decreasing to 22.35±0.82% for the fouth period (Figure 4-3).

Biochar treatment also showed a steady trend in diversity index values, compared with bioferment and control tiles, as well as higher diversity indexes through the study period, with the exception of the last one. Having said this, restoration ecology has been a based conceptually in the succession process, as it suggests there is a pathway to a desired restoration stage (Young 2005), which occur through the colonization of pioneer or opportunistic species until achieve a steady state or climax. Hence, through the two years of colonization, biochar treatment showed that is an an accurate technology for underwater artificial substrates, and an effective material for marine organisms colonization in a more stable way.

Other studies found that richness is usually similar between different colonization substrates at a determined locality; however, it could differ in terms of abundance of species or functional groups depending on the material nature (Dodds et al. 2022), agreeing with our study findings. In general, all the main techniques for coral restoration report similar average survival and growth of corals, so decisions on what techniques to use should be based on local conditions, cost, availability of materials and appropriateness based on stated objectives (Boström-Einarsson et al. 2018). Generally, it is assumed that the type of material will determine the development of the benthic community (Burt et al. 2009).

Interestingly, the evident presence of Polychaeta taxon group could be due cultures of *Sabella spallanzanii* (Gmelin) near the study area which are reported to have better conditions to grow in dephts around 15 m (Pierri et al. 2006), which is similar to the depht implemented in our study (12 m), however the consistence of differences in benthic taxon cover by treatments shows a clear effect of materials on benthic marine organisms colonization. In turn, the colonization of "other" taxon groups appeared from the 3rd period (27 moths after submerging the tiles) in all treatments, accompanied of the algae taxon group only in the cases of Biochar treatment and control tiles.

Qualitatively, as previously mentioned, the tiles of Biochar treatment showed to have a more complex surfaces during the last period of colonization of 18 and 27 months (T3 and T4) compared with the first periods of four and eight months (T1 and T2) (Figure S3). In this sense, researching the mechanisms behind the Biochar material used as a complement in concrete structures for the colonization of marine organisms would help to understand how the apparent increase in structural complexity occurs (e.g., to know if this material additive may offer greater surface availability for colonization or make a difference in other factors such as shelter, shade, habitat, and food availability compared to other materials). This way, we could better understand how to improve biodiversity and biomass loss in degraded ecosystems while assisting marine restoration (Rossi & Rizzo 2020, Seaman 2007).

Also, differences detected related to materials would not be due to differences of instalation conditions, as the proximity of the tiles guarrantee that all the had the same environmental conditions as temperature, salinity, depht, light availability, vertical orientation and dispocition facing the same direction to the current.

Biochar can sequester CO_2 (Campion et al. 2023). In addition, this material showed a more stable response than other tested materials, such as Bioferment (according to the author's observation in the field). This could be related to the physical-chemical stability of the material (Campion et al. 2023, Wang & Wang 2019, Nobre et al. 2023, Venkatachalam et al. 2023), which is an important aspect for the restoration of marine ecosystems as hard materials increase coral transplant survival (Mwaura et al. 2022). Materials must be durable during submersion and removable from the sea bottom, as required by some legislation in European countries (i.e., Spain or Italy).

In addition, bioferments have several uses from mitigators in oil spills (Santos et al. 2022), bio-hydrogen production (Hosseinkhani et al. 2014), for plastic degradation (Cifuentes and Basak, 2021), to antimicrobial component (Kumar et al. 2020). In the same line, composting is an effective method of recycling organic solid waste, and it is the key process linking planting with recycling (Yang et al. 2023). However, bioferment material in the form of layer, was not successful as the material dissolved in seawater (personal observations), and did not contribute to a significant increase in benthic invertebrate cover, as there were no significant differences in the percentage of cover of benthic groups in Bioferment compared to control tiles in the present experiment.

We acknowledge that, although other approaches, which could include biochemical and physical studies of colonized surfaces, could provide more information to understand the interaction between materials and colonizing organisms, the approach we decided to use, through photographs, is widely used and has brought results that contribute to interesting findings, especially when it comes to first tests on new materials for marine restoration.

Moreover, it has recently been determined that hard ARs for transplantation are more effective in a couple of years than ARs without transplantation and other structures, despite being submerged for more than 100 years (Bracho-Villavicencio et al. 2023; Knoester et al. 2020). Hard ARs are usually made of concrete due to the availability and strength of this material when submerged. Materials of organic origin are more difficult to use than hard materials because their nature tends to disintegrate. In this sense, the development of new types of hard organic-originated materials for the creation of ARs as support structures for other restoration actions as transplants, nubbins, sea gardening, among others, is essential. The next step is understanding the economic and energy/material potential constraints to make an efficient upscaling of artificial reefs for marine restoration with new materials such as the concrete–Biochar mixture.

In this study, Biochar material was suitable having a rapid colonization and creating a complex surface in tiles developing a diverse species composition. Last experiences show that the mitigation of human impacts can allow the recovery of marine populations, habitats and ecosystems (Duarte et al., 2020). In this context, if multiple human pressures are mitigated (such as, for example, marine pollution and climate change), the health conditions of the oceans could improve by 2050 (Duarte et al., 2020).

5 CONSIDERAÇÕES FINAIS

Recifes artificiais tem potencial para ser desenvolvidos de forma sustentável com miras para a restauração de ecossistemas marinhos e costeiros. Contudo, no Brasil, pouco é sabido sobre quão eficazes podem ser devido à falta de informação adequada para evidenciar melhoras dos ecossistemas impactados e intervindos ou semelhanças com recifes naturais em bom estado de conservação. No presente trabalho o diagnóstico do estado das artes de RAs no nível mundial entre 1990-2020 permitiu compreender que ações simples como fazer uso de ferramentas para tomadas de decisão (Figura 2-1), determinando o estado de conservação do local para implementar realmente se necessário em ecossistemas recifais degradados, investigando as causas e consequências dos impactos ambientais e planejando RAs que suportem a restauração desses ecossistemas com base aos antecedentes investigados, são passos cruciais na hora de eleger o uso de RAs. Assim, realizar de fato estudos piloto dos projetos de implementação de RAs, selecionar o local de implementação com base científica e aos antecedentes do local, monitoramentos periódicos e ações de jardinagem e monitoramento que evitem a introdução o estabelecimento de espécies invasoras, podem poupar tanto recursos financeiros mal investidos quanto impactos ambientais a mediana e grande escala por implementações mal sucedidas.

Igualmente, a disponibilidade limitada de dados padronizados nos escassos trabalhos científicos que permitiram avaliar a eficácia de RAs em se comparar com RNs, ressalta a necessidade de incentivar a padronização de métodos e técnicas de coleta de dados para avaliações de RAs no mundo. Em geral, as comparações (n=13) mostraram que os ecossistemas de RAs não se assemelharam aqueles ecossistemas de RNs de referencia ou controle. Cabe destacar que a maior parte RAs inclusos na comparação não foram criados especificamente para restauração (i.e. navios afundados). Contudo, alguns exemplos alentadores para o campo da restauração mostraram três casos de similitude de RNs de referência com RAs, cujas características foram diferenciadas enquanto a tamanhos de 16 m^2, 500 m^2 e 1170 m^2; idade com 2 anos, 43 anos e 130 anos de implementação; com materiais variados (concreto, vidro, metal e plástico) ou de metal, e instalados em diferentes profundidades de 8 m, 20 m e 15 m, e presencia e ausência de técnicas de restauração como transplante de corais (KNOESTER *et al.*, 2023; SÁNCHEZ-CABALLERO *et al.*, 2023; PERKOL-FINKEL *et al.*, 2005). Inesperadamente, RAs com 2 anos de antiguidade (KNOESTER et al., 2023) podem ser tão efetivos quanto aqueles com mais de 130 anos de instalação (PERKOL-FINKEL et al., 2005, Figura 3-10), indicando um ganho de tempo em restauração relevante, possivelmente pela aplicação de técnica de transplante de espécies recifais o planejamento da estrutura do RA em escala e complexidade específica, fazendo a diferença na aceleração da restauração de ecossistemas marinhos e costeiros. Além disto, o uso do Índice de Bray-Curtis foi efetivo como medida de comparação entre RAs e RNs para a avaliação de efetividade de restauração em ambientes marinhos e costeiros, previamente aplicado só em ambientes terrestres por Crouzeilles et al. (2016) e por Carrick e Forsythe (2020).

No entanto, ainda são necessários mais esforços para desenvolver pesquisas sobre outras características-chave, como a inovação na matéria prima para a construção dos RAs. Materiais de origem orgânica ou inorgânica-não poluentes, que sejam submergíveis e que mantenham a sua dureza para permitir a colonização eficiente de organismos marinhos, como o biochar que como testado neste trabalho e que resultou ótimo, entre os materiais testados, para uma rápida colonização de organismos bentônicos. Além da origem do material, o processo de criação do material e construção dos RAs também deveria ser considerado em intervenções, sobretudo em aquelas a ser implementadas em grande escala. Este último aspecto é relevante na atualidade vista a crescente onda de conscientização sobre a importância da restauração dos oceanos na adaptação aos efeitos das mudanças climáticas. Materiais de origem orgânico, biomateriais e outros que possam facilitar a colonização de organismos locais devem ser foco em investigações futuras.

Por fim, ecossistemas recifais degradados, segundo cada caso, tem uma oportunidade a mais para ser restaurados por meio de RAs, sempre que um planejamento científico e lógico seja aplicado na criação destas ferramentas com especificidade espaço-temporal. Igualmente, se faz necessário parar de considerar como RAs qualquer estrutura de descarte a ser afundada, mas uma ferramenta cuja aplicabilidade para a toma de decisão caso a caso na escolha de RAs, o uso de materiais orgânicos, uso de espécies locais chave para transplante tomando em conta a escala e a replicabilidade dos RAs para a mitigação dos impactos e restauração de ecossistemas aquáticos, assim como a inclusão de fatores socioambientais no monitoramento e a viabilidade econômica são fatores importantes para obter resultados positivos. O escopo deste trabalho, fora de trazer um modelo único de RA para ser usado a grande escala, é desvendar e oferecer novos métodos para abordar a restauração de ecossistemas marinhos e costeiros, propondo os SAR, ou recifes artificiais simbióticos que integrem estratégias de transplantes de espécies chave para a aceleração da restauração e que servem para responder às prioridades dos ODS, como uma boa estratégia de restauração marina tendo em conta os resultados obtidos e apresentados.

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APÉNDICE A: Material suplementar Capítulo I

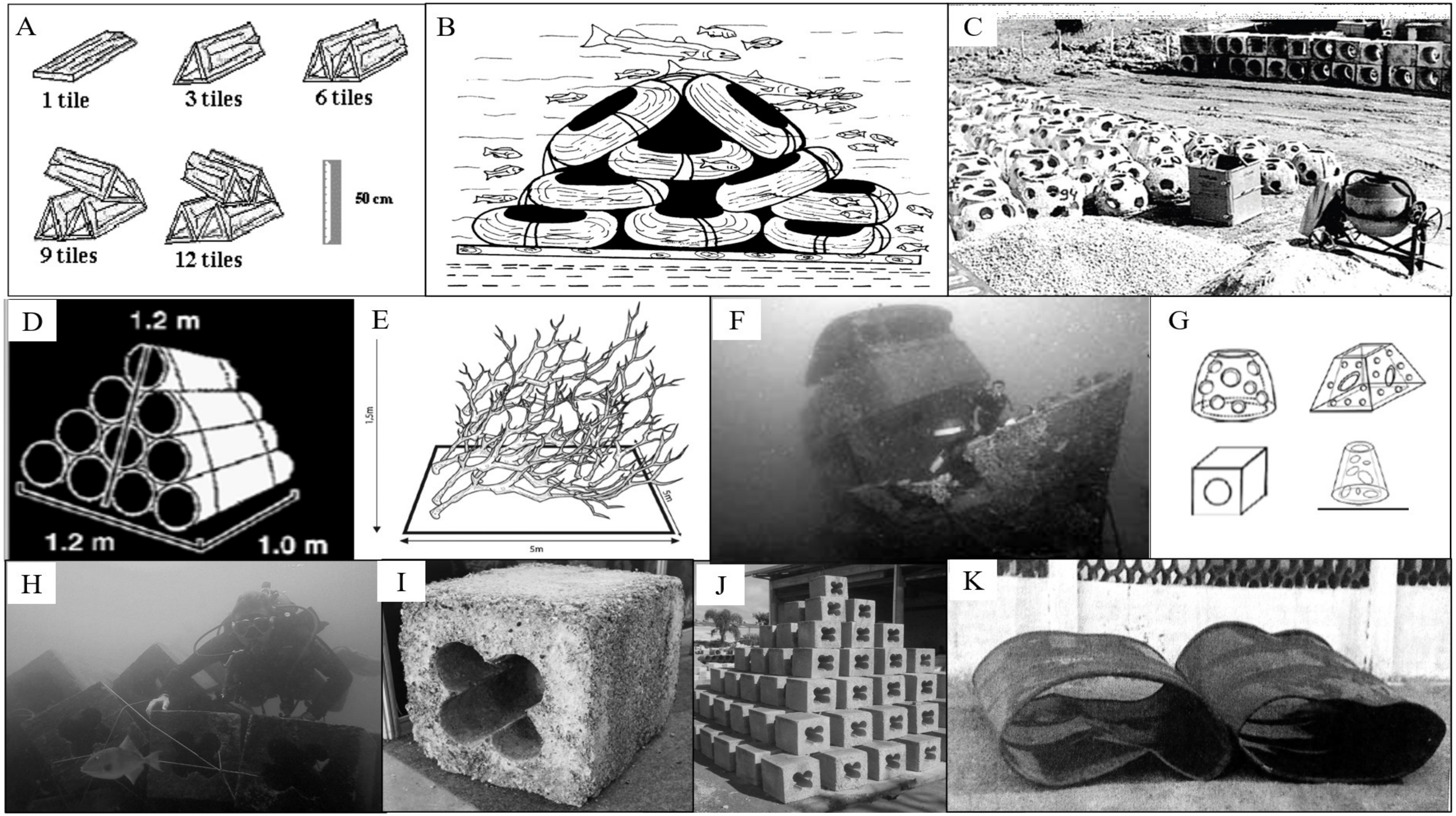

Figure S1. Artificial reefs used in Brazil built from: A) triangular brick (Brotto & Araújo, 2001); B) accumulation of tires (Freitas & Petrere, 2001), C) concrete in the form of reef balls® (Portella et al., 2013); D) PVC pipes (Santos et al., 2011); E) branches of wood (Yamamoto et al., 2014); F) boats (Santos, 2006); G) concrete in various forms (Hackradt; Félix-Hackradt & García-Charton, 2011); H), I) E J) cube-shaped concrete (Brandini, 2020); and K) metal “marambaia-tambor” (Filho, 2011).

Table S1. List of species reported as exotic, invasive, introduced or new, associated with ARs in Brazil

Author	**Year**	**Taxa**	**Scientific name**	**Substrate**	**Status of the species**
Farias *et al.*	2020	Bryozoa	*Smittoidea pacifica* Soule & Soule	Experimental tiles, corals, seashells and rhodoliths	Invasive
Miranda *et al.*	2018	Bryozoa	*Amathia verticillata* (delle Chiaje, 1822) *Arbopercula bengalensis* (Stoliczka, 1869) *Bugula neritina* (Linnaeus, 1758) *Bugulina stolonifera* (Ryland, 1960) *Hippopodina tahitiensis* (Leca & d'Hondt, 1993) *Hippoporina indica* Madhavan Pillai, 1978 *Licornia jolloisii* (Audouin, 1826) *Sinoflustra annae* (Osburn, 1953) *Triphyllozoon arcuatum* (MacGillivray, 1889)	New or artificial substrate	Invasive

Almeida *et al.*	2015	Bryozoa	*Triphyllozoon arcuatum* (MacGillivray, 1889)	Oil platform and sponges	Invasive
Almeida *et al.*	2018	Bryozoa	*Sinoflustra annae* (Osburn, 1953)	Artificial substrate, seashells and rocks	Invasive
Do Amaral *et al.*	2020	Mollusca	*Saccostrea cuccullata* (Born, 1778)	Mangrove roots, rocky litoral, rocky reef, ports.	Invasive
De Araújo *et al.*	2018	Echinoidea	*Ophiothela mirabilis* Verrill, 1867	Port.	Invasive
Spotorno-Oliveira *et al.*	2018	Mollusca	*Eualetes tulipa* (Rousseau in Chenu 1843)	Port Pilars and walls of concrete, metal and wood	Invasive
Anker et al.	2013	Crustacea	*Salmoneus depressus* Anker, 2011 *Salmoneus ortmanni* (Rankin, 1898)	PVC e plants fibers	New
Bumbeer & Rocha	2012	Anthozoa	*Stragulum bicolor* (van Ofwegen & Haddad, 2011) *Carijoa riisei* (Duchassaing & Michelotti, 1860)	Polyethylene sheets and concrete ARs	Introduced
		Hydrozoa	*Garveia franciscana* (Torrey, 1902)	Polyethylene sheets and concrete ARs	Introduced
		Crustacea	*Amphibalanus amphitrite* (Darwin, 1854) *Amphibalanus reticulatus* (Utinomi, 1967)	Polyethylene sheets and concrete ARs	Introduced

			Balanus trigonus (Darwin, 1854)		
			Megabalanus coccopoma (Darwin, 1854)		
			Striatobalanus amaryllis (Darwin, 1854)		
		Tunicata	*Ascidia tenue* (Monniot, 1983)	Polyethylene sheets and concrete ARs	Introduced
Creed & Paula	2007	Cnidaria	*Tubastraea tagusensis* Wells, 1982	Concrete, granite, wood, steel, tires	Invasive
			Tubastraea coccinea Lesson, 1829		
		Bryozoa	*Amathia verticillata* (delle Chiaje, 1822)	Port	Invasive
		Bryozoa	Arbopercula bengalensis (Stoliczka, 1869)	Port	Invasive
			Bugula neritina (Linnaeus, 1758)		
			Bugulina stolonifera (Ryland, 1960)		
			Hippopodina tahitiensis (Leca & d'Hondt, 1993)		
			Hippoporina indica Madhavan Pillai, 1978		
			Licornia jolloisii (Audouin, 1826)		
			Sinoflustra annae (Osburn, 1953)		
			Triphyllozoon arcuatum (MacGillivray, 1889)	Oil platform	

APÉNDICE B: Material Suplementar Capítulo II

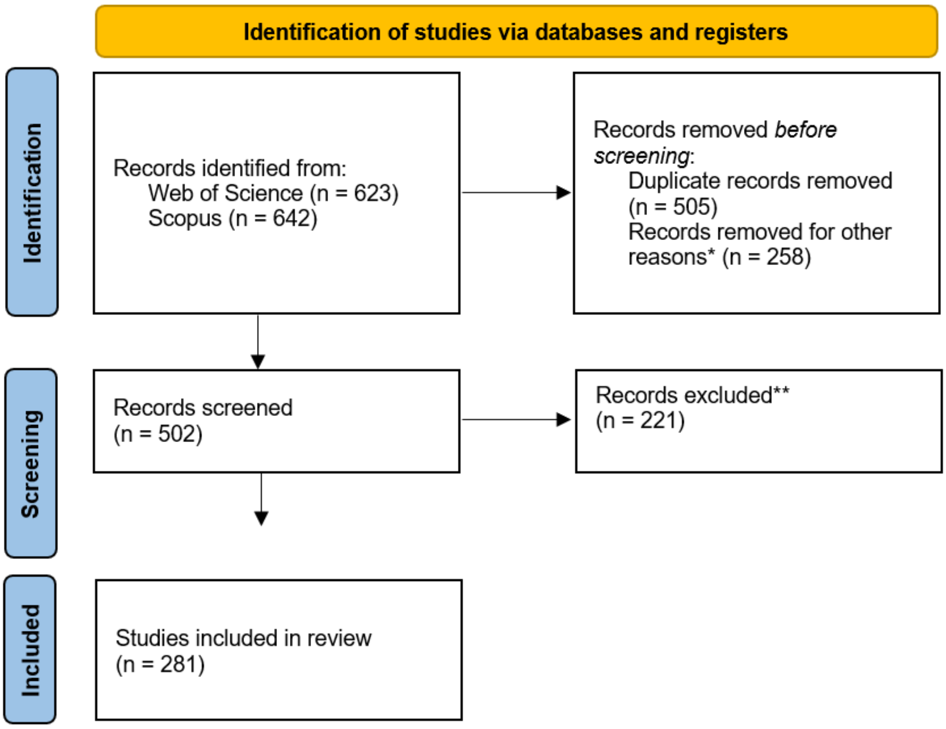

Figure S1. Flow diagram of the systematic literature review on artificial reefs.

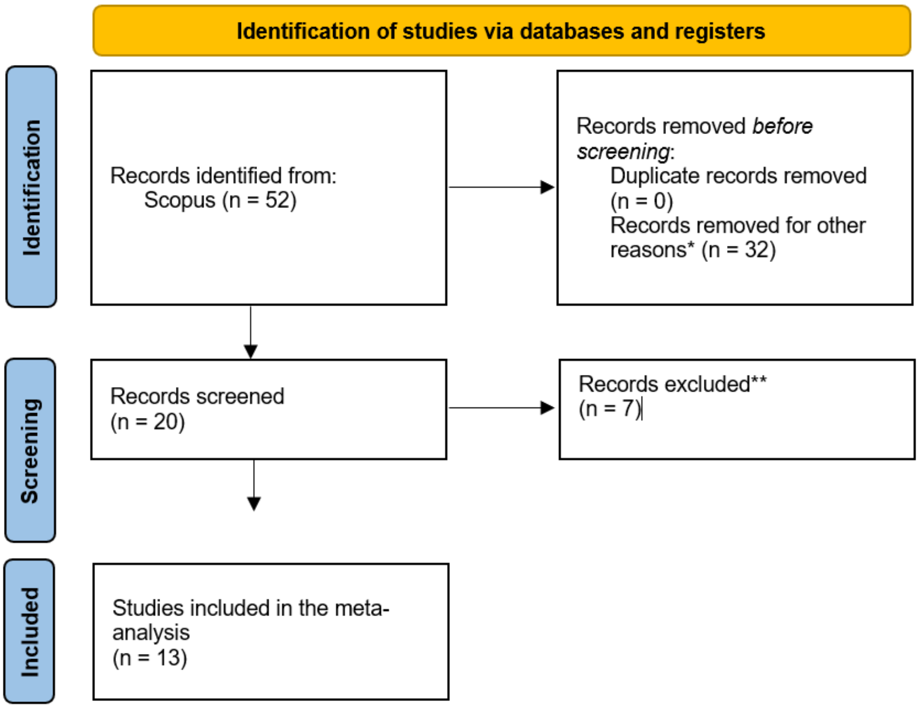

Figure S2. Flow diagram of the supplementary systematic literature review on artificial reefs effectivity.

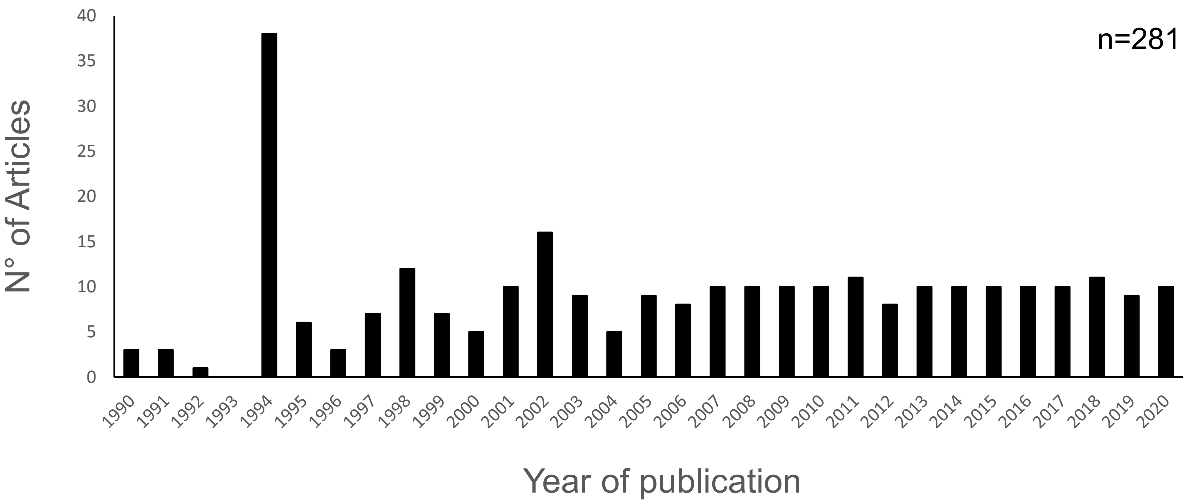

Figure S3. Number of studies on ARs during the period 1990-2020.

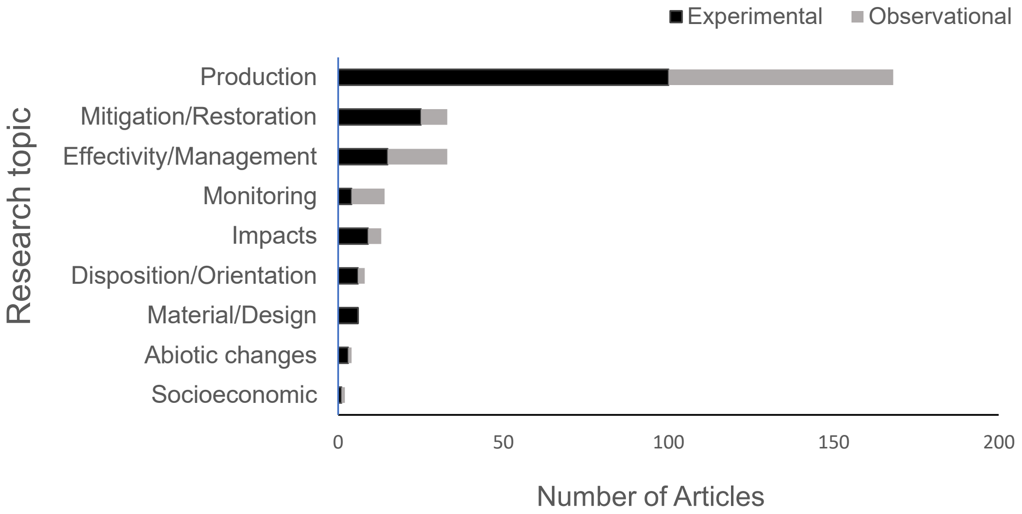

Figure S4. Main research topics found in studies of artificial reefs by type of research.

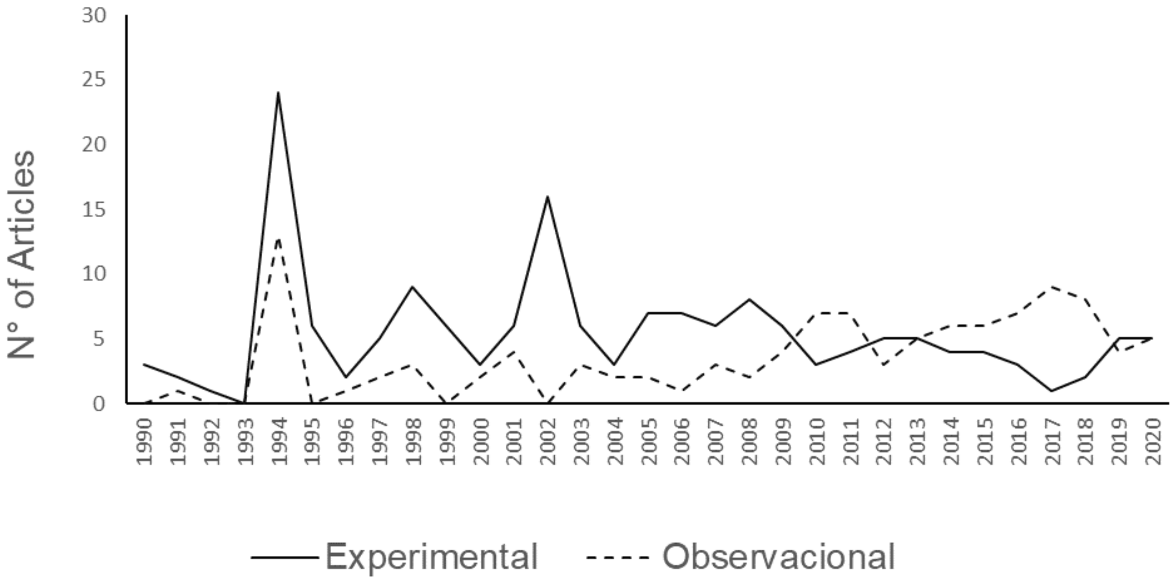

Figure S5. Number of experimental and observational surveys during the period 1990-2020.

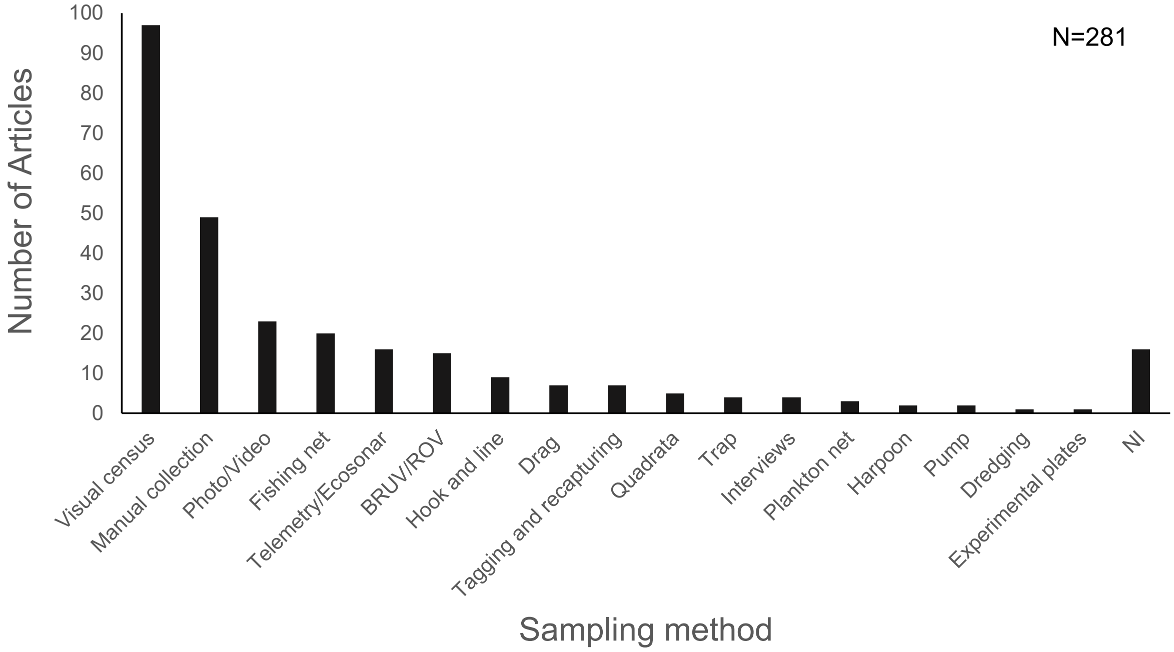

Figure S6. Sampling methods used in studies related to ARs during the period of 1990-2020.

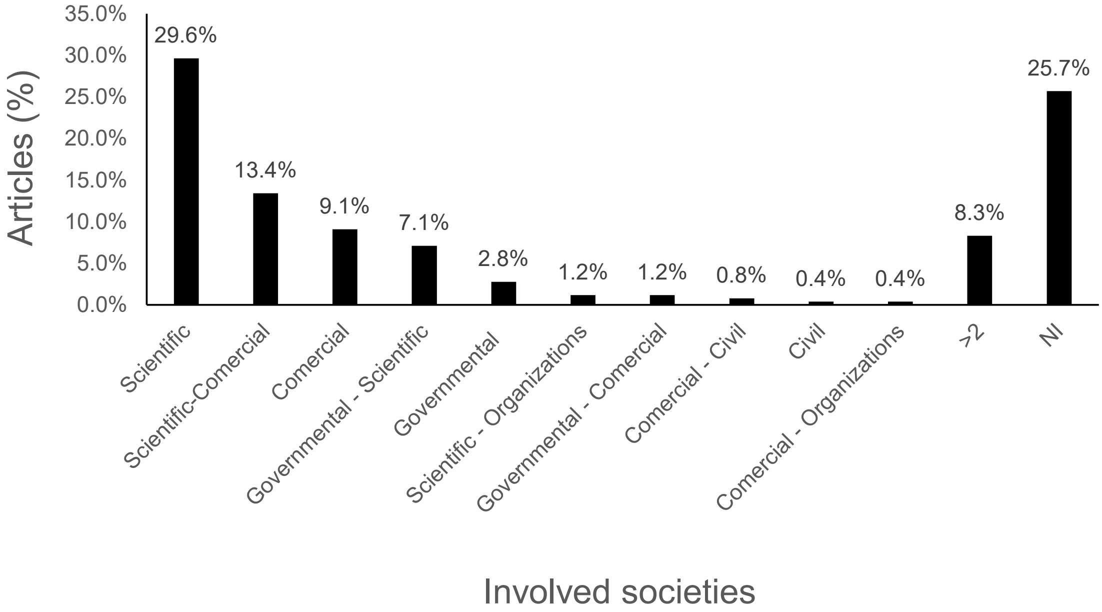

Figure S7. Society members involved in studies around ARs.

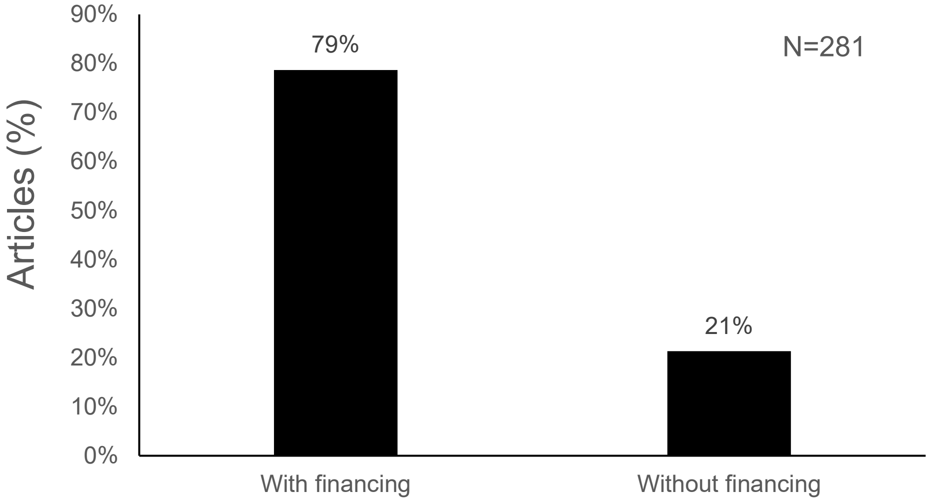

Figure S8. Studies of ARs regarding their financing support

Table S1. Ecosystem type and substrate in which ARs were deployed.

Substrate	Ecosystem				
	Marine	Freshwater	Estuarine	Laboratory	NI
Water column	2			3	
Sand	60		1		1
Muddy-Sand	28		1		
Sand-Reef	5				
Sand-Rocky	2				
Sand-Phanerogams	5				
Sand-Algae	2				
Mud	5				
Phanerogams	13				
Gravel	1				
Muddy-sandy gravel			1		
Sandy gravel	5		1		
Rocky	10				
Reef	11				
> 2 substrates	6				
NI	105	3	8		2

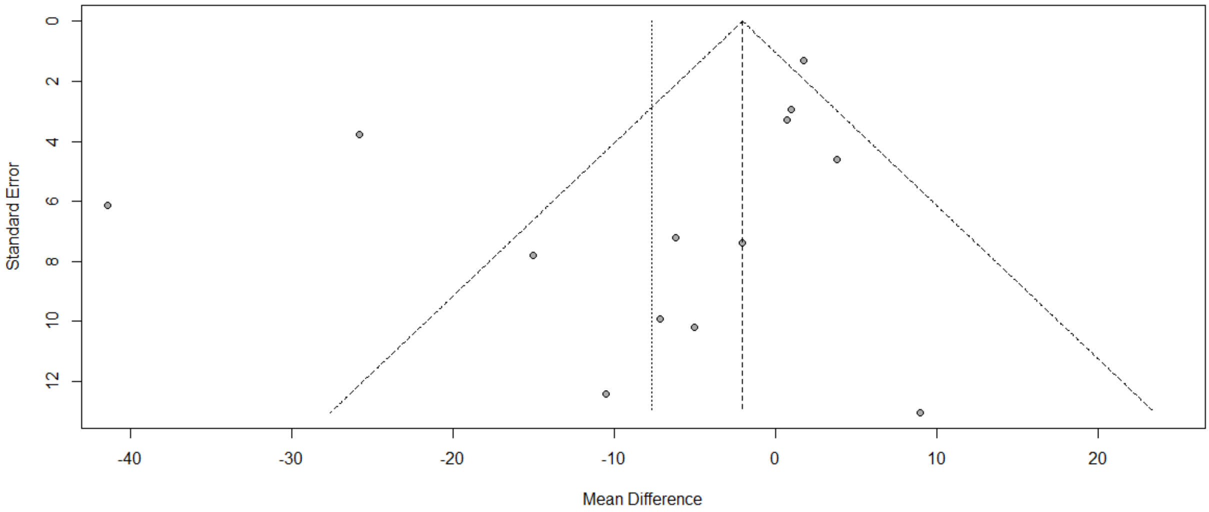

Figure S9. Funnel plot on meta-analysis of ARs effectiveness for marine ecosystem restoration

APÉNDICE C: Material Suplementar Capítulo III

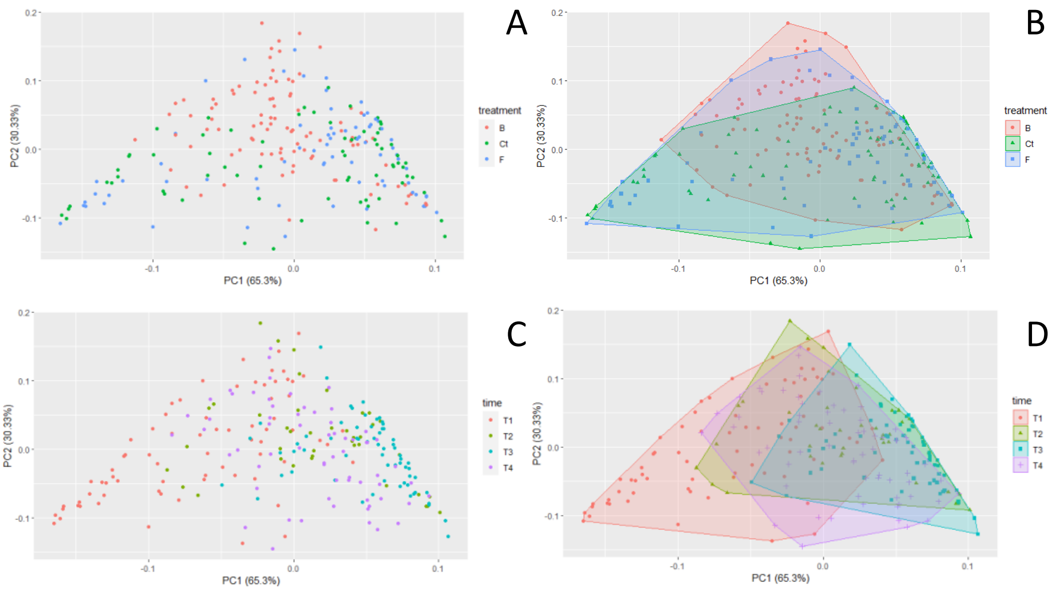

Figure S1. PCA showing the heterogeneous dispersion of data of benthic invertebrate groups by treatments showed in points (A) and overlapped colored frames (B); and by monitoring times in points (C) and colored frames (D).

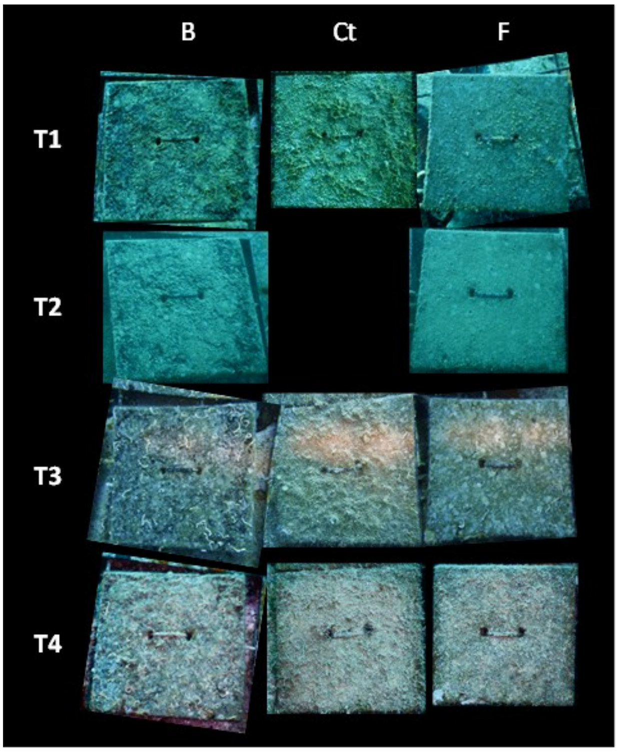

Figure S2. Images of experimental tiles of each treatment during the study periods.