Delft University of Technology

Document Version
Final published version

Licence
Dutch Copyright Act (Article 25fa)

Citation (APA)
Zhao, Z., van der Heide, T., Kamermans, P., Coolen, J., Oude Elferink, A., van Sluis, C., v. Hofstede, R., van Onselen, E., van Koningsveld, M., & More Authors (2026). Rethinking Artificial Reefs to Accelerate and Upscale Marine Biodiversity Recovery. *Environmental Science and Technology*, *60*(21), 14782-14792. https://doi.org/10.1021/acs.est.5c13167

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
In case the licence states “Dutch Copyright Act (Article 25fa)”, this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.

Environmental Science & Technology

pubs.acs.org/est

Perspective

Rethinking Artificial Reefs to Accelerate and Upscale Marine Biodiversity Recovery

Zhiyuan Zhao,* Tjisse van der Heide, Pauline Kamermans, Joop Coolen, Alex Oude Elferink, Christiaan van Sluis, Remment v Hofstede, Eline van Onselen, Wouter van Broekhoven, Wouter Lengkeek, Juste Motuzaite, Jon Dickson, Rob Witbaard, Mark van Koningsveld, Karel van den Wijngaard, Ernst Schrijver, Karin Didderen, and Tjeerd J. Bouma

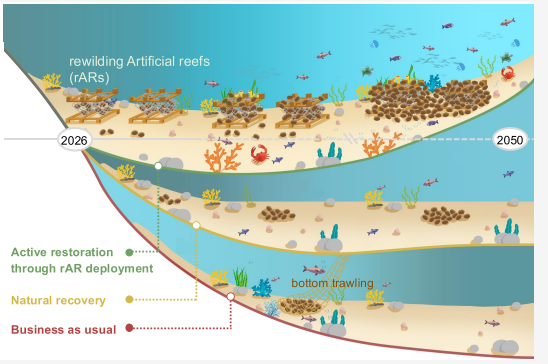
Cite This: *Environ. Sci. Technol.* 2026, 60, 14782−14792

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

Downloaded via TU DELFT on June 15, 2026 at 08:44:09 (UTC).
See https://pubs.acs.org/sharingguidelines for options on how to legitimately share published articles.

ABSTRACT: Artificial reefs (ARs), a form of anthropogenic intervention in marine habitats, have a long history of deployment and continue to proliferate worldwide. Based on a comprehensive literature review and meta-analysis, we show that (i) ARs have evolved from socioeconomic-oriented tools into often-used components of active marine restoration, yet this transition conflicts with the continued use of eco-unfriendly materials, hindering upscaling; (ii) ARs positively impact marine organisms at community, population, and individual levels, but their contributions to organismal fitness remain limited compared to natural reefs. To address these limitations, we advocate a paradigm shift toward "rewilding ARs"—temporary structures designed to create opportunities for natural reef formation, enhance habitat quality, and gradually degrade to minimize human impact. These features support the transition from active intervention to spontaneous recovery, promoting sustainable biodiversity recovery by improving organism fitness and facilitating upscaling. Integrating insights from ecologists, engineers, legal experts, environmental consultants, and NGOs, we introduce six guiding principles for "rewilding ARs" to ensure effective, durable, no-regret, scalable, permit-friendly, and outcome-optimized implementation. Lastly, we present pioneering examples of innovative ARs progressing toward these principles, serving as references for future endeavors.



KEYWORDS: *active restoration, biodiversity recovery, artificial reef, rewilding, windows of opportunity, marginal sea*

INTRODUCTION

Beneath the sea's surface lies a vast treasury of life forms and genetic resources underpinning global biodiversity.[1] This biodiversity sustains essential ecosystem functions,[2,3] such as facilitating carbon sequestration and storage to help mitigate climate change[2] and supporting marine industries worth trillions of dollars annually.[3] Yet anthropogenic influences, from top-down impacts like overfishing[4] to bottom-up impacts such as eutrophication,[5] have destroyed one-third to half of vulnerable marine habitats,[1] driving species declines and the loss of critical ecosystem functions.[4,6] Moreover, climate change is exacerbating these impacts on marine ecosystems.[7,8]

Ecological restoration is gaining prominence as a major tool to reverse the current trend and rejuvenate marine biodiversity and functionality.[9,10] Current efforts range from passive recovery-oriented measures, such as the establishment of marine protected areas (MPAs) that primarily alleviate pressures rather than directly restoring degraded habitats, to active interventions designed to accelerate and shape recovery trajectories.[2,11,12] Recognition of the latter is steadily growing, given that degraded marine ecosystems often struggle to recover spontaneously without crucial system components,[13,14] even within MPAs boasting suitable habitats.[9,15] Nevertheless, recent studies suggest that related endeavors currently fall short of compensating for historic habitat losses,[1,12,16] as limitations in clear objectives, technology, funding, and permitting make it challenging to scale active marine restoration from local to regional or global scales.[3,17,18]

Artificial reefs (ARs), hard structures submerged intentionally or accidentally by humans,[19] have emerged as promising active interventions.[20,21] By relieving habitat pressures and providing opportunities for marine life to colonize, shelter, feed, and reproduce, ARs foster diverse and productive

Received: September 23, 2025
Revised: May 13, 2026
Accepted: May 14, 2026
Published: May 19, 2026



© 2026 American Chemical Society

https://doi.org/10.1021/acs.est.5c13167
Environ. Sci. Technol. 2026, 60, 14782−14792

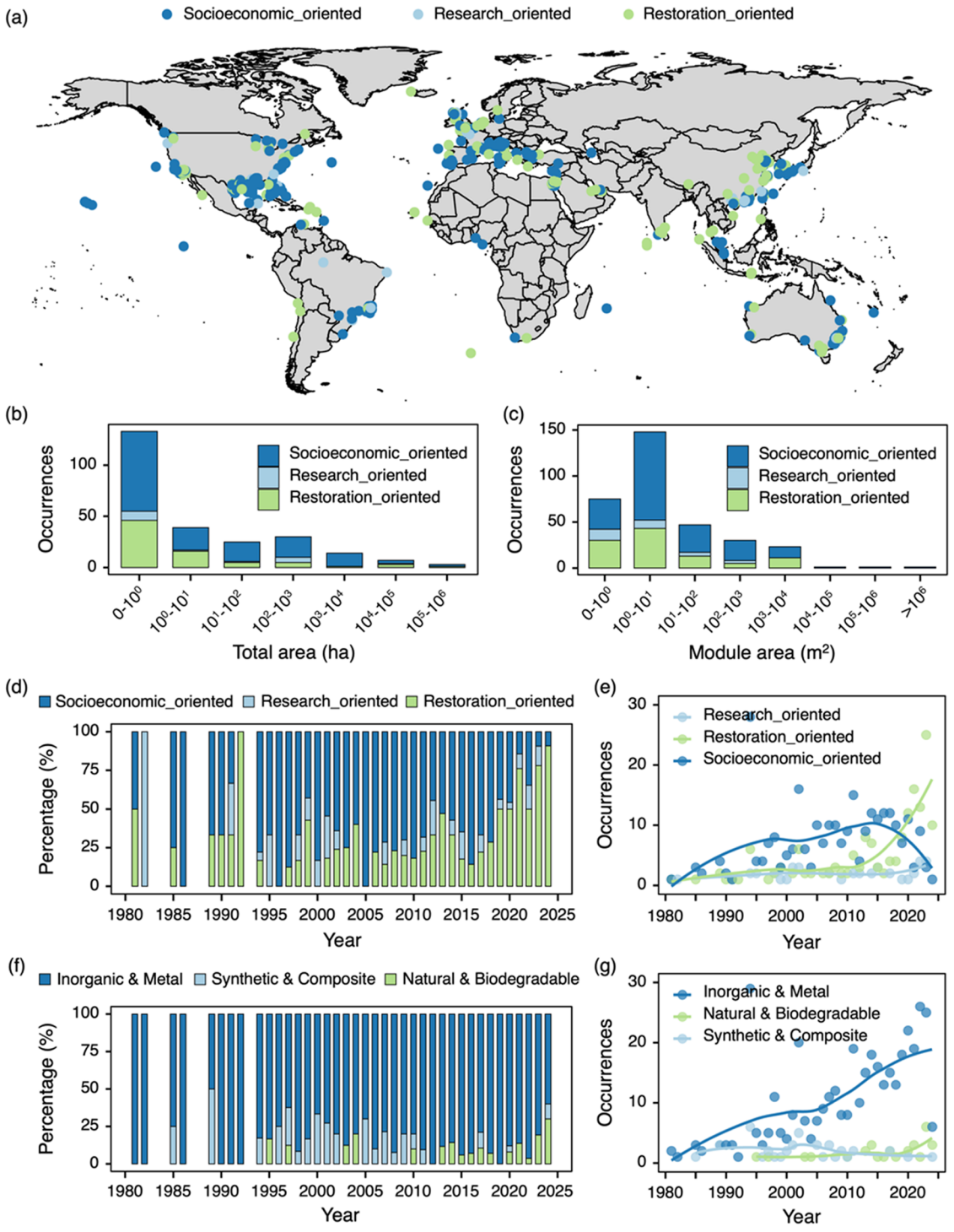


Figure 1. Overview of artificial reef (AR) studies from 1980 to 2024. (a) Distribution by purpose. (b, c) Deployment and module areas. (d, e) Temporal trends by purpose. (f, g) Temporal trends by material.

ecosystems.[22,23] Today, ARs are widely present in global seas and are proliferating rapidly,[24] evolving from accidental ARs like shipwrecks to purpose-built conventional ARs tailored to ecological needs.[25] However, conventional ARs often face criticism for their reliance on unsustainable materials and the generation of harmful waste.[25,26] In response, green ARs featuring a reduced carbon footprint have begun to take shape, starting to take environmental and sustainability issues into account.[25,27] Nonetheless, beyond a few high-profile cases of success or failure, the biodiversity benefits surrounding ARs have not been widely examined.[19,21,23] Given indications that ARs could be altering marine ecosystems on a massive scale,[28,29] it is imperative to critically assess their effectiveness in enhancing biodiversity and to optimize their role in advancing marine biodiversity recovery.

Here, we systematically review AR applications and conduct a meta-analysis quantifying their biodiversity effects across multiple biological levels. Building on these insights, we propose "rewilding ARs (rARs)" as a next-generation AR approach that moves beyond habitat provision to initiate

https://doi.org/10.1021/acs.est.5c13167
Environ. Sci. Technol. 2026, 60, 14782−14792

sustainable marine biodiversity recovery. Designed to create "Windows of Opportunity (WoO)", i.e., limited periods of low disturbances and/or stable settlement substrates that allow reef-building species to establish (*see* Supporting Information *for conceptual details*), rARs enable transitions from active intervention to natural reef regeneration, supporting spontaneous scaling and biodiversity enhancement while minimizing human intervention. We further outline six fundamental principles for rARs implementation and showcase pioneering examples to inspire future applications.

GROWING TREND OF ARTIFICIAL REEFS IN SEA RESTORATION

Our systematic review compiled 495 peer-reviewed publications from 1980 to 2024 (*see* Supporting Information*for Methods*). While this number does not fully capture all AR deployments, it reflects the overall research interest in ARs worldwide (Figure 1A). Regardless of their objectives or materials, AR applications remained limited in scale, with a median module size of 3.38 m^2 and a median deployment area of 0.65 ha (Figure 1b,c). This contrasts with natural benthic habitats, such as oyster reefs and coral reefs, that commonly exceed 1 ha,[9,30] highlighting the need for scaling up.

The deployment of ARs has historically been dominated by socioeconomic-oriented applications (Figure 1d), with 275 ARs examined primarily aimed at boosting commercial fisheries, supporting marine aquaculture, and promoting tourism. Since the 2010s, restoration-oriented ARs (n = 162; Figure 1d) have increased rapidly and are designed to protect specific habitats, mitigate habitat degradation, or facilitate habitat recovery. Publications on restoration-oriented ARs in the past five years (n = 84) exceed those from the previous 40 years (n = 78; Figure 1e), overtaking socioeconomic-oriented ones as the dominant focus. This shift reflects mounting public concerns about overfishing,[4] ecosystem degradation,[1] and climate change,[8] coupled with increased support from international and regional policies, legislation, and funding dedicated to ecological restoration.[10,17,31] A smaller but rising number of ARs (n = 42) have been deployed for research-oriented purposes (Figure 1d,e), such as evaluating different AR designs, tracking biological responses, or assessing changes in abiotic conditions.

Materials have been central to AR studies (n = 481) because physicochemical properties, texture, and color affect AR cost, performance, and carbon footprint.[19,21,26] From 1980 to 2024, inorganic and metal components such as cement, lime, clay, slag, and steel dominated AR construction (n = 409; Figure 1f), including custom-made concrete structures, rock piles, intentionally or accidentally submerged ships, and decommissioned oil rigs. Synthetic and composite materials (n = 42; Figure 1f), such as plastics, PVC, glass, ceramics, and discarded tires, peaked before 2010 (86%; Figure 1g) but have since declined due to environmental risks (e.g., toxic release, heavy metals, and microplastics[19,31]) and legislative restrictions (e.g., dumping laws[32]). Few ARs (n = 30) used natural or biodegradable materials (Figure 1f), such as wood, shells, and biopolymers from underutilized biomass, with 50% of such ARs appearing in the past five years (2020−2024) and 67% within the past decade (2015−2024; Figure 1g).

Notably, within restoration-oriented AR studies, 79% (n = 128) employed inorganic and metal materials, and 7.4% (n = 12) used synthetic and composite materials. Continued reliance on these materials raises marine compatibility and permitting concerns, undermining restoration goals and hindering scaling up.

EFFECTIVENESS OF ARTIFICIAL REEFS IN SUPPORTING MARINE LIFE

We extracted 443 response ratios from 151 studies to assess how ARs benefit marine organisms at community, population, individual, and fitness levels (*see* Supporting Information *for Methods*). Most studies compared AR sites with natural reef reference sites (47.4%) or unstructured control sites (e.g., adjacent bare substrate; 44%), while only 8.6% used predeployment degraded sites as controls (i.e., before vs after) (Figure 2).

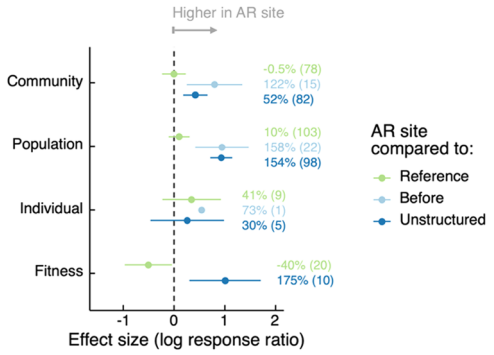


Figure 2. Forest plots of response ratios for community, population, individual, and fitness metrics affected by artificial reefs (AR). Points represent the overall effect sizes and error bars indicate 95% confidence intervals. Positive values indicate that metrics at AR sites are higher than at natural reefs (reference), nearby unstructured habitats (unstructured), or preinstallation conditions (before), whereas negative values indicate they are lower. Sample sizes are shown in parentheses.

Compared to unstructured and before controls, population metrics (abundance, density) in AR areas were higher by 154% and 158% (Figure 2), respectively, with stronger effects at larger module areas and similar patterns across AR objectives and material types (Figure 3). Community metrics (diversity, richness, evenness) in AR areas were 122% higher than before controls and 52% higher than unstructured controls (Figure 2). Individual metrics (size, mass) in AR areas increased by 73% and 30% relative to before and unstructured controls (Figure 2), respectively. Both responses showed little variation across AR objectives, material types, and deployment scales (Figure 3). Fitness metrics (growth, reproduction, and recruitment) in AR areas were 175% higher than in unstructured controls (Figure 2), suggesting enhanced organismal performance, particularly at larger deployment areas (Figure 3). No data regarding fitness were available for comparison with the before controls. Taken together, these uniformly positive responses across biological levels primarily reflect strong structural habitat enhancement associated with AR deployment rather than directly resolving attraction versus production mechanisms.

Compared to natural reef reference sites, AR deployment enhanced population metrics by 10% and individual metrics by 41% (Figure 2). Community metrics (−0.5%) were comparable between AR areas and reference sites (Figure 2). Unexpectedly, despite variability among studies, fitness metrics in AR areas were significantly lower than in reference sites

https://doi.org/10.1021/acs.est.5c13167
Environ. Sci. Technol. 2026, 60, 14782−14792

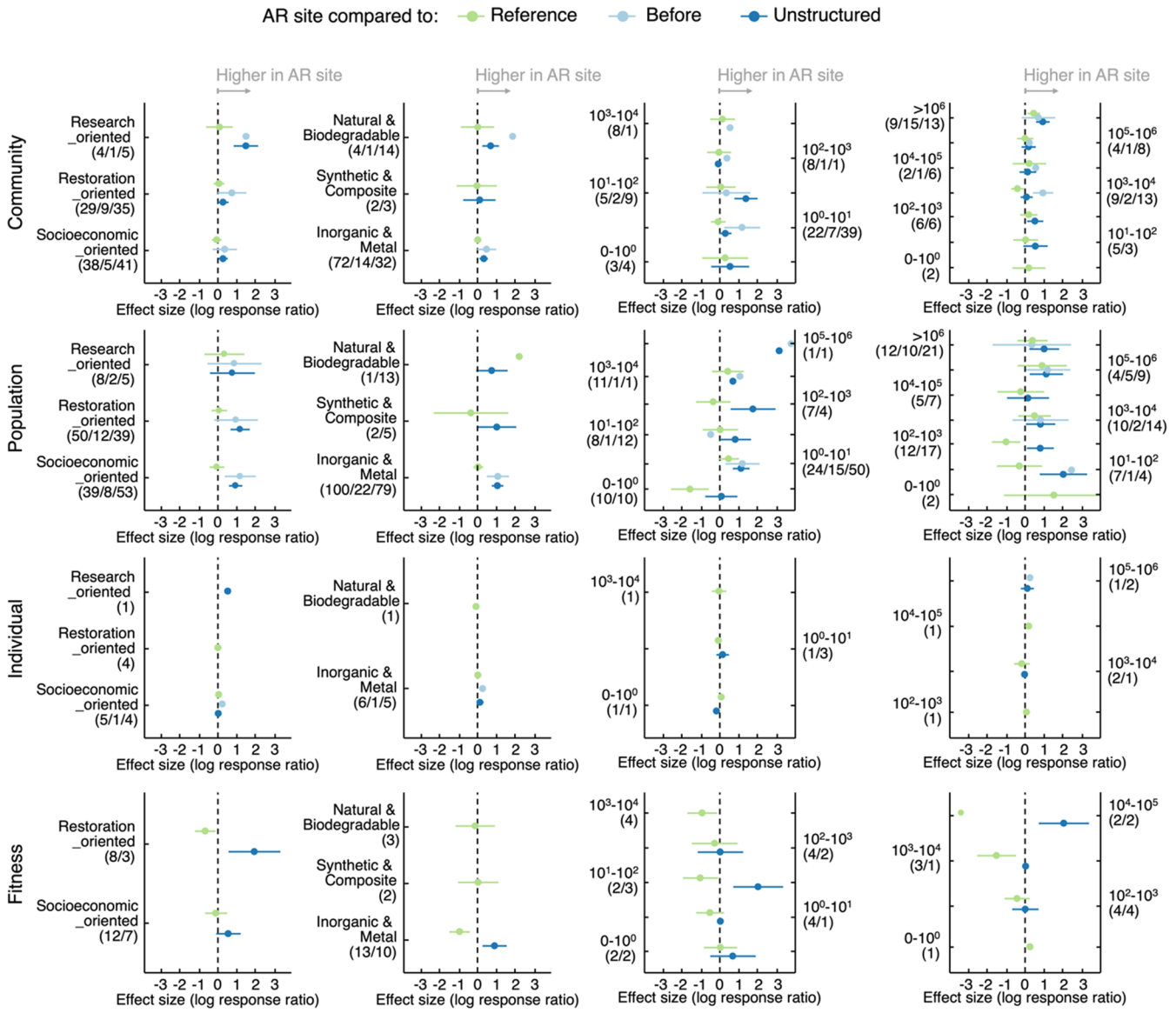


Figure 3. Forest plots of response ratios for community, population, individual, and fitness metrics affected by artificial reefs (AR), grouped by objective, material type, module area, and deployment area (panels from left to right). Sample sizes in parentheses on the *y*-axis correspond to Reference, Before, and Unstructured.

(−40%; Figure 2, Table S3), particularly when inorganic and metal materials were used and at larger deployment areas (Figure 3). Negative response ratios indicate lower metric values in AR areas than in reference sites, rather than negative effects of AR deployment. These results indicate a density−performance decoupling, which may reflect organism concentration around ARs rather than fully enhanced demographic production.

Overall, ARs provide consistent benefits to marine organisms by enhancing community diversity, population abundance, and individual size. Nonetheless, the contrasting fitness responses relative to unstructured controls and reference habitats suggest that ARs have not yet achieved ecological equivalence with natural reef ecosystems. Sensitivity and publication-bias diagnostics further indicated that these findings are robust to effect-size nonindependence and potential small-study effects (Tables S4−S6; Figure S2). Notably, our meta-analysis primarily captures local ecological responses at AR sites and does not directly quantify organism redistribution or potential ecological trade-offs (e.g., losses in surrounding habitats), which would require spatially explicit assessments of movement or regional population dynamics.

INNOVATING ARTIFICIAL REEF APPROACH FOR SUSTAINABLE BIODIVERSITY RECOVERY

While the overall ecological effects of ARs are strongly positive (Figure 2), their small size and limited deployment highlight the need for a paradigm shift in AR approaches to achieve significant upscaling (Figure 1b). Moreover, AR applications could be more effective in promoting sustainable biodiversity recovery by addressing fitness shortfalls linked to inappropriate materials and deployment scales (Figure 3) and by integrating complementary active reef restoration techniques to further enhance habitat quality.

To date, active reef restoration and AR deployment have often been developed in parallel, with partially overlapping but distinct emphases. The former targets degraded habitats with minimal natural recovery, where limited settlement substrates

https://doi.org/10.1021/acs.est.5c13167
Environ. Sci. Technol. 2026, 60, 14782−14792

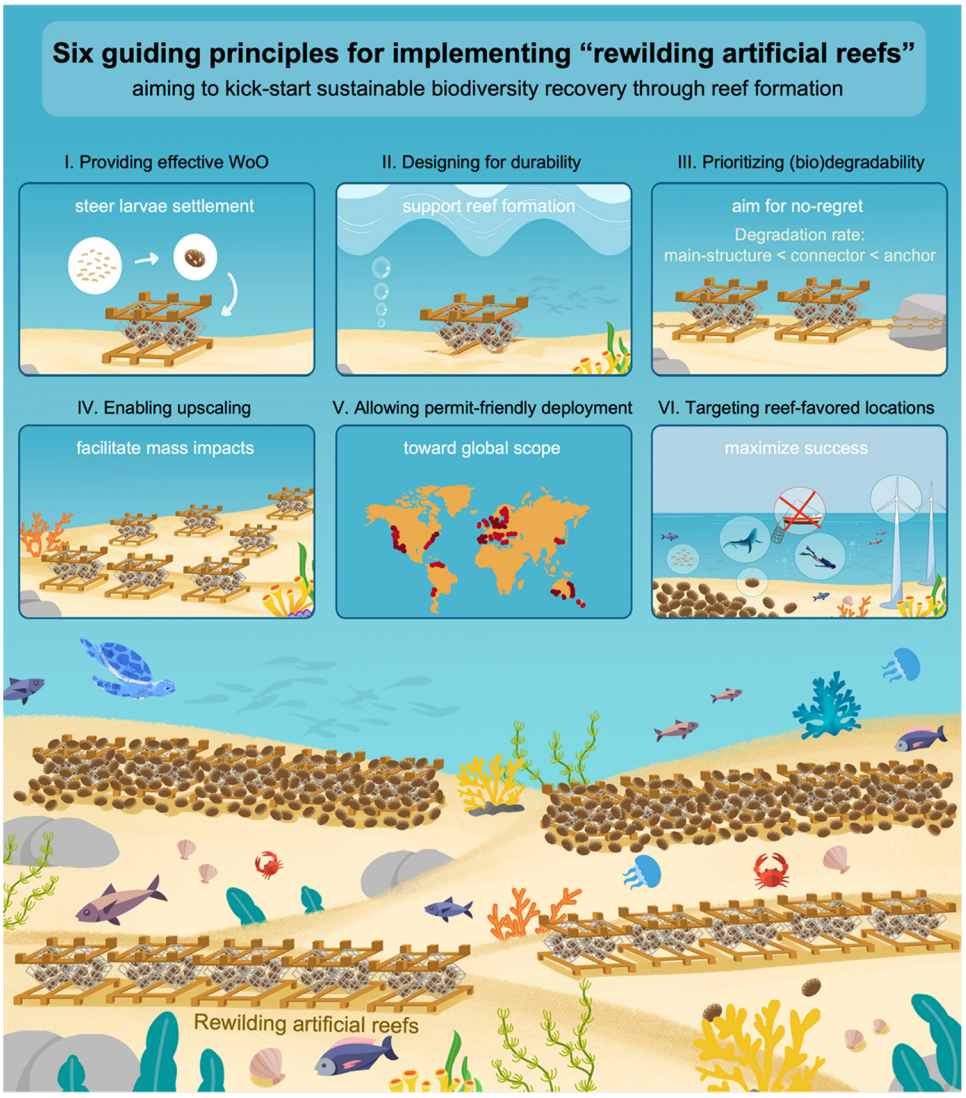


Figure 4. Conceptual diagram illustrating the six guiding principles for the development and deployment of rewilding artificial reefs.

or unreliable larval supply hinder reef-building species establishment.[33,34] Common techniques include adult/spat transplantation,[35] substrate modification,[36] positive species interactions,[37] acoustic enrichment,[38] and integrated multi-trophic aquaculture.[39] Yet these approaches are often constrained to small-scale applications due to implementation costs, logistical complexity, and context-dependent feasibility.[9,40] Furthermore, reef formation is inherently a long-term process (e.g., ~10 years for oyster reefs,[40] ~30 years for coral reefs[41]), providing minimal biodiversity support until sufficient relief height is reached.[16,42] In contrast, AR efforts have largely focused on enhancing the physical structure of habitats,[24,43] a feature immediately contributing to biodiversity recovery. However, static AR structures alone do not necessarily lead to the gradual development of self-sustaining, expanding living reef ecosystems, especially in degraded systems with limited larval supply.[44,45] Integrating active reef restoration techniques into AR innovation can maximize the benefits of both components, delivering immediate and midterm biodiversity gains comparable to conventional AR designs while also fostering the gradual development of reef-building species to enhance habitat quality, thereby promoting sustainable biodiversity recovery by addressing bottlenecks that limit the fitness of resident organisms (Figure 2).

We therefore advocate an innovative AR approach, termed "rewilding ARs" (rARs), which draws on the widely used concept of "rewilding" from terrestrial ecosystems.[46,47] The rAR is conceptually analogous to the use of temporary, degradable habitats in terrestrial restoration (e.g., postbushfire cardboard shelters[48]) that facilitate early recovery before naturally phasing out. In the marine context, however, such structures serve a dual role by not only providing physical habitat but also buffering stressors to create WoO for transition to living functional reefs, enabling gradual degradation to minimize human impact.

SIX GUIDING PRINCIPLES FOR IMPLEMENTING "REWILDING ARTIFICIAL REEFS"

Here, six guiding principles for developing and applying rARs are formulated by integrating scientific insights and practical expertise from ecologists, civil engineers, legal experts, environmental consultants, and NGOs specializing in sea restoration (Figure 4).

https://doi.org/10.1021/acs.est.5c13167
Environ. Sci. Technol. 2026, 60, 14782−14792

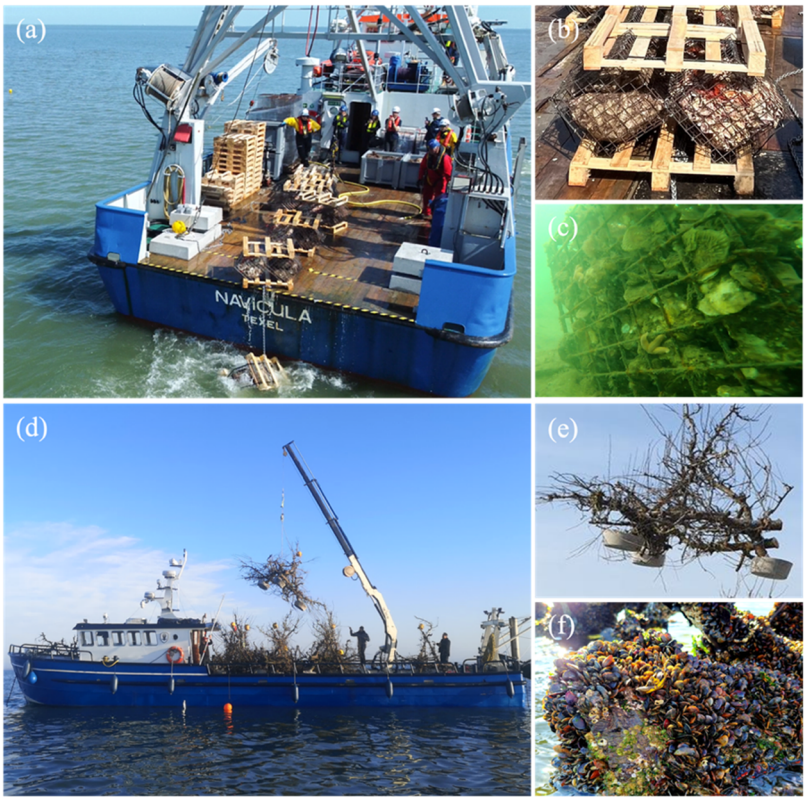


Figure 5. Examples of "rewilding artificial reefs" under development. (a−c) Oyster cradles; photo credit: ARK Rewilding Nederland. (d−f) Tree-reefs; photo credit: Jon Dickson.

Principle I. Providing Effective WoO — Steer Larvae Settlement

Reef-building larvae prefer hard, rough substrate surfaces,[21,49] requiring rARs to use rigid materials with complex surface textures.[50] To attract preferred reef-building larvae and facilitate transitions from physical structures to target reefs, rARs could mimic natural reefs in structure and morphology while incorporating shells or fragments of target species to serve as settling cues.[42,51] In larvae-limited areas, live individuals of the target species may be introduced, provided they are disease- and contaminant-free.[52] Installation timing of rARs should align with species-specific life history traits, such as deploying them during the optimal spawning season of target species, to minimize competition with opportunistic colonizers.[53]

Principle II. Designing for Durability — Support Reef Formation

After installation, rARs should require no further procedures (e.g., maintenance), allowing recovery to progress naturally with minimal human intervention.[46,47] They must therefore maintain sufficient stability over time to resist disruptive displacement and structural failure under the design hydrodynamic load (e.g., surge with a 50- or 100-year return period).[21,54] Structural optimization, rather than merely increasing mass,[55] is recommended—for example, incorporating holes in the main structure or introducing irregular extensions to create porous structures with restricted drag. Sediment accumulation during or after intense hydrodynamic events,[56,57] especially in soft-bottom systems, presents another challenge. It is thus essential to incorporate adequate vertical relief to ensure that rARs maintain functionality even when partially buried. Both stability and relief considerations are site-specific and require assessments before on-site deployment (see Principle VI), including consideration of drag increases associated with ecological colonization when evaluating stability.

Principle III. Prioritizing (Bio)Degradability — Aim for No-Regret

rARs are essentially temporary, leveraged to facilitate WoO for reef-builder recruitment (see Principle I). Once they result in living reefs hosting self-sustaining populations of adults, rARs should gradually disappear, allowing natural forces to take precedence in subsequent development.[47] It is therefore essential to use (bio)degradable materials in the production of rARs, with the expectation that they serve in providing WoO for reef formation over the required time span, gradually degrading thereafter until complete disappearance. Even in the worst-case scenario where rARs fail to initiate nature reef formation postinstallation, their degradable nature eliminates the necessity for retrieval and their crafted three-dimensional structure may also foster biodiversity as a temporary benefit before complete degradation, leaving no regrets after installation. Biodegradability is preferred, but some degree of degradability is often unavoidable, as offshore safety may require using (thin) steel for construction and lifting; persistent weights such as thick metal plates should be avoided. The specific minimum degradation period should match the time span required for functional recovery of target habitats; for instance, ∼10 years for oyster reefs[40] and ∼ 30 years for coral reefs.[41] In cases where rARs involve different components, their logical degradation sequence should be considered, such as: main structure lifespan < connector

https://doi.org/10.1021/acs.est.5c13167
Environ. Sci. Technol. 2026, 60, 14782−14792

lifespan < anchor weight lifespan. This helps cut costs while ensuring effectiveness (see Principle IV).

Principle IV. Enabling Upscaling — Facilitate Mass Impacts

Scalable strategies are indispensable for effective sea restoration with rARs, requiring both mass production and mass deployment at reduced costs. Concerning mass production, viable implementation approaches involve utilizing locally sourced (bio)degradable materials (e.g., economically unviable fruit trees[58]), affordable commercial biobased materials (e.g., BESE[59]), and industrially mass-manufactured products. These can be seamlessly integrated as components for rARs without major modifications to their dimensions, resulting in rARs of varying sizes to enhance habitat diversity and support multiple reef-dwelling species. For mass deployment, leveraging the industrial experience of local offshore operations[60] is recommended, as they have discovered economies of scale and can provide technological advancements to reduce transportation costs, streamline deployment processes, and rationalize deployment tools, thereby enhancing scalability efficiency. One context-specific deployment example is the use of connectors to side-cast multiple rAR units (Figure 5), enabling controlled spacing at reduced costs and with fewer vessel constraints than crane methods.

Principle V. Allowing Permit-Friendly Deployment — Toward Global Scope

ARs face strict regulations (e.g., dumping legislation[32]) due to concerns such as improper material usage,[24,31] with deployment requiring intricate permitting and, in most cases, dismantling arrangements.[31] International law, particularly the United Nations Convention on the Law of the Sea[61] and relevant conventions,[32] excludes from "dumping" any placement serving legitimate purposes, implying that restoration-oriented rARs—further supported by the Convention of Biological Diversity[62] for their role in ecosystem recovery and biodiversity targets—do not constitute dumping. Moreover, the "degradation" of rARs is essentially synonymous with "dismantling" and occurs spontaneously without incurring costs or effort. Within this legal framework, coastal states retain authority to develop national procedures for large-scale rAR applications. Using (bio)degradable materials could mitigate these legal restrictions and simplify the permitting process (see Principle III). Additionally, the judicious selection of deployment sites for rARs represents a pivotal stride in advancing permit-friendly deployment (see Principle VI).

Principle VI. Targeting Reef-Favored Locations — Maximize Success

Site selection is critical for rAR deployment, with priority given to areas meeting three core criteria: (i) suitable ecological niches where target reef-building species currently or historically existed (i.e., conducive to reef growth[63]); (ii) larval sinks receiving propagules from nearby or distant reefs (i.e., larval availability[64]); and (iii) absence or strict prohibition of human stressors such as trawling (e.g., in MPAs[11]). Additional advantages arise from locations near aquaculture farms cultivating target species, coastal or marine facilities incorporating nature-inclusive designs, and well-regulated tourism and sightseeing zones. Where conditions and budgets allow, site suitability assessments using in situ monitoring or model simulations can refine location choices. Recommended indicators include (i) maximum hydrodynamic intensity, which should not surpass the stability threshold of rARs; (ii) maximum sediment accumulation, which should fall significantly below the relief height of rARs; and (iii) water conditions during extreme events, which should remain within the tolerance range of target reef-building species. For rAR applications in scenarios lacking larvae due to the absence or extinction of target reef-building species, measures to ensure adequate larval supply should be implemented in tandem.[60]

INSPIRATIONAL EXAMPLES FOR APPLYING "REWILDING ARTIFICIAL REEFS"

Here, we showcase two cutting-edge rAR examples that have made significant strides in applying the six principles, aiming to inspire future sea restoration practices for sustainable biodiversity recovery rather than to serve as universally applicable designs.

Example 1: Rebuilding Marine Life in the North Sea Using "Oyster Cradles"

In the North Sea, bottom-trawl fisheries and diseases have driven native European flat oysters to near extinction,[15,30] hindering any natural recovery due to the barren sandy seafloor and lack of larvae.[52] Since 2016, initiatives have actively worked to restore flat oyster reefs and associated biodiversity,[15,52,65] yet scaling up remains a challenge.[18]

A restoration project launched in spring 2023 in Voordelta, where bottom trawling is prohibited (Principle VI), marked a pilot aimed at enabling the upscaling of local oyster reef restoration. This was realized by constructing 45 innovative oyster cradles (developed by ARK Rewilding Nederland, https://arkrewilding.nl/) from low-cost (bio)degradable (Principals III and IV) materials, including standard wooden pallets and ungalvanized, nonpermanent gabions (Figure 5b). These materials are produced with low-carbon emissions and obviate the need for postdeployment retrieval (Principals V). Oyster cradles were filled with oyster shells coated with disease-free two-week-old oyster spat cultivated in hatcheries, providing substrate, addressing the local scarcity of larvae, and avoiding the introduction of unwanted fouling species (Principles I and VI). The use of wooden pallets at the bottom minimizes the risk of burial, while the porous structure of gabions and dispersed arrangement of multiple oyster cradles attenuate hydrodynamics (Principle II). Additionally, oyster cradles featured a modular design to simplify assembly on board and were connected in a string to streamline deployment in a side-cast manner (Principle IV; Figure 5a), enabling all of the 45 oyster cradles to be deployed within one day.

After six months, all oyster cradles remained in place, with young flat oysters surviving and growing, and inhabited by marine life of diverse trophic levels (Figure 5c). This signals a robust commencement, fostering sustainable biodiversity recovery by leveraging ARs to create a WoO for reef formation.

Example 2: Biodiversity Recovery in the Wadden Sea Using "Tree-Reefs"

In the Wadden Sea, biodiversity is declining due to the loss of biogenic reefs following destructive fishing.[58] Ongoing sediment import and altered bathymetry from damming further inhibit the natural recruitment of reef-forming species.[58,66] Inspired by marine biodiversity hotspots associated with in situ tree stumps or sunken driftwood,[67] innovative Tree-reefs (developed by NIOZ, https://www.nioz.nl/en) have been deployed to kick-start biodiversity recovery.

https://doi.org/10.1021/acs.est.5c13167
Environ. Sci. Technol. 2026, 60, 14782−14792

In a pilot project initiated in 2022, 32 Tree-Reefs were deployed using small fishing vessels at locations where trawling is prohibited and away from major shipping lanes (principle VI; Figure 5d). Each of the Tree-Reefs is constructed from six short-stemmed pear trees that are no longer economically viable, with three assembled into a pyramid shape and the other three used as horizontal beams anchored at the base (principle IV; Figure 5e). The resulting three-dimensional complexity, combined with internal interstitial spaces, provides shelter while attenuating local hydrodynamics to ensure stability (principle II). With sufficient relief height, the Tree-Reefs effectively mitigate the risk of being buried (principle II). The nature of Tree-Reefs determines that they are nontoxic, compatible with the marine environment, and leave a negligible carbon footprint (Principle V). Furthermore, the Tree-Reefs provide complex-surfaced hard substrates for larval settlement (principle I) and gradually degrade over several decades (principle III).

The preliminary investigation conducted six months postdeployment indicated that the introduction of Tree-Reefs has effectively enhanced the diversity and abundance of local biological communities (Figure 5f), spanning from bryozoans to shrimps to predatory fish.[58] As reef-building populations thrive, natural wilding of community composition is anticipated.

Note that oyster cradles and tree-reefs currently reside within the small-scale pilot initiatives. While exhibiting short-term prospects, both necessitate future refinement to fully align with Principles III and IV. Specifically, both should replace concrete anchoring blocks with (bio)degradable materials and optimize cost-effective manufacturing for hectare-scale deployment. Oyster cradles might replace nongalvanized gabions with biobased cages (if alternatives are strong enough) and incorporate larger vertical structures to support a wider range of reef-dependent species.

OUTLOOK

ARs have demonstrated their effectiveness in bending the curve of marine biodiversity loss and reviving associated ecosystem functions. Notably, current evidence synthesis is primarily based on structural ecological metrics, while functional or ecosystem-level indicators (e.g., trophic interactions or biogeochemical processes) remain rarely reported across AR studies, highlighting an important priority for future research. In parallel, conventional ARs require material, structural, and functional innovations to achieve scalable, cost-effective, and ecologically sustainable restoration. Our six guiding principles provide practical direction, emphasizing the use of (bio)degradable materials and the creation of WoOs for self-sustaining reefs. Although fully principle-aligned rAR applications are rare and in early stages, pilot initiatives already show promising short-term prospects for enhancing local biodiversity.[58] To maximize long-term success, a stepwise implementation is advised: start with small-scale pilot projects with successful reef-builder recruitment as a phased benchmark, and then scale up to larger projects with suitably adjusted designs and deployment methods. rAR deployment should remain transparent, with regulatory, industry, and public input shaping rAR design and deployment plans.[18,21,60] Equally important is the establishment of standardized long-term monitoring and cost-benefit reporting frameworks, alongside swiftly disseminating technical specifics from successful cases.[16,65] This will facilitate the integration and systematic evaluation of related practices conducted across countries with diverse policy, socioeconomic, and ecological contexts, advancing more effective and sustainable global sea restoration strategies.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.5c13167.

Box 1 | Introducing the concept of Windows of Opportunity; methods for (i) literature review on the trend of artificial reef applications and (ii) meta-analysis of artificial reefs in supporting marine life; and publications used for literature research and meta-analysis (PDF)

AUTHOR INFORMATION

Corresponding Author

Zhiyuan Zhao − *State Key Laboratory of Estuarine and Coastal Research, East China Normal University, 200241 Shanghai, China; Royal Netherlands Institute for Sea Research, 4401 NT Yerseke, The Netherlands;* orcid.org/0000-0002-4113-3796; Email: zhiyuan.zhao@nioz.nl

Authors

Tjisse van der Heide − *Royal Netherlands Institute for Sea Research, 4401 NT Yerseke, The Netherlands*

Pauline Kamermans − *Wageningen Marine Research, 1780 AB Den Helder, The Netherlands*

Joop Coolen − *Wageningen Marine Research, 1780 AB Den Helder, The Netherlands*

Alex Oude Elferink − *Netherlands Institute for the Law of the Sea; Utrecht University Centre for Water, Oceans and Sustainability Law School of Law, Utrecht University, 3512 HT Utrecht, The Netherlands*

Christiaan van Sluis − *North Sea Foundation, 3511 MJ Utrecht, The Netherlands*

Remment v Hofstede − *Delft University of Technology, Civil Engineering and Geosciences, 2628 CN Delft, The Netherlands; Van Oord Dredging and Marine Contractors, 3063 NH Rotterdam, The Netherlands;* orcid.org/0000-0003-0958-5669

Eline van Onselen − *North Sea Foundation, 3511 MJ Utrecht, The Netherlands*

Wouter van Broekhoven − *Van Oord Dredging and Marine Contractors, 3063 NH Rotterdam, The Netherlands*

Wouter Lengkeek − *Waardenburg Ecology, 4101 CK Culemborg, The Netherlands*

Juste Motuzaite − *ARK Rewilding Netherland, 6541 AH Nijmegen, The Netherlands*

Jon Dickson − *Royal Netherlands Institute for Sea Research, 4401 NT Yerseke, The Netherlands*

Rob Witbaard − *Royal Netherlands Institute for Sea Research, 4401 NT Yerseke, The Netherlands*

Mark van Koningsveld − *Delft University of Technology, Civil Engineering and Geosciences, 2628 CN Delft, The Netherlands; Van Oord Dredging and Marine Contractors, 3063 NH Rotterdam, The Netherlands*

Karel van den Wijngaard − *ARK Rewilding Netherland, 6541 AH Nijmegen, The Netherlands*

Ernst Schrijver − *ARK Rewilding Netherland, 6541 AH Nijmegen, The Netherlands*

https://doi.org/10.1021/acs.est.5c13167
Environ. Sci. Technol. 2026, 60, 14782−14792

Karin Didderen − *Waardenburg Ecology, 4101 CK Culemborg, The Netherlands*
Tjeerd J. Bouma − *Royal Netherlands Institute for Sea Research, 4401 NT Yerseke, The Netherlands; Faculty of Geosciences, Department of Physical Geography, Utrecht University, 3584 CB Utrecht, The Netherlands; HZ University of Applied Sciences, Building with Nature group, 4382 NW Vlissingen, The Netherlands*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.5c13167

Author Contributions

Conceptualization: Z.Z., T.v.d.H., and T.J.B.; Methodology: Z.Z., and T.J.B.; Visualization: Z.Z.; Supervision: T.J.B.; Writing—original draft: Z.Z. and T.J.B.; Writing—review and editing: Z.Z., T.v.d.H., P.K., J.C., A.O.E., C.v.S., R.t.H., E.v.O., W.v.B., W.L., J.M., J.D., R.W., M.v.K., K.v.d.W., E.S., K.D., and T.J.B.

Notes

The authors declare no competing financial interest.

Biography



Dr. Zhiyuan Zhao received a Ph.D. in Geosciences from Utrecht University, subsequently worked as a postdoctoral researcher at the Royal Netherlands Institute for Sea Research (NIOZ), and is now a Principal Investigator at East China Normal University. Dr. Zhao's research focuses on understanding the responses of coastal ecosystems to climate change and human disturbances, spanning multiple habitats including intertidal salt marshes, subtidal mussel beds, and offshore oyster reefs. He is proficient in applying interdisciplinary and integrative methodologies that combine field monitoring, flume and mesocosm experiments, numerical modeling, and big data analytics, and has accumulated extensive hands-on experience in coastal multihabitat restoration.

■ ACKNOWLEDGMENTS

This work was funded by start-up research funding from East China Normal University, the No-Regret project (NZ4721.0) funded by the national program Natuurversterking Noordzee, and the Winor project (LWV20.234) cofunded by TKI Agri & Food and TKI Wind op Zee.

■ REFERENCES

(1) Duarte, C. M.; Agusti, S.; Barbier, E.; Britten, G. L.; Castilla, J. C.; Gattuso, J.-P.; Fulweiler, R. W.; Hughes, T. P.; Knowlton, N.; Lovelock, C. E.; Lotze, H. K.; Predragovic, M.; Poloczanska, E.; Roberts, C.; Worm, B. Rebuilding marine life. *Nature* **2020**, *580* (7801), 39−51.
(2) Roberts, C. M.; O'Leary, B. C.; McCauley, D. J.; Cury, P. M.; Duarte, C. M.; Lubchenco, J.; Pauly, D.; Sáenz-Arroyo, A.; Sumaila, U. R.; Wilson, R. W.; Worm, B.; Castilla, J. C. Marine reserves can mitigate and promote adaptation to climate change. *Proc. Natl. Acad. Sci. U.S.A.* **2017**, *114* (24), 6167−6175.
(3) Worm, B.; Barbier, E. B.; Beaumont, N.; Duffy, J. E.; Folke, C.; Halpern, B. S.; Jackson, J. B. C.; Lotze, H. K.; Micheli, F.; Palumbi, S. R.; Sala, E.; Selkoe, K. A.; Stachowicz, J. J.; Watson, R. Impacts of biodiversity loss on ocean ecosystem services. *Science* **2006**, *314* (5800), 787−790.
(4) Yan, H. F.; Kyne, P. M.; Jabado, R. W.; Leeney, R. H.; Davidson, L. N. K.; Derrick, D. H.; Finucci, B.; Freckleton, R. P.; Fordham, S. V.; Dulvy, N. K. Overfishing and habitat loss drive range contraction of iconic marine fishes to near extinction. *Sci. Adv.* **2021**, *7* (7), No. eabb6026.
(5) Micheli, F. Eutrophication, fisheries, and consumer-resource dynamics in marine pelagic ecosystems. *Science* **1999**, *285* (5432), 1396−1398.
(6) McCauley, D. J.; Pinsky, M. L.; Palumbi, S. R.; Estes, J. A.; Joyce, F. H.; Warner, R. R. Marine defaunation: animal loss in the global ocean. *Science* **2015**, *347* (6219), No. 1255641.
(7) Penn, J. L.; Deutsch, C. Avoiding ocean mass extinction from climate warming. *Science* **2022**, *376* (6592), 524−526.
(8) Urban, M. C. Accelerating extinction risk from climate change. *Science* **2015**, *348* (6234), 571−573.
(9) Hughes, T. P.; Baird, A. H.; Morrison, T. H.; Torda, G. Principles for coral reef restoration in the anthropocene. *One Earth* **2023**, *6* (6), 656−665.
(10) Fischer, J.; Riechers, M.; Loos, J.; Martin-Lopez, B.; Temperton, V. M. Making the UN decade on ecosystem restoration a social-ecological endeavour. *Trends Ecol. Evol.* **2021**, *36* (1), 20−28.
(11) Grorud-Colvert, K.; Sullivan-Stack, J.; Roberts, C.; Constant, V.; Horta e Costa, B.; Pike, E. P.; Kingston, N.; Laffoley, D.; Sala, E.; Claudet, J.; Friedlander, A. M.; Gill, D. A.; Lester, S. E.; Day, J. C.; Gonçalves, E. J.; Ahmadia, G. N.; Rand, M.; Villagomez, A.; Ban, N. C.; Gurney, G. G.; Spalding, A. K.; Bennett, N. J.; Briggs, J.; Morgan, L. E.; Moffitt, R.; Deguignet, M.; Pikitch, E. K.; Darling, E. S.; Jessen, S.; Hameed, S. O.; Di Carlo, G.; Guidetti, P.; Harris, J. M.; Torre, J.; Kizilkaya, Z.; Agardy, T.; Cury, P.; Shah, N. J.; Sack, K.; Cao, L.; Fernandez, M.; Lubchenco, J. The MPA Guide: A framework to achieve global goals for the ocean. *Science* **2021**, *373* (6560), No. eabf0861.
(12) Sala, E.; Mayorga, J.; Bradley, D.; Cabral, R. B.; Atwood, T. B.; Auber, A.; Cheung, W.; Costello, C.; Ferretti, F.; Friedlander, A. M.; Gaines, S. D.; Garilao, C.; Goodell, W.; Halpern, B. S.; Hinson, A.; Kaschner, K.; Kesner-Reyes, K.; Leprieur, F.; McGowan, J.; Morgan, L. E.; Mouillot, D.; Palacios-Abrantes, J.; Possingham, H. P.; Rechberger, K. D.; Worm, B.; Lubchenco, J. Protecting the global ocean for biodiversity, food and climate. *Nature* **2021**, *592* (7854), 397−402.
(13) Eger, A. M.; Earp, H. S.; Friedman, K.; Gatt, Y.; Hagger, V.; Hancock, B.; Kaewsrikhaw, R.; Mcleod, E.; Moore, A. M.; Niner, H. J.; Razafinaivo, F.; Sousa, A. I.; Stankovic, M.; Worthington, T. A.; Bayraktarov, E.; Saunders, M.; Vergés, A.; Reeves, S. The need, opportunities, and challenges for creating a standardized framework for marine restoration monitoring and reporting. *Biol. Conserv.* **2022**, *266*, No. 109429.
(14) Howie, A. H.; Bishop, M. J. Contemporary oyster reef restoration: responding to a changing world. *Front. Ecol. Evol.* **2021**, *9*, No. 689915.
(15) Kamermans, P.; Walles, B.; Kraan, M.; Van Duren, L. A.; Kleissen, F.; Van der Have, T. M.; Smaal, A. C.; Poelman, M. Offshore Wind Farms as Potential Locations for Flat Oyster (*Ostrea edulis*) Restoration in the Dutch North Sea. *Sustainability* **2018**, *10* (11), No. 3942.
(16) Hemraj, D. A.; Bishop, M. J.; Hancock, B.; Minuti, J. J.; Thurstan, R. H.; Zu Ermgassen, P. S. E.; Russell, B. D. Oyster reef

restoration fails to recoup global historic ecosystem losses despite substantial biodiversity gain. *Sci. Adv.* **2022**, *8* (47), No. eabp8747.
(17) Hermoso, V.; Carvalho, S. B.; Giakoumi, S.; Goldsborough, D.; Katsanevakis, S.; Leontiou, S.; Markantonatou, V.; Rumes, B.; Vogiatzakis, I. N.; Yates, K. L. The EU Biodiversity Strategy for 2030: Opportunities and challenges on the path towards biodiversity recovery. *Environ. Sci. Policy* **2022**, *127*, 263−271.
(18) ter Hofstede, R.; van Koningsveld, M. Defining operational objectives for nature-inclusive marine infrastructure to achieve system-scale impact. *Front. Mar. Sci.* **2024**, *11*, No. 1358851.
(19) 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* **2023**, *10* (7), No. 121.
(20) Lee, M. O.; Otake, S.; Kim, J. K. Transition of artificial reefs (ARs) research and its prospects. *Ocean Coastal Manage.* **2018**, *154*, 55−65.
(21) Vivier, B.; Dauvin, J. C.; Navon, M.; Rusig, A.-M.; Mussio, I.; Orvain, F.; Boutouil, M.; Claquin, P. Marine artificial reefs, a meta-analysis of their design, objectives and effectiveness. *Global Ecol. Conserv.* **2021**, *27*, No. e01538.
(22) Tickell, S. C. y.; Sáenz-Arroyo, A.; Milner-Gulland, E. J. Sunken worlds: The past and future of human-made reefs in marine conservation. *BioScience* **2019**, *69* (9), 725−735.
(23) Higgins, E.; Metaxas, A.; Scheibling, R. E. A systematic review of artificial reefs as platforms for coral reef research and conservation. *PLoS One* **2022**, *17* (1), No. e0261964.
(24) Ramm, L. A.; Florisson, J. H.; Watts, S. L.; Becker, A.; Tweedley, J. R. Artificial reefs in the Anthropocene: a review of geographical and historical trends in their design, purpose, and monitoring. *Bull. Mar. Sci.* **2021**, *97* (4), 699−728.
(25) Carral, L.; Tarrío-Saavedra, J.; Barros, J. J. C.; Fabal, C. C.; Ramil, A.; Álvarez-Feal, C. Considerations on the programmed functional life (one generation) of a green artificial reef in terms of the sustainability of the modified ecosystem. *Heliyon* **2023**, *9* (4), No. e14978.
(26) Grasselli, F.; Strain, E. M. A.; Airoldi, L. Material type and origin influences the abundances of key taxa on artificial structures. *Coastal Eng.* **2024**, *187*, No. 104419.
(27) Huang, X.; Wang, Z.; Liu, Y.; Hu, W.; Ni, W. On the use of blast furnace slag and steel slag in the preparation of green artificial reef concrete. *Constr. Build. Mater.* **2016**, *112*, 241−246.
(28) Paxton, A. B.; Steward, D. N.; Mille, K. J.; Renchen, J.; Harrison, Z. H.; Byrum, J. S.; Brinton, C.; Nelson, A.; Simpson, E.; Clarke, P. J.; LaPorta, C.; Barrett, P. D.; Rousseau, M.; Newton, D. C.; Rigby, R. B.; Williams, D. T.; Shipley, J. B.; Murakawa, P.; Runde, B. J.; Riley, K. L.; Bacheler, N. M.; Kellison, G. T.; Taylor, J. C. Artificial reef footprint in the United States ocean. *Nat. Sustainability* **2024**, *7* (2), 140−147.
(29) Folpp, H. R.; Schilling, H. T.; Clark, G. F.; Lowry, M. B.; Maslen, B.; Gregson, M.; Suthers, I. M. Artificial reefs increase fish abundance in habitat-limited estuaries. *J. Appl. Ecol.* **2020**, *57* (9), 1752−1761.
(30) Thurstan, R. H.; McCormick, H.; Preston, J.; Ashton, E. C.; Bennema, F. P.; Cetinić, A. B.; Brown, J. H.; Cameron, T. C.; da Costa, F.; Donnan, D. W.; Ewers, C.; Fortibuoni, T.; Galimany, E.; Giovanardi, O.; Grancher, R.; Grech, D.; Hayden-Hughes, M.; Helmer, L.; Jensen, K. T.; Juanes, J. A.; Latchford, J.; Moore, A. B. M.; Moutopoulos, D. K.; Nielsen, P.; von Nordheim, H.; Ondiviela, B.; Peter, C.; Pogoda, B.; Poulsen, B.; Pouvreau, S.; Roberts, C. M.; Scherer, C.; Smaal, A. C.; Smyth, D.; Strand, Å.; Theodorou, J. A.; zu Ermgassen, P. S. E. Records reveal the vast historical extent of European oyster reef ecosystems. *Nat. Sustainability* **2024**, *7*, 1719−1729.
(31) Techera, E. J.; Chandler, J. Offshore installations, decommissioning and artificial reefs: Do current legal frameworks best serve the marine environment? *Mar. Policy* **2015**, *59*, 53−60.
(32) London Convention. Convention on the prevention of marine pollution by dumping of wastes and other matter 1972 https://Www.Imo.Org/En/OurWork/Environment/Pages/London-Convention-Protocol.Aspx..
(33) Rinkevich, B. Climate change and active reef restoration—ways of constructing the reefs of tomorrow. *J. Mar. Sci. Eng.* **2015**, *3* (1), 111−127.
(34) Rinkevich, B. Rebuilding coral reefs: does active reef restoration lead to sustainable reefs? *Curr. Opin. Environ. Sustainability* **2014**, *7*, 28−36.
(35) Rinkevich, B. Novel tradable instruments in the conservation of coral reefs, based on the coral gardening concept for reef restoration. *J. Environ. Manage.* **2015**, *162*, 199−205.
(36) Goelz, T.; Vogt, B.; Hartley, T. Alternative substrates used for oyster reef restoration: A review. *J. Shellfish Res.* **2020**, *39* (1), 1−12.
(37) Reeves, S. E.; Renzi, J. J.; Fobert, E. K.; Silliman, B. R.; Hancock, B.; Gillies, C. L. Facilitating better outcomes: How positive species interactions can improve oyster reef restoration. *Front. Mar. Sci.* **2020**, *7*, No. 656.
(38) Gordon, T. A. C.; Radford, A. N.; Davidson, I. K.; Barnes, K.; McCloskey, K.; Nedelec, S. L.; Meekan, M. G.; McCormick, M. I.; Simpson, S. D. Acoustic enrichment can enhance fish community development on degraded coral reef habitat. *Nat. Commun.* **2019**, *10* (1), No. 5414.
(39) Giangrande, A.; Gravina, M. F.; Rossi, S.; Longo, C.; Pierri, C. Aquaculture and restoration: Perspectives from mediterranean sea experiences. *Water* **2021**, *13* (7), No. 991.
(40) Hernández, A. B.; Brumbaugh, R. D.; Frederick, P.; Grizzle, R.; Luckenbach, M. W.; Peterson, C. H.; Angelini, C. Restoring the eastern oyster: how much progress has been made in 53 years? *Front. Ecol. Environ.* **2018**, *16* (8), 463−471.
(41) Rooper, C. N.; Wilkins, M. E.; Rose, C. S.; Coon, C. Modeling the impacts of bottom trawling and the subsequent recovery rates of sponges and corals in the Aleutian Islands, Alaska. *Cont. Shelf Res.* **2011**, *31* (17), 1827−1834.
(42) Schulte, D. M.; Burke, R. P.; Lipcius, R. N. Unprecedented restoration of a native oyster metapopulation. *Science* **2009**, *325* (5944), 1124−1128.
(43) Lemoine, H. R.; Paxton, A. B.; Anisfeld, S. C.; Rosemond, R. C.; Peterson, C. H. Selecting the optimal artificial reefs to achieve fish habitat enhancement goals. *Biol. Conserv.* **2019**, *238*, No. 108200.
(44) Lemasson, A. J.; Somerfield, P. J.; Schratzberger, M.; Thompson, M. S. A.; Firth, L. B.; Couce, E.; McNeill, C. L.; Nunes, J.; Pascoe, C.; Watson, S. C. L.; Knights, A. M. A global meta-analysis of ecological effects from offshore marine artificial structures. *Nat Sustainability* **2024**, *7* (4), 485−495.
(45) Beck, M. W.; Brumbaugh, R. D.; Airoldi, L.; Carranza, A.; Coen, L. D.; Crawford, C.; Defeo, O.; Edgar, G. J.; Hancock, B.; Kay, M. C.; Lenihan, H. S.; Luckenbach, M. W.; Toropova, C. L.; Zhang, G.; Guo, X. Oyster reefs at risk and recommendations for conservation, restoration, and management. *BioScience* **2011**, *61* (2), 107−116.
(46) Perino, A.; Pereira, H. M.; Navarro, L. M.; Fernández, N.; Bullock, J. M.; Ceausu, S.; Cortés-Avizanda, A.; van Klink, R.; Kuemmerle, T.; Lomba, A.; Pe'er, G.; Plieninger, T.; Rey Benayas, J. M.; Sandom, C. J.; Svenning, J.-C.; Wheeler, H. C. Rewilding complex ecosystems. *Science* **2019**, *364* (6438), No. eaav5570.
(47) Svenning, J.-C. Rewilding should be central to global restoration efforts. *One Earth* **2020**, *3* (6), 657−660.
(48) Australian Wildlife Conservancy. Biodegradable Flat-Pack Homes to help Wildlife Survive after Bushfires 2021 https://www.australianwildlife.org/news-and-resources/press-release/biodegradable-flat-pack-homes-to-help-wildlife-survive-after.
(49) Johns, K. A.; Emslie, M. J.; Hoey, A. S.; Osborne, K.; Jonker, M. J.; Cheal, A. J. Macroalgal feedbacks and substrate properties maintain a coral reef regime shift. *Ecosphere* **2018**, *9* (7), No. e02349.
(50) Carlson, R. R.; Crowder, L. B.; Martin, R. E.; Asner, G. P. The effect of reef morphology on coral recruitment at multiple spatial scales. *Proc. Natl. Acad. Sci. U.S.A.* **2024**, *121* (4), No. e2311661121.

(51) Hanke, M. H.; Bobby, N.; Sanchez, R. Can relic shells be an effective settlement substrate for oyster reef restoration? *Restor. Ecol.* **2021**, *29* (4), No. e13371.
(52) Pogoda, B.; Brown, J.; Hancock, B.; Preston, J.; Pouvreau, S.; Kamermans, P.; Sanderson, W.; Nordheim, H.; von. The Native Oyster Restoration Alliance (NORA) and the Berlin Oyster Recommendation: bringing back a key ecosystem engineer by developing and supporting best practice in Europe. *Aquat. Living Resour.* **2019**, *32*, No. 13.
(53) van den Brink, A. M.; Maathuis, M. A. M.; Kamermans, P. Optimization of off-bottom spat collectors for restoration and production of the European flat oyster (*Ostrea edulis*) in Dutch coastal waters. *Aquat. Conserv.: Mar. Freshwater Ecosyst.* **2020**, *30* (11), 2087−2100.
(54) Wellman, E. H.; Baillie, C. J.; Puckett, B. J.; Donaher, S. E.; Trackenberg, S. N.; Gittman, R. K. Reef design and site hydrodynamics mediate oyster restoration and marsh stabilization outcomes. *Ecol. Appl.* **2022**, *32* (2), No. e2506.
(55) Schmidt-Roach, S.; Klaus, R.; Al-Suwailem, A. M.; Prieto, A. R.; Charrière, J.; Hauser, C. A. E.; Duarte, C. M.; Aranda, M. Novel infrastructure for coral gardening and reefscaping. *Front. Mar. Sci.* **2023**, *10*, No. 1110830.
(56) Colden, A. M.; Lipcius, R. N. Lethal and sublethal effects of sediment burial on the eastern oyster *Crassostrea virginica*. *Mar. Ecol.: Prog. Ser.* **2015**, *527*, 105−117.
(57) Zhao, Z.; van Belzen, J.; van Sluis, C.; de Smit, J.; Wu, M.; van Ijzerloo, L.; van Poppel, J.; Somers, P.; van der Heide, T.; ter Hofstede, R.; Kardinaal, E.; Kamermans, P.; van de Koppel, J.; Bertolini, C.; Bouma, T. J. Short-term hydro-sediment dynamics govern reef restoration success in temperate marginal seas. *One Earth* **2026**, No. 101679.
(58) Dickson, J.; Franken, O.; Watson, M. S.; Monnich, B.; Holthuijsen, S.; Eriksson, B. K.; Govers, L. L.; van der Heide, T.; Bouma, T. J. Who lives in a pear tree under the sea? A first look at tree reefs as a complex natural biodegradable structure to enhance biodiversity in marine systems. *Front. Mar. Sci.* **2023**, *10*, No. 1213790.
(59) Temmink, R. J. M.; Christianen, M. J. A.; Fivash, G. S.; Angelini, C.; Boström, C.; Didderen, K.; Engel, S. M.; Esteban, N.; Gaeckle, J. L.; Gagnon, K.; Govers, L. L.; Infantes, E.; van Katwijk, M. M.; Kipson, S.; Lamers, L. P. M.; Lengkeek, W.; Silliman, B. R.; van Tussenbroek, B. I.; Unsworth, R. K. F.; Yaakub, S. M.; Bouma, T. J.; van der Heide, T. Mimicry of emergent traits amplifies coastal restoration success. *Nat. Commun.* **2020**, *11* (1), No. 3668.
(60) ter Hofstede, R.; Bouma, T. J.; van Koningsveld, M. Five golden principles to advance marine reef restoration by linking science and industry. *Front. Mar. Sci.* **2023**, *10*, No. 1143242.
(61) United Nations Convention on the Law of the Sea (UNCLOS). 1982 Https://Www.Un.Org/Depts/Los/Convention_agreements/Texts/Unclos/Unclos_e.Pdf (accessed April 23, 2026).
(62) Convention on Biological Diversity (CBD). 1992 https://Www.Cbd.Int/Convention/Text/ (accessed April 23, 2026).
(63) Hylkema, A.; Debrot, A. O.; Cammenga, R. A. R.; van der Laan, P. M.; Pistor, M.; Murk, A. J.; Osinga, R. The effect of artificial reef design on the attraction of herbivorous fish and on coral recruitment, survival and growth. *Ecol. Eng.* **2023**, *188*, No. 106882.
(64) Ushijima, B.; Richards, G. P.; Watson, M. A.; Schubiger, C. B.; Häse, C. C. Factors affecting infection of corals and larval oysters by *Vibrio coralliilyticus*. *PLoS One* **2018**, *13* (6), No. e0199475.
(65) Bos, O. G.; Duarte-Pedrosa, S.; Didderen, K.; Bergsma, J. H.; Heye, S.; Kamermans, P. Performance of European oysters (*Ostrea edulis* L.) in the Dutch North Sea, across five restoration pilots. *Front. Mar. Sci.* **2023**, *10*, No. 1233744.
(66) Capelle, J. J.; Leuchter, L.; de Wit, M.; Hartog, E.; Bouma, T. J. Creating a window of opportunity for establishing ecosystem engineers by adding substratum: a case study on mussels. *Ecosphere* **2019**, *10* (4), No. e02688.
(67) Wohl, E.; Iskin, E. P. Damming the wood falls. *Sci. Adv.* **2021**, *7* (50), No. eabj0988.

https://doi.org/10.1021/acs.est.5c13167
Environ. Sci. Technol. 2026, 60, 14782−14792