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Recommendations for built marine infrastructure that supports natural habitats

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The extent of built marine infrastructure—from energy infrastructure and ports to artificial reefs and aquaculture—is increasing globally. The rise in built structure coverage is concurrent with losses and degradation of many natural habitats. Although historically associated with net negative impacts on natural systems, built infrastructure—with proper design and innovation—could offer a largely unrealized opportunity to reduce those impacts and support natural habitats. We present nine recommendations that could catalyze momentum toward using built structures to both serve their original function and benefit natural habitats (relative to the status quo, for example). These recommendations integrate functional, economic, and social considerations with marine spatial planning and holistic ecosystem management. As the footprint of the Anthropocene expands into ocean spaces, adopting these nine recommendations at global scales can help to ensure that ecological harm is minimized and that, where feasible, ecological benefits from marine built structures are accrued.

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Marine ecosystems face compounding threats from factors including habitat degradation, climate change, eutrophication, overexploitation, pollution, changes in sediment inputs, disease, and invasive species (Halpern *et al.* 2007). These threats have triggered losses in habitat coverage and ecological function across marine ecosystems. As compared to previously documented global extents, native oyster reefs have declined by ~85% (Beck *et al.* 2011), seagrasses by ~29% (Waycott *et al.* 2009), coral reefs by ~50% (Eddy *et al.* 2021), and mangroves by ~35% (Valiela *et al.* 2001), while salt marshes decline at a rate of 0.28% per year (Campbell *et al.* 2022). Kelp forests have also exhibited declines in multiple regions around the world (Krumhansl *et al.* 2016).

In a nutshell:

- Marine ecosystems face increases in built infrastructure amidst declines in natural habitats
- There is an unrealized opportunity to harness the ability of new and existing built marine structures to better support ecosystem functioning
- We provide nine recommendations that can help make the vision of built structures that support natural habitats a global reality
- These recommendations integrate knowledge from ecology, economics, sociology, engineering, and elsewhere to implement ocean management strategies that create synergies between the built environment and healthy marine ecosystems

Marine conservation and restoration efforts aim to stem or reverse biodiversity and habitat declines, and to preserve and restore ecosystem services. These efforts can successfully increase habitat cover, as evidenced by the recent large-scale recovery of seagrass beds in the Chesapeake Bay, on the eastern US seaboard, following 50 years of pollution reduction (Lefcheck *et al.* 2018). At global scales, however, the billions of dollars in restoration investment—averaging $1.6 million per hectare restored (Bayraktarov *et al.* 2016)—have been much more successful at slowing marine ecosystem declines (Duarte *et al.* 2020) than at increasing their extents toward historical levels.

To promote the switch from *slowing* marine ecosystem loss and degradation to *increasing* habitat coverage, and therefore boosting the provisioning of ecosystem goods and services, the UN declared the 2020s as the "Decade on Ecosystem Restoration" (IUCN 2022). Although traditional ecological restoration focuses on the recovery of native ecosystems to pre-disturbance "baseline" or "reference" conditions, it is generally accepted that ecosystem restoration now has a much broader scope that encompasses rehabilitation and remediation strategies and departs from the strict use of reference systems (Nelson *et al.* 2023). An underpinning feature of the UN initiative is the 17 Sustainable Development Goals (SDGs) for improving resilience of ecosystems and the human

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communities that depend on them, and for combating climate change (UN General Assembly 2015). Achieving SDG targets will depend heavily on our ability to effectively restore ecosystems and their services. For marine ecosystems, restoration holds great promise, but to date results have been mixed, as vegetation plantings often fail, are very expensive, or cannot be implemented at the necessary scale (Bayraktarov *et al.* 2016). Yet recent bright spots suggest that marine restoration success rates can be improved through the incorporation of ecological theory, innovative technology, stakeholder engagement, and strategic spatial planning and management to help meet the SDGs (DeAngelis *et al.* 2020; Saunders *et al.* 2020).

In terrestrial ecosystems, restoration strategies have evolved to account for—and in some cases directly incorporate—built structures and novel ecosystems that comprise a large portion of the landscape (Hobbs *et al.* 2006, 2014). One recent study estimated that 80% of the terrestrial biosphere has been transformed by humans into urban, residential, and agricultural lands (Ellis *et al.* 2021). Such spaces often do not fully function like their unaltered analogs and are unlikely to be restored to historical states (Hobbs *et al.* 2014). For these reasons, the modern paradigm for terrestrial restoration includes designing and managing built structures to support natural habitats, because the alternative (ie not doing so) means potentially missing out on opportunities to increase biodiversity and enhance ecosystem service delivery (Hobbs *et al.* 2014). In cities, for example, the roofs of certain buildings are intentionally vegetated, supporting biodiversity by creating habitat, filling voids in vegetation services (eg improved air quality, heat reduction), and reducing energy consumption (Berardi *et al.* 2014). Likewise, in residential and urban settings, implementation of water-sensitive design practices, such as bioretention systems and vegetated swales, helps to restore the natural water cycle, providing multiple benefits to natural ecosystems and people (Ahammed 2017). These recent advances in applying "nature-based solutions", which leverage built terrestrial "gray" structures to support natural ecosystems and their services as hybrid "gray–green" infrastructure, bode well for the future.

Despite bright spots (eg Dafforn *et al.* 2015; Airoldi *et al.* 2021) and increasing awareness about built structures in marine systems (eg Bulleri and Chapman 2010; Chapman and Underwood 2011), the marine science community (ie resource managers, scientists, policymakers, restoration practitioners, and industry) has yet to fully realize or embrace the potential for built structures to minimize negative impacts and support natural ecosystems by assisting in their recovery, supplementing their extent, and improving the services they provide. We define built marine structures as intentionally built artificial or gray infrastructure. Our definition of built marine structures also includes hybrid structures, which we define as those that incorporate both conventional gray infrastructure and natural or nature-based elements (gray–green infrastructure). The footprint of these built marine structures, such as aquaculture infrastructure, ports, artificial reefs, and energy infrastructure, was estimated at 32,000 km^2 in 2018 and is projected to be 39,400 km^2 by 2028 (Bugnot *et al.* 2020). This expansion is occurring against a backdrop of natural habitat loss, requiring innovative solutions to reverse declines (Saunders *et al.* 2020).

Evidence suggests that built structures typically lead to overall negative impacts to marine ecosystems; however, with proper design, the ecological harm introduced by marine built structures can potentially be minimized, and in some cases these structures can support natural habitat rehabilitation and recovery (Chapman *et al.* 2018; Todd *et al.* 2019; Firth *et al.* 2020; Paxton *et al.* 2025). Given that the continued human expansion into the ocean—the "blue acceleration" (Jouffray *et al.* 2020)—will inevitably involve installation of built marine structures, the time is now to mainstream and scale-up innovations that overcome obstacles and allow such built structures to not only accomplish their primary functions (eg coastal protection, food production, energy extraction or production, resource extraction) but also provide co-benefits to natural habitats. Below, we offer nine recommendations that can guide a future vision of built marine infrastructure that supports humans and minimizes harm to nature. The nine recommendations were developed as priorities by, and are meant to reflect the diverse disciplinary perspectives of, our international team, spanning environmental engineering, ecosystem restoration, spatial planning, and other areas of expertise. Several of the recommendations are not new, as they have been previously discussed in the literature and, in some cases, have even been adopted at fine scales; however, we believe that these deserve widespread and more pressing adoption given the increasing extent of built structures amidst an industrialized ocean economy (Jouffray *et al.* 2020).

Preserve the built structure's original function

Constructing marine infrastructure that supports natural habitats should not compromise the structure's primary function (eg energy extraction, recreation). Strategic designs should aim to produce co-benefits that complement the intended primary function (Figure 1a). For example, adaptations to scour aprons around wind turbines do not compromise performance or longevity (ie by reducing scour) but can provide benefits for marine life by creating structured habitat (Degraer *et al.* 2020). Breakwaters and sills are designed to provide wave attenuation and shoreline stabilization, but can also be designed to recruit and sustain native flora and fauna, without compromising the structures' primary coastal protection intentions (Mitchell *et al.* 2019). In some cases, innovative designs could aim not only to add natural functions but also to boost the primary function. Living shorelines that are built with the primary purpose of protecting the shoreline can create habitat for species such as oysters (Smith *et al.* 2020). In turn, oysters can create complex three-dimensional habitat that can help dissipate wave energy as breakwaters

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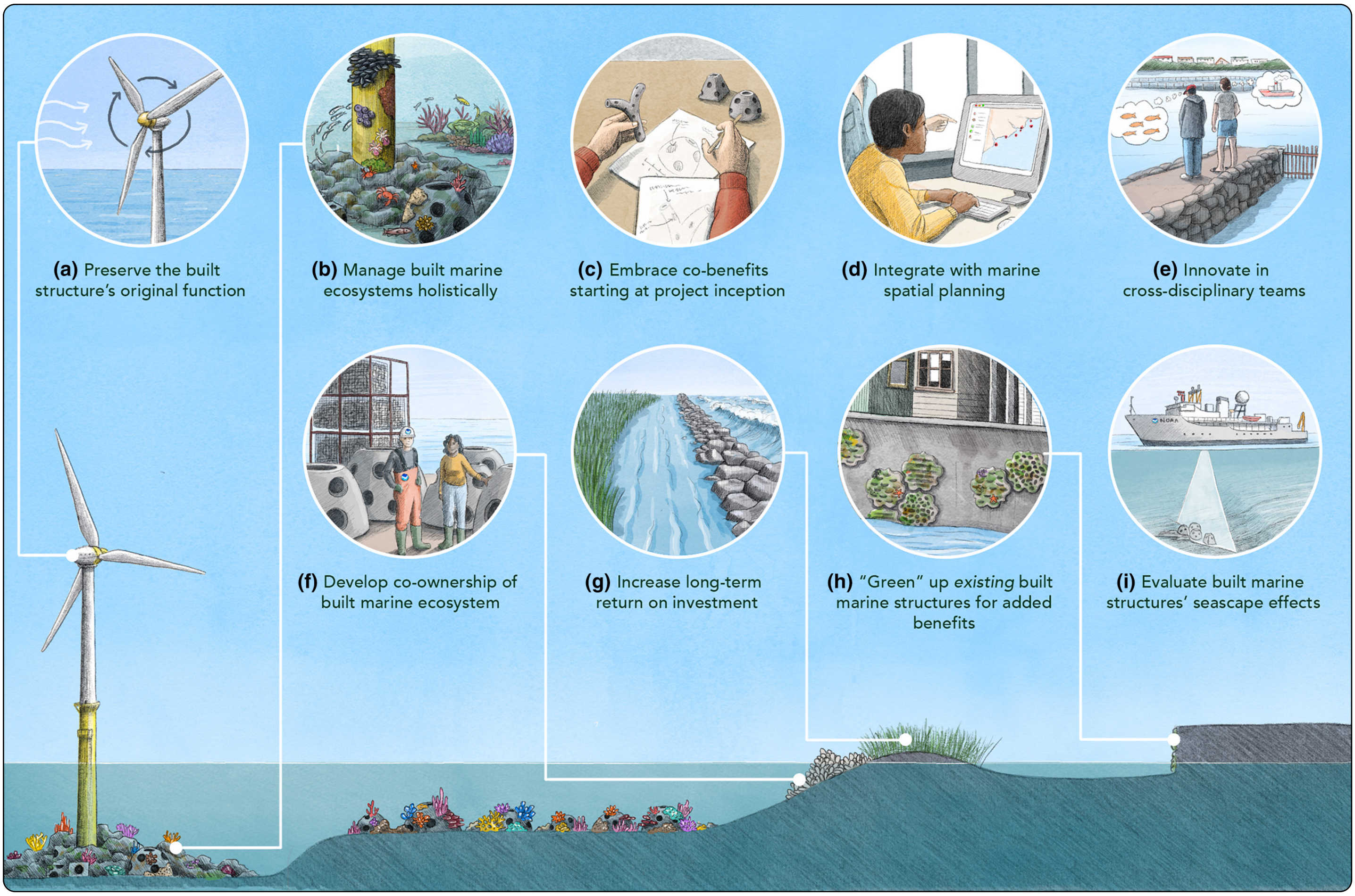

Figure 1. Nine recommendations that can be adopted to help ensure built marine infrastructure reduces impacts to and potentially supports natural habitats. These recommendations integrate understanding from ecology, economics, sociology, engineering, and other fields to develop a new paradigm of ocean management. Illustration by Alex Boersma.

(Chowdhury *et al*. 2019) and accrete vertically to keep pace with rising seas, thereby potentially contributing to greater shoreline protection and also improving infrastructure longevity.

Manage built marine ecosystems holistically

We suggest a holistic ecosystem perspective toward built structures in the marine environment (Figure 1b), consistent with broader calls for integrated ocean management as the model for future sustainability (eg Winther *et al*. 2020). As part of this integration, it may be necessary for built structures to be viewed within the context of the ecosystems in which they are installed; the contexts, thus, may differ substantially for particular built structures due to spatial scale, geographic location, and other nuances. In some instances (eg those that use natural and nature-based elements or where built structures have been documented not to cause harm), one option that could be considered to help promote a holistic ecosystem perspective would be to avoid drawing discrete boundaries between "artificial" and "natural" habitats but rather consider them more collectively as part of the broader ecosystem. In the Anthropocene, no habitats or ecosystems are fully natural or undisturbed, just as no built structures exist in pure isolation from nature. This view is consistent with scholarship on novel ecosystems, which recognizes that many ecosystems are so changed by human disturbance and intervention that their species composition, community structure, and ecological function have no historical analog (Hobbs *et al*. 2006). This perspective, rather than passing value judgements on novel ecosystems as "degraded" or less worthy of management attention than more undisturbed systems, seeks to understand these systems and the services that they provide. Moreover, it recognizes that novel ecosystems (and related hybrid and designed ecosystems, which are defined as more heavily managed) can provide ecosystem services (Evers *et al*. 2018). Although the novel ecosystem concept has been developed for and applied mostly to terrestrial systems, there is growing recognition of its applicability to marine systems, including work appreciating the role of human-made structures in marine ecosystems (Schlappy and Hobbs 2019). A holistic ecosystem approach to marine management and restoration, one that acknowledges natural and built habitats as co-occurring within an ecosystem and seeks to maximize the ecosystem service co-benefits from built structures, is more likely to achieve societal and ecosystem conservation objectives than approaches that try to silo people and engineered structures from nature.

Embrace co-benefits starting at project inception

Designing built structures with the aim of minimizing ecological risks and supporting natural habitats where possible should begin at project inception and continue systematically through project siting, implementation, and completion, rather than occurring as an afterthought (Figure 1c) or as part of retrofitting (see recommendation 8 below). For example, some new policy mandates for offshore wind development require *net gain* or *net positive impact*, such as the UK ECOWind program, which explicitly includes "net gain and marine environmental restoration" as core objectives of the national program (https://ecowind.uk/about), suggesting that such intentions should be integrated into projects from the start. Furthermore, consideration of how to benefit natural habitats and reduce unintended consequences should not end once the structure has been introduced to the marine environment, and should be evaluated and adaptively managed. Such adaptive management is called for in restoration initiatives (Bayraktarov *et al.* 2020) but has received less attention for gray and gray–green infrastructure in the ocean.

Adopting a proactive approach to generating co-benefits has distinct advantages. First, it ensures that infrastructure entering the water can quickly begin to support natural habitats and augment ecosystem functions and services. Second, it helps avoid the need to retrofit structures to achieve natural habitat benefits after they have been introduced to the marine environment, which can be costly (Bridges *et al.* 2021). The construction of artificial reef modules in a high-energy environment to reduce wave energy and improve resilience of nearby communities and infrastructure demonstrates the feasibility of incorporating natural habitat rehabilitation targets early in a project's lifecycle (Reguero *et al.* 2018). Although the reef modules were designed to meet their primary goal of coastal protection using engineering assessments and wave energy data, their design was also informed by knowledge of coral colonization to meet a secondary goal of creating substrate for coral recruitment and restoration.

Integrate with marine spatial planning

One of the keys to unlocking co-benefits of built marine structures is strategic planning and siting (Figure 1d). There are now many examples of marine spatial planning at a range of spatial scales, from local to regional to national (www.mspglobal2030.org/msp-roadmap/msp-around-the-world), and deliberate management of where different activities can occur in coastal and marine areas often reduces user conflicts, minimizes negative environmental impacts, and yields better social and economic outcomes (Lester *et al.* 2013). In many cases, marine spatial plans identify priority or suitable areas—or even designate specific zones—for various ocean uses that involve built infrastructure, including aquaculture, offshore energy, seafloor cabling, and ports or moorings. Thus, marine spatial planning initiatives provide an ideal platform to aim for co-benefits even *prior to* project inception. When identifying locations where built structures can be sited, spatial planning can account for both ecological impacts and the possibility of achieving co-benefits, by incorporating knowledge of complex geographic patterns in predicted ecosystem service supply, demand, and value provided by natural or artificial habitats (Tallis *et al.* 2012). Trade-off analyses and other types of multi-objective optimizations can be used to determine locations that balance the primary objective of the built structures with achieving ecosystem service co-benefits (Best and Halpin 2019). For example, Lester *et al.* (2018) applied bioeconomic modeling and trade-off analysis to different types of offshore aquaculture, to identify locations that would be profitable for aquaculture farms with minimal impacts (typically <1% reduction in value) on existing ocean sectors and the environment, relative to the outcomes achieved without strategic planning. These same types of planning analyses can be leveraged to model the expected ecosystem service co-benefits of built structures—benefits that will often vary across the seascape—and pinpoint locations most likely to provide win–win outcomes. For instance, shellfish or seaweed aquaculture can be sited in locations with high nutrient loading (Gentry *et al.* 2019), whereas offshore energy facilities can be located where targeted fish populations would benefit from de facto fisheries exclusion zones (although, in many circumstances, fishing activity is allowed inside the boundaries of offshore energy leases).

Innovate in cross-disciplinary teams

Built structures that support natural habitats will require innovation that can only be achieved through integration of diverse expertise (Figure 1e). Historically, civil, coastal, and environmental engineers working alongside industrial manufacturers, construction firms, and financial institutions have led the design, planning, construction, maintenance, and financing of built marine infrastructure. Simultaneously, the natural resource management, conservation, and ecosystem science community has led the advancement of our understanding of how coastal and marine systems "work" and guided their conservation and restoration. Moving forward, there is a need for these

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large and complex communities to integrate and co-develop a shared strategy for managing the built and natural marine environment (Saunders *et al*. 2024). Such efforts should be conducted in conjunction with the priorities of local stakeholders to ensure buy-in and equitable and just outcomes (Morris *et al*. 2022; www.darpa.mil/news-events/2022-06-15). This is often an overlooked objective but can facilitate successful cross-sector integration. Such integration also has great potential to support valuable cross-pollination of expertise, including local and traditional knowledge. Indigenous coastal and ocean communities, particularly in island nations, have long traditions of managing and using natural ecosystems in combination with resource extraction techniques (McCoy *et al*. 2017) or developing coastal protection structures that are tailored to the local context (Narayan *et al*. 2020). Such knowledge will need to be recognized and appropriately integrated with modern ocean resource management and the structures that affect these traditionally managed seascapes and linked communities. Although there are frameworks for transdisciplinary approaches to nature-based solutions, expertise in facilitation and program management will be key to cultivating multisector and transdisciplinary collaboration, as will programs that train the workforce to operate in dynamic and multifaceted teams.

Develop co-ownership of built marine ecosystem

Sustaining built marine structures that support natural habitats will likely require co-ownership of projects and shared responsibilities across a diverse suite of stakeholders (Figure 1f). The notion of co-ownership of projects—and the need for clearly defined ownership of risk and liability—by multiple stakeholders, including government agencies (and local governments), private entities, nonprofit organizations, and the public, is increasingly seen as critical to project success (Saunders *et al*. 2020). In this context, integrating local knowledge into project design, evaluation, and monitoring can improve the overall efficacy of the project and gain needed support from local stakeholders, especially those who may be affected by project outcomes, both positive and negative. Local stakeholders are also an important labor resource that can potentially offer a win–win outcome for the project (through the addition of local knowledge and subsequent buy-in) and coastal communities (through job creation). Co-ownership can be integrated from the start of the design process, through funding and construction, to monitoring and managing the finished project. An example of such co-ownership includes large-scale oyster restoration efforts that are funded and managed as partnerships between public sectors (government agencies) and private sectors (NGOs, private citizens, and companies) in the US (DeAngelis *et al*. 2020). Integrating the notion of co-ownership of built marine structures into projects can help realize benefits for nature and people though will likely require changes in public perceptions and social norms on the efficacy of built structures to provide co-benefits beyond their intended primary function (Gittman *et al*. 2021). In addition, changes to existing regulations, particularly changes that recognize the fluidity of marine ecosystem boundaries and connections across legislative and political boundaries, will be necessary (Jones and Pippin 2022). However, there can be key, nuanced barriers toward implementing co-ownership within an eco-engineering approach that deserve consideration (Evans *et al*. 2019).

Increase long-term return on investment

Designing and constructing built marine structures to reduce risks to and improve support of natural habitats does not need to increase long-term project expenditures and may even reduce costs through returns on investment from the provision of co-benefits over the lifetime of the structures (Figure 1g). Structures that support natural marine habitats and processes can be designed to take advantage of the natural adaptive capacity of these habitats. On intertidal coastlines, built structures that incorporate natural and nature-based vegetative features benefit in multiple ways from the increase in vegetated biomass over time, in contrast to the degradation of a built structure and its function over the same period (Feagin *et al*. 2021). Intertidal vegetation can enhance the coastal protection benefit of the built structure and potentially lower maintenance costs (Smith *et al*. 2017). Even if natural habitat enhancement increases initial infrastructure costs and does not augment the intended function of the built structure, these habitats can provide multiple valuable co-benefits that increase the long-term return on investment and could even help finance restoration. For example, one new program, the Sustainable Development Verified Impact Standard (https://verra.org/programs/sd-verified-impact-standard), aims to create an economic market through the valuation of co-benefits that contribute to SDGs from the enhancement of natural habitats, in addition to existing carbon markets.

"Green" up *existing* built marine structures for added benefits

Opportunities also exist to add "green" components to existing built marine infrastructure to support, or reduce adverse effects on, natural habitats (Figure 1h). Retrofitting can range from simple, low-cost solutions to more intensive and expensive actions (Bridges *et al*. 2021). For instance, hardened shorelines can be modified to become living seawalls by adding tiles with micro-complexity (Taira *et al*. 2020). These retrofitting actions promote greater

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fish biodiversity and provide more foraging resources as compared to hardened shorelines, while still retaining the ability to protect coastal infrastructure and communities (Taira *et al*. 2020). Aquaculture infrastructure can also be modified to improve co-benefits, as suggested by a recent synthesis that found elevated bivalve gear hosted higher abundance and species richness of wild macrofauna than on-bottom or longline gear (Theuerkauf *et al*. 2021). Even existing infrastructure that already blends gray and green elements can incorporate additional green elements, such as in cases where the habitat value of an existing living shoreline can be optimized by adding "windows" or gaps in sills to allow nekton movement as in natural marshes (Mitchell *et al*. 2019).

Evaluate built marine structures' seascape effects

Monitoring the ability of built marine infrastructure to deliver (desired and undesired, intended and unintended) seascape effects at relevant temporal and spatial scales should be integrated into project design and funding decisions (Figure 1i). Information gained from monitoring can be used to adaptively modify built infrastructure to support, and reduce negative effects on, natural habitats. Such monitoring efforts, however, are lacking for most built structures, especially those located far from shore. For example, some state-managed US artificial reef programs conduct rigorous monitoring of marine life associated with structures and track the condition of structures (degradation, subsidence, scour), whereas others conduct little to no post-deployment monitoring; moreover, monitoring approaches often differ among states. This lack of consistency precludes standardized calculations of artificial reef coverage and regional valuations of these structures for habitat, recreation, and other co-benefits. For wind energy infrastructure in the US, developers will be required to monitor a suite of metrics, which may help avoid such gaps for offshore wind structures (Barrie *et al*. 2014). Similarly, US marine aquaculture farms must maintain standards meant to minimize negative impacts on water quality, submerged aquatic vegetation, and wildlife, among others. However, most US marine aquaculture is located in state (as opposed to federal) waters, and there is no cross-state standardization of regulations or monitoring frameworks (Lester *et al*. 2021). Furthermore, aquaculture operations are not required to be designed or monitored with seascape effects in mind, hindering the ways in which farms can support natural systems or maximize co-benefits.

Standardized frameworks to evaluate outcomes across infrastructure types could help track broader patterns in the performance and extent of built marine ecosystems in tomorrow's ocean, as has been recently developed for outcomes of mangrove restoration (Gatt *et al*. 2024). Yet, challenges prevail as project budgets for ecological monitoring are typically limited, and projects designed to achieve other purposes are unlikely to include monitoring costs in their budgets, an issue that is apparent in ecological restoration more broadly (Saunders *et al*. 2024). Solutions to the lack of uniform and comparable evaluations of infrastructure include developing standardized frameworks for monitoring, incorporating monitoring into funding plans, and adopting novel technologies for monitoring. In particular, uncrewed systems outfitted with remote-sensing tools can be useful in monitoring both below-water and emergent ocean infrastructure. Synthetic aperture radar, for instance, can identify emergent structures that have not been properly decommissioned and could be used to prioritize restoration and connectivity assessments (Wong *et al*. 2019).

Conclusions

Humans are dramatically changing the Earth. Changes in coastal waters and the open ocean due to natural habitat loss and marine infrastructure development are no exception. Although several global public- and private-sector actors are making substantial progress toward promoting a sustainable blue economy, such advancements often involve minimal scientific evaluation or planning. Adopting the recommendations highlighted here would be a tangible step toward expanding ocean management to ensure that when marine built structures are inevitably installed they can not only serve their intended function but also support (or at least mitigate impacts to) natural habitats. These nine recommendations are our top suggestions, but this is not an exhaustive list; other recommendations, such as creating funding opportunities for multifunctional built marine structures and incorporating built structures into marine modeling efforts, could also be implemented to further catalyze progress. We expect that there will be barriers to each of these nine recommendations; however, we also expect that, with careful consideration and interdisciplinary collaboration, these barriers can be overcome so that built structures can begin to function to reduce harm to and potentially better support natural habitats. Importantly, we emphasize that a systematic process is needed to help make this vision a reality.

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No data were collected for this study.

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