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Special Feature: Honoring Charles H. Peterson, Ecologist

Fitting ecological principles of artificial reefs into the ocean planning puzzle

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Abstract

Humans use the coastal ocean and its resources as a source of food and energy, as well as for a variety of other purposes, including transportation and recreation. Over the past several decades, uses of the coastal ocean have been increasingly accompanied by the installation of artificial structures. These artificial structures come in different shapes and sizes, ranging from energy and aquaculture infrastructure that incidentally form habitat for marine organisms to artificial reefs that are often deployed intentionally to become habitat. Marine spatial planning has offered a robust framework for siting artificial structures to minimize conflicts with other uses and maximize societal and economic benefits with other intended uses of the seascape, but ecological criteria are seldom considered in the planning process. In contrast, artificial reefs are intentionally sunk to form structured habitat and provide a variety of ecological functions, yet ecological principles are not often incorporated into the siting and planning process. Instead, artificial reefs are sited largely to advance societal and economic benefits and minimize conflicts with other uses, such as shipping traffic, military use, or impacts to sensitive areas. We outline a framework to further incorporate ecological principles into artificial reef siting, design and construction, and evaluation that features place-based and adaptive management coupled with tenets from experimental field ecology. This framework accounts for complexities of and interactions among ecological, societal, and economic criteria associated with artificial reefs to ensure they meet defined goals.

KEYWORDS

artificial habitat, artificial reefs, marine spatial planning, ocean planning, place-based management, Special Feature: Honoring Charles H. Peterson, Ecologist

UBIQUITY OF ARTIFICIAL STRUCTURES IN THE COASTAL OCEAN

Humans rely on the coastal ocean for a variety of purposes, including extracted resources for food and energy, thoroughfares for shipping and transportation, and locations for recreation. Over the past several decades, human uses of the coastal ocean have been increasingly accompanied by the intentional introduction of artificial structures that facilitate diverse anthropogenic uses of the ocean. This phenomenon, often referred to as "marine urbanization" (Dafforn et al., 2015) or "ocean sprawl" (Bishop et al., 2017), is projected to continue increasing with anticipated 50%–70% growth in structure footprint or area for some sectors, such as energy and aquaculture, by 2028 (Bugnot et al., 2021). More broadly, the physical footprint of marine built structures globally is expected to grow from 32,000 km^2 in 2018 to 39,400 km^2 over the next decade (Bugnot et al., 2021).

Artificial structures in the coastal ocean come in a variety of shapes and sizes, reflecting their diverse uses (Bugnot et al., 2021; Heery et al., 2017). Infrastructure has been erected near the shoreline in the form of piers, breakwaters, jetties, bulkheads, and artificially constructed islands to provide coastal defense or opportunities for industry or recreation (Chee et al., 2017; Gittman et al., 2015; Todd et al., 2019). Offshore moorings and pens associated with aquaculture aid food production (Froehlich et al., 2017). Offshore energy infrastructure, including oil and gas platforms, wind turbines, tidal turbines, wave energy converters, and transmission pipes and cables, extract energy and are either installed directly on or into the seafloor (e.g., grounded design) or anchored to it (Miller et al., 2013). These structures incidentally provide habitat while they are in operation and, in many cases, after they are decommissioned, such as with oil platforms that are toppled or partially removed to be "reefed" (Macreadie et al., 2011). Artificial reefs comprised of decommissioned vessels, designed modules, or secondary-use concrete materials are another prevalent type of artificial structure placed in the coastal ocean primarily to enhance fish habitat or access for recreational fishing and diving (Becker et al., 2018).

Here, we synthesize the ecological function of artificial reefs and then describe the current processes for placing them in the seascape. We illustrate the largely unrealized opportunity to incorporate ecological principles into artificial reef planning. We also review applications of marine spatial planning (MSP) to artificial structures that incidentally form habitat, like offshore energy infrastructure, and can likewise be applied to artificial reefs deployed to form habitat. We then conclude by outlining a framework toward improved incorporation of ecological principles into the existing framework for artificial reef siting, design and construction, and evaluation that features place-based and adaptive management, as well as tenets from experimental field ecology. This proposed framework seeks to account for a complex array of ecological, social, and economic criteria to ensure artificial reefs best meet ecological goals and human needs.

NOVEL HABITAT CREATED BY ARTIFICIAL STRUCTURES

Artificial structures introduced to the coastal ocean become an integral part of the seascape, creating novel habitat for a diversity of flora and fauna. Animals across a variety of taxa and levels of the ocean food web have been documented to occur around artificial structures, ranging from attached fauna like sponges, corals, and other invertebrates, to fishes, sharks and marine mammals. Benthic microalgae, macroalgae, and both mobile and sessile invertebrates rapidly colonize artificial structures (Clark & Edwards, 1994), providing biotic complexity that complements the structural complexity of the artificial habitat itself (Champion et al., 2015; Leitão, 2013), while also forming prey for higher trophic levels (Cresson, Ruitton, & Harmelin-Vivien, 2014; Degraer et al., 2020). Fish representing broad trophic guilds forage on macroalgae and invertebrates living on artificial structures or zooplankton drifting near the structure; piscivorous fish also seek prey opportunities by foraging on smaller fish species, and top predators, such as large sharks can also be observed on artificial structures. For example, small gobies (*Gobiusculus flavescens*, *Pomatoschistus minutus*) (Wilhelmsson et al., 2006), as well as larger species, such as Atlantic cod (*Gadus morhua*) (Reubens et al., 2013) and flatfish (Wilber et al., 2018) can concentrate around wind turbines. Large predatory tiger sharks (*Galeocerdo cuvier*) and porbeagle sharks (*Lamna nasus*) have been detected near oil and gas platforms (Ajemian et al., 2020; Haugen & Papastamatiou, 2019). Sandbar sharks (*Carcharhinus plumbeus*), as well as tiger sharks, have also been documented near ocean-farming cages (Papastamatiou et al., 2010). Marine mammals can be sighted around artificial structures; for example, five species of cetaceans, including harbor porpoise (*Phocoena phocoena*), minke whale (*Balaenoptera acutorostrata*), along with two pinniped species, harbor seal (*Phoca vitulina*) and gray seal (*Halichoerus grypus*) were observed around oil and gas platforms (Delefosse et al., 2018).

Whereas many artificial structures, including offshore renewable energy infrastructure and oil platforms, form de facto habitat, artificial reefs are a special case where their deployment is often intended to enhance habitats and ecosystems (Becker et al., 2018). Artificial reefs also host a diversity of marine life, ranging from benthic invertebrates and reef fish to large predators (Figure 1). Benthic invertebrates recruit to artificial reefs, often following system-specific colonization trajectories (Figure 1a). For example, in the Red Sea, artificial reefs were initially dominated by soft corals before transitioning to a sponge dominated community composition (Perkol-Finkel & Benayahu, 2005), and an artificial reef in Hawaii was colonized quickly by fast growing bryozoans, crustose coralline algae, and fleshy algae (Bailey-Brock, 1989). Stable isotope analyses of France suggest that such invertebrate communities on artificial reefs depend upon organic matter production pathways both demersally (e.g., benthic macroalgae, benthic microalgae) and pelagically (e.g., phytoplankton) and that invertebrates form a key prey source for fish also inhabiting artificial reefs (Cresson, Ruitton, & Harmelin-Vivien, 2014).

A diversity of demersal and pelagic fish taxa from across trophic guilds can occupy artificial reefs (Figure 1b,c). Artificial reefs can host cryptic demersal fish, such as blennies and gobies, as well as bottom-associated reef fish from a variety of trophic groups, including invertivores and herbivores (Cresson, Ruitton, Ourgaud, & Harmelin-Vivien, 2014; Paxton, Newton, et al., 2020). These structures can also support high concentrations of pelagic fishes, including planktivores (Arena et al., 2007; Champion et al., 2015) and piscivores (Ajemian et al., 2015; Paxton, Newton, et al., 2020). And, similar to energy infrastructure, artificial reefs form habitat for large predators (Figure 1d), like sand tiger sharks (*Carcharias taurus*), which have been observed to exhibit site fidelity to artificial reefs (Paxton, Blair, et al., 2019), as well as top predators, including white sharks (*Carcharodon carcharias*) (A. Paxton, personal observation, 2015).

ECOLOGICAL FUNCTIONS OF ARTIFICIAL REEFS

The introduction of novel human-made reefs to the ocean seafloor can yield both positive and negative

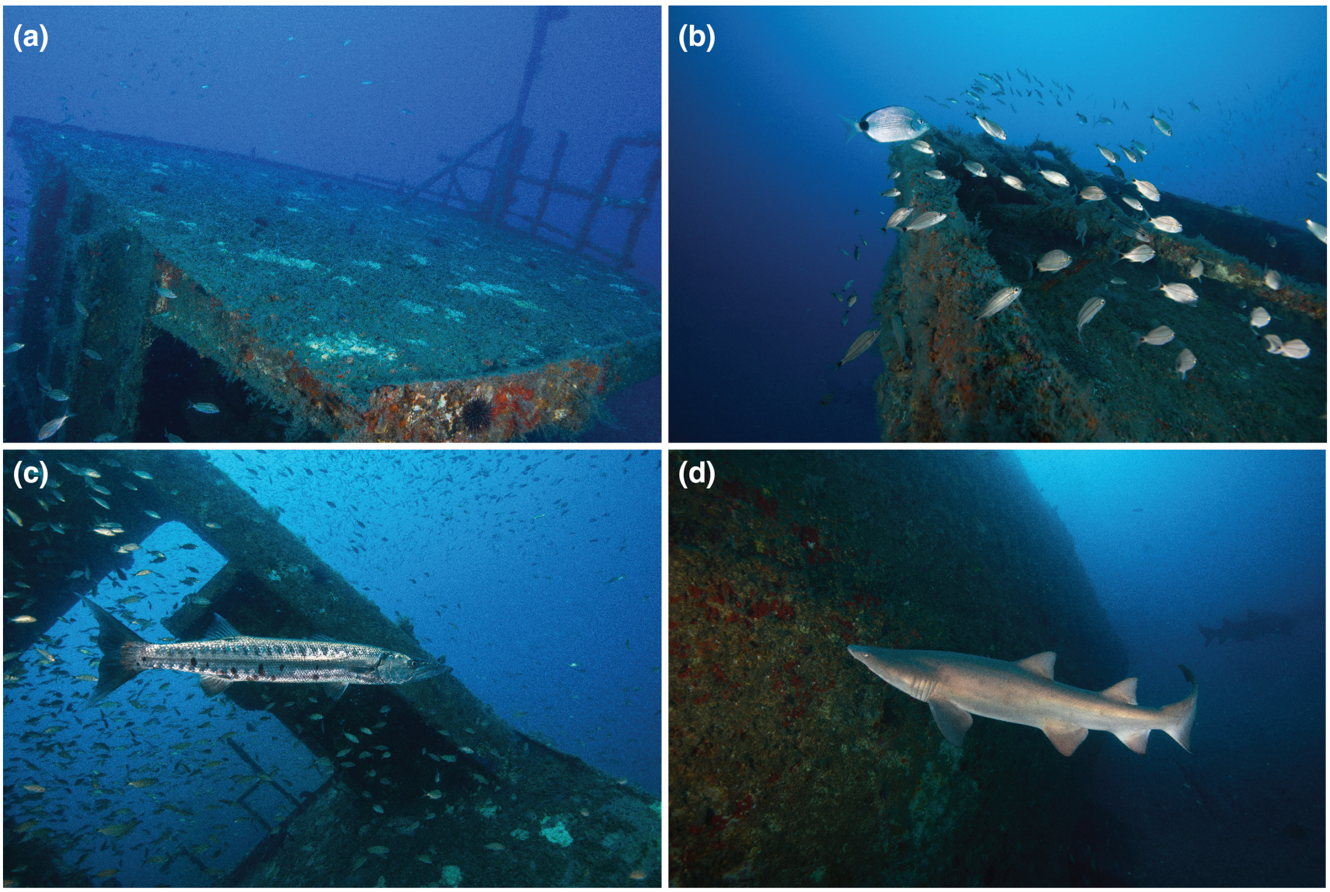

FIGURE 1 Artificial reefs form habitat for diverse flora and fauna. Shown here are sessile and mobile benthic invertebrates (a), reef fish (b) and large predators (c, d) observed on an artificial reef off North Carolina during one particular survey. Photo credit: J. McCord, Coastal Studies Institute

ecological impacts within the seascape. These outcomes are largely detected in comparison to other existing natural habitats so can manifest from inherent differences between artificial reefs and natural habitats, including reef structural characteristics and spatial distribution. Simply put, artificial reefs provide additional habitat that is often more structurally complex (e.g., vertical relief, rugosity, area, volume, number of holes) than natural habitats. For example, in the southeastern United States, artificial reefs were on average three times more structurally complex or rugose than nearby natural reefs, yet there were nuances based on the type of artificial reef, with low-lying concrete structures and modules providing less vertical height than vertically extensive ships (Paxton et al., 2017). Artificial reef structural complexity can relate to community metrics, with more vertically extensive and complex artificial reefs often hosting higher fish abundance, biomass, and species richness than less complex natural reefs (Charbonnel et al., 2002; Hackradt et al., 2011); although in some systems, this relationship is more nuanced (Paxton et al., 2017). For instance, artificial reefs deployed in habitat-limited Australian bays increased fish abundance, such that 2 years post-deployment, fish abundance was comparable to or higher than that on the closest rocky reefs (Folpp et al., 2020), and hydroacoustic surveys of an artificial reef in the Gulf of Mexico revealed higher fish biomass and density compared to nearby natural reefs (Boswell et al., 2010). Structural complexity has also been demonstrated to relate to ecological functions, as in the Red Sea, for instance, coral reef fish recruitment was greater on high-relief artificial reefs than on their low-relief counterparts (Rilov & Benayahu, 2002). Recent numerical models indicate that artificial reefs can support high concentrations of zooplankton-consuming fish because the reef structural complexity provides fish with a safe habitat to forage on zooplankton (Champion et al., 2015).

While the material of artificial reefs dictates the level of structural complexity, experimental investigations of how artificial reef material influences community composition have revealed that different materials can host different assemblages. For example, an observational field study in the southeast United States revealed that while metal ships hosted higher fish abundance than concrete modules, the abundance was similar on concrete modules and natural rocky reefs (Lemoine et al., 2019). Other studies have demonstrated differences in fish community metrics with artificial reef materials, too, yet there are usually location-specific nuances that require regional assessments of how particular materials relate to ecological communities (see Paxton, Shertzer, et al., 2020). For example, benthic invertebrate colonization patterns have been linked not only to reef material but also to factors including reef size, proximity to nearby reefs, hydrodynamics, and the orientation of the artificial reef (Higgins et al., 2019).

Deployment of artificial reefs can enhance spatial connectivity within seascapes. Studies that examine habitat connectivity by tracking individually tagged fish with acoustic telemetry demonstrate that particular fish species exhibit varying degrees of residency on artificial reefs, as well as movement between or among artificial and natural reefs. For example, 72% of acoustically tagged and tracked individual red snapper (*Lutjanus campechanus*) spent over 1 year on specific artificial reefs in the Gulf of Mexico (Topping & Szedlmayer, 2011). Examinations of movement between artificial and natural reefs reveal that certain species, such as white sea bream (*Diplodus sargus*) in Portugal, occupy both artificial and nearby natural reefs, taking excursions from one to another (Abecasis et al., 2013). A similar pattern has been documented for eastern fiddler rays (*Trygonorrhina fasciata*) in Australia, which displayed high fidelity to artificial reefs and also moved frequently between nearby natural habitats (Keller et al., 2017). More broadly, spatial connectivity provided by artificial reefs compared to natural reefs, especially in areas that may be habitat limited, can facilitate fish at climatic range edges (Paxton, Peterson, et al., 2019) and potentially provide corridors for large predator movement (Paxton, Newton, et al., 2020). In contrast, improved connectivity can create ecological risks by providing "stepping stones" or connectivity corridors that facilitate the spread of invasive species, including macroalgae (Bulleri & Airoldi, 2005) and invertebrates (Dafforn et al., 2012), as well as predatory fish like lionfish (*Pterois miles* and *Pterois volitans*) (Morris & Akins, 2009).

Enhanced spatial connectivity associated with artificial reefs has implications for ontogenetic movement and use of these novel habitats by fish species in different life phases. For example, observations on vessel artificial reefs off Florida, revealed truncated size distributions for reef-associated fishes, which was hypothesized to be from ontogenetic movement of younger or smaller fish away from the vessel reefs through ontogeny (Dance et al., 2011), similar to observations of gag grouper reliance on artificial reefs during their pre-reproductive transition across the continental shelf off Florida (Lindberg et al., 2006). Interestingly, stable isotope and stomach contents analysis on red snapper (*L. campechanus*) in the Gulf of Mexico suggest that this particular species exhibits feeding shifts throughout ontogeny; these feeding shifts are supported primarily by prey associated with sand and mud near artificial reefs, whereas the artificial reefs provided refuge from predation (Wells et al., 2008). Overall, enhanced spatial connectivity can confer both ecological benefits and risks at scales ranging from genes to ecosystems (Bishop et al., 2017).

Similarities and differences in ecological functions of artificial habitats compared to natural habitats often relate to patterns in community metrics and composition of flora and fauna. For example, while a recent global meta-analysis revealed that artificial reefs can support similar fish community metrics to natural reefs, the analysis also revealed nuances based on aforementioned attributes, such as reef location and material (Paxton, Shertzer, et al., 2020). In some instances, artificial reefs performed better than natural habitats, hosting higher fish abundance, biomass, richness, and diversity (Arena et al., 2007; Bohnsack et al., 1994), whereas in other systems there was either no difference (Lemoine et al., 2019; Stone et al., 1979) or artificial reefs performed more poorly than natural reefs (Carr & Hixon, 1997; Froehlich & Kline, 2015). Benthic invertebrate and macroalgal communities often differ initially between artificial and natural habitats (Perkol-Finkel et al., 2005), and these differences can be dependent on the age of the artificial reef or finer-scale attributes. For instance, undersides of artificial reefs can host more algal colonies, while topsides of artificial reefs can host more invertebrates than nearby natural reefs (Higgins et al., 2019). Evidence also exists that benthic communities may converge on artificial and natural reefs over time, given similar structural characteristics (Perkol-Finkel et al., 2006; Thanner et al., 2006).

Disentangling the comprehensive ecological impacts and functions of artificial reefs is an ongoing challenge. Key questions remain to be answered, including the extent to which artificial reefs may displace fish from existing habitats or increase production (Bohnsack & Sutherland, 1985; Layman et al., 2016; Peterson et al., 2003; Pickering & Whitmarsh, 1997; Powers et al., 2003), how artificial reefs perform at broad and fine spatial scales within the seascape (Bishop et al., 2017; Rosemond et al., 2018; Smith et al., 2017), and how artificial reefs influence broader regional species and community dynamics (Bishop et al., 2017; Cresson et al., 2019). Even though much remains to be understood about ecological functions of artificial reefs, given their apparent ecological influence and widespread global prevalence, installing artificial structures requires strategic planning to balance ecological outcomes with societal uses.

PLACING ARTIFICIAL REEFS IN THE SEASCAPE

Despite their ecological role and associated functions, when artificial reefs are added to the seascape, they are often considered solitary additions to the existing seascape. This is largely a byproduct of the existing artificial reef planning framework, where intended purposes of artificial reefs follow their funding origins. For example, in the United States, artificial reef funding often aims to provide recreation opportunities, socioeconomic benefits to coastal communities, and reductions of fishing pressure on nearby natural reefs (NOAA, 2007) or to provide ecological mitigation (Hueckel et al., 1989; NOAA, 2007). Such funding-derived purposes lead to artificial reefs being planned as self-contained individual management areas that are not intended to account for ecological scale or ecological interactions with other reefs or marine features in the seascape.

Specific planning processes for artificial reefs differ globally, yet most planning processes do not fully incorporate ecological considerations. In the United States, a National Artificial Reef Plan provides guidelines for siting, design, construction, and monitoring of artificial reefs, as well as details components of the regulatory framework (NOAA, 2007; Stone, 1985). Artificial reef siting and design in the United States is usually conducted at localized (state, county) levels and through federal permitting channels (33 C.F.R. § 322.5) to ultimately limit ocean use conflicts and disruption to navigable waters and existing habitat, and to prevent future cleanup of pollutants and displaced materials associated with poorly sited artificial reefs. Permitting and corresponding legal infrastructure help alleviate concerns of poorly sited artificial reefs, and additional planning processes, including fisheries management consultations, center on identifying cumulative negative impacts of artificial reefs on endangered species or critical habitat areas (Crabtree, 2017, 2019). Despite identification of some ecological considerations for artificial reef planning, the United States artificial reef framework does not rigorously harness the existing MSP framework nor does the framework function to explicitly optimize ecological outcomes.

Outside of the United States, artificial reefs follow a diverse range of ecological planning and management procedures. The siting and design of artificial reefs in Europe, mostly in the Mediterranean Sea, is governed by several conventions and regional plans derived from those focusing primarily on preventing degradation and pollution of the marine environment (Fabi et al., 2011). In Australia, artificial reefs are planned and developed by various local government fisheries agencies and fishing clubs with individualized ecological goals and are permitted through federal agencies; the major concerns of permitting artificial reefs in Australia are the longevity and stability of material and presence of a monitoring plan (Diplock, 2010). Japan, however, focuses artificial reef strategies around their return on investment within fisheries and manages them at regional levels (Suda et al., 2017). Japanese artificial reefs are also planned as either aggregation reefs in important fisheries areas or propagation reefs in recruitment areas (Ito, 2011). In Brazil, artificial reefs are planned, implemented, and managed locally specifically for fishing opportunities (Jardeweski & de Almeida, 2006). While artificial reefs are planned globally with varying levels of ecological intention, an opportunity exists to further balance ecological outcomes with social and economic outcomes by including artificial reefs in MSP.

EXISTING FRAMEWORK FOR MSP

Planning for artificial reefs can harness the existing framework of MSP, which has been successfully applied to other types of artificial structures, such as offshore renewable energy infrastructure. MSP aims to efficiently manage coastal and marine spaces and their multiple uses to simultaneously achieve social and economic objectives, while also protecting and managing ecosystems for various services (Ehler & Douvere, 2009). The integrated, place-based framework of MSP includes multiple adaptive steps, such as identifying planning goals, preparing a spatial management plan, implementing the plan, monitoring outcomes, and adapting the plan iteratively to better meet desired outcomes (Ehler & Douvere, 2009; Lubchenco & Sutley, 2010). For over a decade, MSP has provided a framework for understanding and seeking balances in the use of the coastal ocean to benefit societal and economic goals (Foley et al., 2010; Halpern et al., 2012).

Siting and installation of artificial structures, especially renewable energy and offshore aquaculture that form habitat de facto, have been at the forefront of the MSP framework in recent years. In Europe, many countries implement MSP through developing spatial plans for use of and zoning of the coastal environment to help facilitate multiple uses of the coastal ocean, including renewable energy extraction (Douvere & Ehler, 2009). In the United States, MSP is also prevalent in offshore energy development, especially in the northeastern United States, where MSP helps minimize spatial use conflicts with wind farm siting. In Rhode Island and Massachusetts, for instance, practitioners mapped ocean uses and negotiated conflict resolution among sectors to guide multiple ocean uses, such as sand gravel mining, shipping, fishing, and port expansion with offshore energy development (Nutters & Pinto da Silva, 2012). Similarly, biogeographic assessments conducted in New York mapped and evaluated ocean uses, vulnerable habitats, and species of conservation concern to help site offshore wind farms while minimizing spatial-use conflicts (Caldow et al., 2015).

The MSP framework is frequently employed when designating marine protected areas (MPAs) (Arafeh-Dalmau et al., 2017). Using MSP tenets, areas of the ocean judged to be ecologically important, vulnerable, or valuable are identified as potential MPA sites through systematic planning efforts by marine management regulators and various international agencies (Vaughan & Agardy, 2019). These potential MPA sites are then evaluated to ensure that boundaries encapsulate targeted ecological processes and productivity to maximize benefits of designating a given site as an MPA (Vaughan & Agardy, 2019). Other approaches use conservation planning software, such as Marxan, to help prioritize potential sites for MPA designation through mathematical analyses of costs and benefits (e.g., site footprint, risk of anthropogenic factors, and opportunity costs derived from site protection), which because of its holistic approach can help reduce spatial fragmentation of MPAs (Smith et al., 2009). Within the southeastern United States, for example, design alternatives for an MPA were evaluated by a multidisciplinary team of experts and stakeholders using data that helped identify benefits and risks within a complex framework of multiple human uses (Caldow et al., 2015). In addition to applications for MPA designation and offshore energy siting, MSP has been applied to other ocean use planning issues, such aquaculture planning (Lester et al., 2018) and coastal tourism (Papageorgiou, 2016), and thus represents a viable option for artificial reef planning.

FITTING ECOLOGICAL PRINCIPLES OF ARTIFICIAL REEFS INTO MSP

Goals for creating artificial reefs are often assumed or only broadly articulated. A recent review by Becker et al. (2018) that examined 270 research articles revealed that 38% of studies did not clearly articulate goals of artificial reef deployment. Of all articles reviewed by Becker et al., including articles lacking explicitly stated goals, a minority focused on social or economic aspects of artificial reefs (14% of papers reviewed in Becker et al.), whereas the majority focused on ecological assessments (86% of papers reviewed). Diverse and sometimes overlapping ecological objectives identified by Becker et al. in studies with stated goals included installing artificial reefs to prevent trawling, increase fishing access opportunities and yield, restore and enhance habitats, and mitigate habitat loss. Following deployment, artificial reefs are often studied for 1 year or less (37% of papers reviewed by Becker et al.) but are seldom studied for 10 years or longer (3% of papers reviewed by Becker et al.). Given that artificial reef deployments commonly aim to enhance habitat or retain key taxa, Becker et al.

concluded that ecological artificial reef objectives warrant further articulation and also require additional assessment and monitoring to ensure that objectives are met.

There is an opportunity to improve the ecological benefits of artificial reefs—regardless of whether their deployment goal is ecological, social, economic, or a combination—by intentionally and explicitly incorporating ecological principles into artificial reef planning (Figure 2). Incorporating ecological principles into artificial reef planning hinges upon strategic spatial placement of artificial reefs within the seascape, to the extent feasible based on economic and social limitations (e.g., sometimes artificial reefs are opportunistic and planning does not include much leeway for strategic placement). Indeed, understanding habitat spatial arrangements (e.g., connectivity, scale) and configurations (e.g., structural complexity, material, and size) and associated ecological interactions is a theoretical and fundamental goal of ecology (Fahrig & Paloheimo, 1988; Levin, 1975; MacArthur & Wilson, 1967) and if applied to artificial reef planning could help predict ecological outcomes from artificial reef deployment. When placed on the coastal ocean seafloor, artificial reefs are introduced to an existing matrix of habitats, such as soft sediment, hard bottom, and biogenic reefs. By forming habitat for a diversity of flora and fauna, artificial

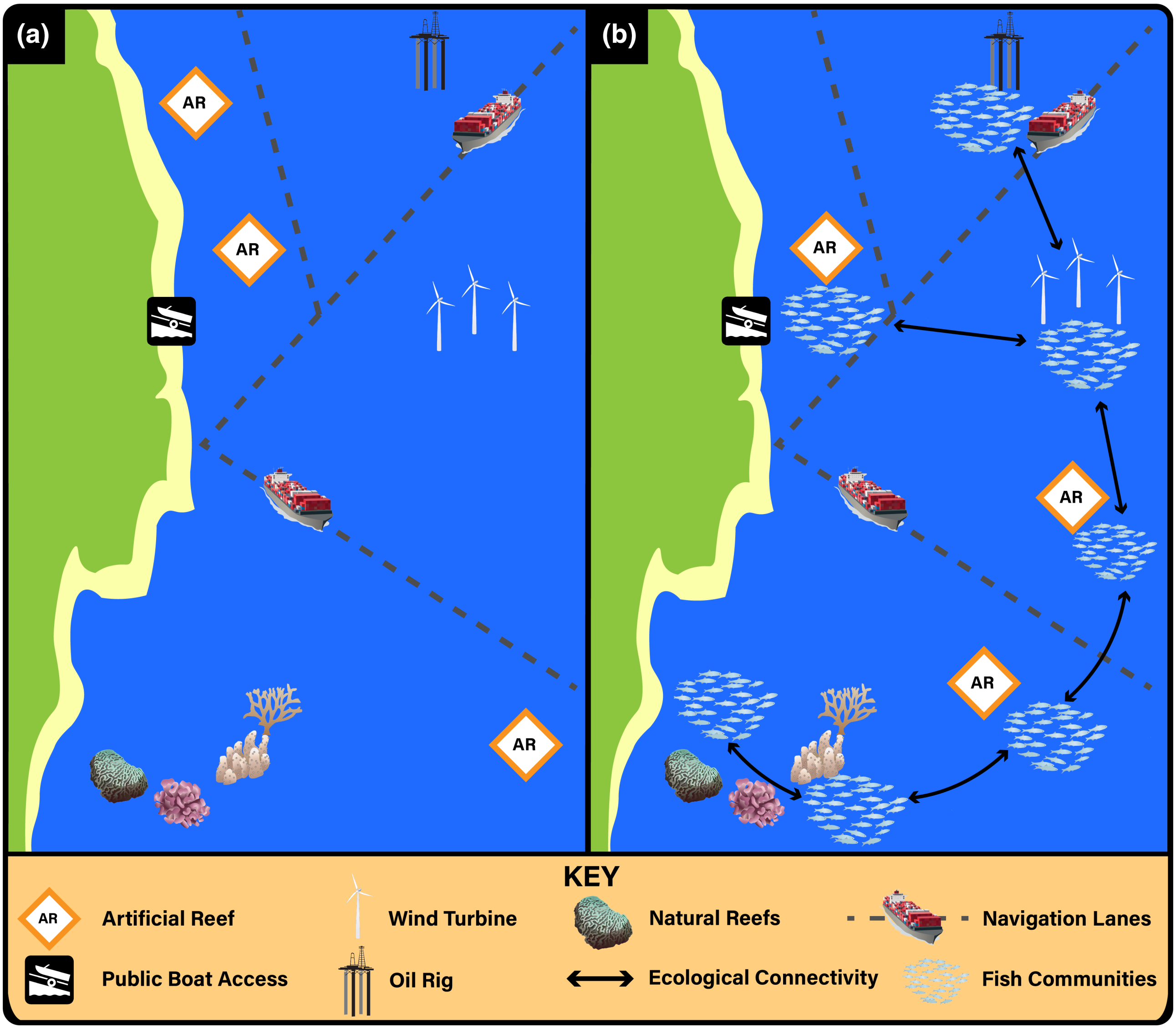

FIGURE 2 Potential frameworks for placing artificial reefs in the seascape based on (a) economic and social criteria and (b) a combination of economic, social, and ecological considerations. In (a), artificial reefs are sited largely based upon economic and social considerations, such as navigation routes, shipping lanes, government use areas, and stakeholder access. In (b), principles from place-based management and lessons learned from rigorous evaluations are applied to include ecological criteria into siting, design, and construction decisions for artificial reefs, in addition to economic and social criteria. Incorporating ecological criteria, such as connectivity and distribution relative to nearby natural habitats, can help heighten ecological benefits of artificial reefs

reefs provide ecological roles and functions that are sometimes complementary to those associated with nearby habitats but other times distinct. To help predict and plan for such ecological outcomes, spatial considerations from localized (e.g., artificial reef zone or permitted area) to ecosystem scales should be considered in the planning process.

There are multiple avenues that can facilitate this level of spatial planning, but key to inclusion is to address ecologically relevant considerations for target taxa or target goal (e.g., enhance, restore, and mitigate). These considerations can be explicitly tested through a priori field experiments, assessments, or monitoring of similar artificial reefs or rigorous investigations can be built into post-deployment stages in support of adaptive management. For example, managers tasked with siting and constructing artificial reefs to enhance habitat for certain fish species may examine the spatial habitat use patterns (e.g., home range, site fidelity, migration, etc.) to understand optimal connectivity among habitats and thus where to place the new structure. Others aiming to restore degraded habitat through artificial reef deployments may investigate ecological metrics and associated functions of artificial reefs either compared to the degraded or nondegraded habitats that they aim to ecologically surpass or emulate, respectively. And, those aiming to facilitate bottom-up habitat enhancement predicated upon colonization of artificial reefs by certain benthic invertebrates may test recruitment of different candidate artificial reef materials.

Even though artificial reefs often aim to fulfill ecological goals, they are also used as recreation sites to enhance stakeholder access to and use of the coastal ocean in pursuit of social and economic goals. It is not practical, therefore, for artificial reef planning to incorporate ecological considerations as sole criteria for planning decisions. Instead, planning must weigh and balance a complex matrix of ecological, societal, and economic criteria. This is inherently an exercise in resolving human-use conflicts for areas of the coastal ocean so can draw upon the framework of MSP, which prescribes a governance approach toward deconflicting myriad uses of the coastal ocean. This framework can account for the intricacy that human use conflicts often result in discrete classifications or designations of ocean space which assume loss of natural function (e.g., shipping lane not considered ecologically, just socially, and economically). For artificial reefs, these structures, while conforming to discrete classifications, still function ecologically, so the MSP framework could help managers plan based on local or scalable priorities and goals.

We propose that by harnessing the existing framework of MSP, incorporation of ecological principles into artificial reef planning can occur in three discrete yet interacting

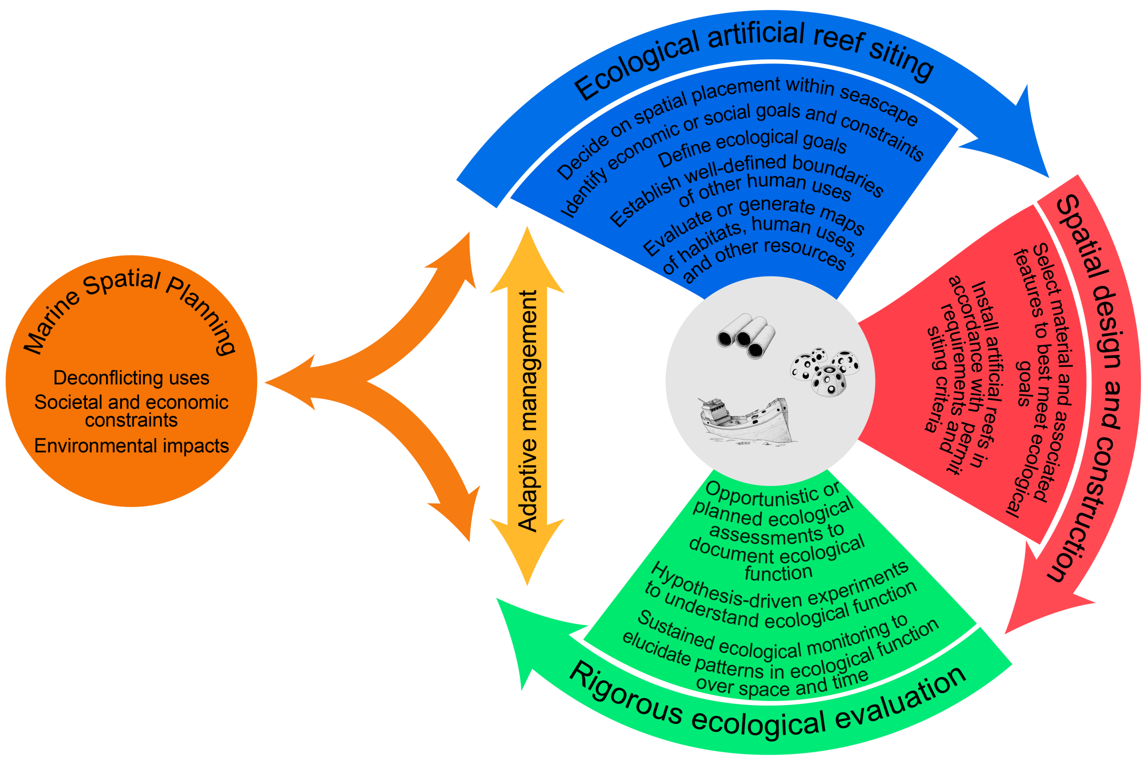

FIGURE 3 Conceptual diagram of proposed framework and recommendations for incorporating ecological principles into the broader process of marine spatial planning for artificial reefs. The cyclical process includes ecological siting, spatial design and construction, and ecological evaluation. This construct is specific to artificial reefs and should be considered within the context of other social and economic criteria already incorporated into the overall artificial reef planning process. Illustrations of artificial reef materials by Alex Boersma

TABLE 1 Ecological metrics that can be used to measure artificial reef success

Category	Metrics
Population	Abundance, biomass, recruitment rate, length-frequencies, and genetic connectivity
Community	Community composition and metrics (abundance, biomass, richness, and diversity)
Ecosystem	Predator–prey dynamics, temporal patterns, invasive species, nutrient cycling, connectivity among habitats, and spatial distribution

Note: Metrics are divided into ecological categories for populations, communities, and ecosystems. These metrics are examples and are not all-inclusive.

phases: (1) ecological siting, (2) spatial design and construction, and (3) rigorous ecological evaluation (Figure 3). First, strategic ecological artificial reef siting should occur. In this phase, managers should decide on spatial placement of artificial reefs within the existing seascape context, such as the location of artificial reefs relative to natural habitats. As is the current practice, economic and societal goals and constraints must be identified. In its most basic form, this is defined by costs for transport of materials, proximity to harbors, boat ramps, or other uses (NOAA, 2007; Seaman, 2019). These considerations then interplay with the defining ecological objectives. As described above, these include increasing habitats for key fisheries, mitigating loss of habitats, or providing connectivity corridors. Additionally, given the need to balance social and economic factors with ecological factors, it is imperative that well-defined boundaries of human uses are established in a geospatial framework. These human-use maps should also incorporate habitat maps and maps of other natural resources. Second, artificial reef structures should be designed and constructed—or selected, as feasible, in the case of secondary-use materials—to best meet ecological goals. During this phase, artificial reef materials and associated features (e.g., size, complexity, spatial configuration, orientation, relief, stability, and durability; NOAA, 2007; Seaman, 2019) should be selected to heighten chances of successfully achieving ecological goals and then installed in the seascape in accordance with permitting requirements and aforementioned siting criteria (Lindberg & Seaman, 2011). Third, following deployment, rigorous ecological evaluation should be undertaken. Three types of ecological evaluations—assessments, experiments, and monitoring—should be considered yet are not mutually exclusive. For clarity, however, we describe assessments as opportunistic or planned ecological characterizations and experiments as hypothesis-driven research, both aimed toward understanding principal drivers of ecological processes (e.g., predator prey interactions and connectivity between habitats). Assessments, experiments, and monitoring can all help evaluate ecological metrics for artificial reef success across habitats, populations, communities, and ecosystems (Table 1). Moreover, the framework is adaptive, as ecological evaluations can help define future strategic siting and vice versa. Adaptive management, for example, could harness knowledge learned during evaluation about the implications of siting, design, and construction decisions to optimize outcomes when enhancing existing artificial reefs or deploying new artificial reefs.

The three-step cyclical framework that we outline for strategic siting, design and construction, and evaluation aims to fundamentally incorporate ecological principles into artificial reef planning and management. The framework explicitly features sampling and observation events to measure the success of artificial reefs in meeting prescribed goals across population, community, and ecosystem scales. This proposed framework is a balancing act, aiming to still achieve social and economic goals associated with currently practiced artificial reef planning while highlighting a pathway toward more deliberate inclusion of ecological considerations into the planning process. In conclusion, artificial reef planning can benefit from increased reliance on tenets of MSP that intentionally incorporate ecological criteria into strategically sited, spatially designed and constructed, and explicitly evaluated artificial reefs that continue to facilitate intended human uses while improving chances of achieving ecological goals.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

No data were collected for this study.

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