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Policy and Management Considerations for Artificial Reefs in the Arabian Gulf

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Executive Summary

A diverse and productive mosaic of highly important ecosystems border the coastline of the Arabian Gulf, providing invaluable goods and services to coastal populations and representing the most biodiverse habitats in a region better known for its arid deserts. Recently, however, these ecosystems have come under escalating pressure from urbanization, fisheries activity, and global climate change. Artificial reefs have been in use for centuries in the Gulf region, where they were inherited through family lines and regulated under the senat al-bahar (the 'code of the sea'). Today, regional marine managers and policymakers are increasingly promoting artificial reefs as a tool to mitigate the ongoing impacts on Gulf ecosystems and fisheries. Artificial reefs may support some goals of marine managers and policymakers, but they are not a panacea and involve many risks. Without appropriate design, regulation, and management, artificial reefs can exacerbate existing problems or inadvertently create new issues that add to management burdens in coastal areas.

The purpose of this policy report is to summarize the available knowledge on artificial reefs as tools for marine management, specifically in the unique environmental and social context of the Arabian Gulf. The paper highlights the importance of Gulf coastal ecosystems and recent regional changes to demonstrate the need for more active interventions from marine managers. Next, the paper conducts a global assessment of the proposed goals and benefits of artificial reefs from the scholarly literature. We then highlight potential detrimental effects of artificial reefs that are often unrecognized or overlooked, but which can profoundly impact the success of artificial reef programs. The paper concludes with six key recommendations for policymakers and marine managers considering artificial reef programs in the Arabian Gulf.

The Importance of Coastal Ecosystems in the Arabian Gulf

Unlike arid terrestrial ecosystems of the Arabian Gulf, coastal ecosystems are highly productive and support high levels of diversity, making them both ecologically and economically important (Vaughan et al., 2019). Mangrove forests, mudflats, and sabkha algal mats represent highly productive ecosystems whose energy and nutrients can support diverse coastal and subtidal food webs at the land-sea interface.(Barth & Böer, 2002; Basson et al., 1977; Hegazy, 1998; Price et al., 1993; Sheppard et al., 1992). Critically important nearshore

Figure 1: Artificial reefs are increasingly being deployed across the Arabian Gulf

ecosystems such as coral reefs, seagrass meadows, algal beds, and oyster reefs cover extensive areas of seafloor (Vaughan et al., 2019). Coral reefs are the most diverse habitat in the region, providing complex three-dimensional habitat and important foraging areas for hundreds of species, including critically endangered fauna such as the hawksbill turtle (Sheppard et al., 1992) and commercially important species such as the prized grouper, *hammour* (Burt et al., 2009). Over 5% of the world's seagrass beds occur in the Gulf. These highly productive ecosystems serve as a food source for numerous species, including large populations of the endangered green turtle and the second-largest dugong population in the world (Erftemeijer & Shuail, 2012; Price & Coles, 1992). Consequently, coastal ecosystems are the most ecologically significant habitats for Arabian Gulf nations.

Aside from biological benefits, these coastal ecosystems also support human populations along the Gulf. These ecosystems serve as nursery and foraging habitats for numerous commercially important species to support local fisheries, which are second only to oil in economic importance as a resource (Erftemeijer & Shuail, 2012; Siddeek et al., 1999; Van Lavieren et al., 2011; Vaughan et al., 2019). Tourist activities such as diving, snorkeling on reefs, and kayaking in mangrove forests also provide considerable economic benefits to local communities (Blignaut et al., 2016; Nouri et al., 2008; Ryan et al., 2012). Coastal ecosystems can also protect against erosion (Erftemeijer et al., 2020) and sequester carbon, thereby reducing regional contributions to anthropogenic gas emissions (Campbell et al., 2015; Rabaoui et al., 2019; Schile et al., 2017).

Given the extreme environmental conditions of the Arabian Gulf, there is also increasing research on these ecosystems as 'natural laboratories' in climate change adaptation research, and as such, these systems represent essential natural assets for science in the region (Bouwmeester et al., 2021; Burt, 2013; Burt et al., 2020; Burt et al., 2014; Friis et al., 2021).

Figure 2: Coral reef in Ras Al Khaimah

Note. Important coastal ecosystems, such as this coral reef in Ras Al Khaimah, are under increasing pressure across the Arabian Gulf.

Pressures on Gulf Coastal Ecosystems

Recent intense human population growth has put increased pressure on coastal ecosystems across the Arabian Gulf (Firth et al., 2020). Gulf nations have a population growth rate that is nearly double the global average. Much of this population growth occurs in coastal cities (Van Lavieren et al., 2011). As a result, there has been extensive modification of coastlines through widespread dredging and land reclamation, development of industrial facilities (such as ports, power, desalination, and wastewater treatment plants), and the addition of coastal defense infrastructure to support burgeoning coastal cities (Burt, 2014; Sale et al., 2011; Sheppard et al., 2010). As cities have grown, so too has the discharge of effluents and accidental spills (Freije, 2015; Naser, 2013), and incidents of metal contamination, eutrophication, hypoxia, and harmful algal blooms (Al Muftah et al., 2016; Alshahri, 2017; Bauman et al., 2010; Naser, 2013; Rajan et al., 2014; Zhao et al., 2016).

Environmental regulation has tended to lag behind the pace of development in the Gulf, and consequently, there has been coastal ecosystem degradation and loss across the region (Burt, 2014; Sale et al., 2011; Sheppard et al., 2010). Infilling and reclamation of nearshore areas to expand real estate and dredging networks of channels to support marine traffic have negatively impacted coastal habitats through dredge removal or burial, and indirectly through construction-related sedimentation or long-term changes in currents and hydrology (Burt, 2014; Erftemeijer & Shuail, 2012; Lokier, 2013). Coastal development is now considered the primary threat to marine ecosystems in the Gulf (Sale et al., 2011). Additionally, the growing network of wastewater treatment facilities has enhanced eutrophication and pollution of nearshore habitats, causing hypoxic events and toxic algal blooms that have precipitated mass die-offs of fishes and other marine organisms (Al-Yamani & Naqvi, 2019; Ali et al., 2015; Glibert et al., 2002; Rajan et al., 2014; Shriadah, 2002).

Fisheries-related pressure has intensified the challenges facing coastal ecosystems. The regional fishing industry had expanded rapidly to support growing populations in recent decades, leading to dramatic declines in fish stocks across the Arabian Gulf (Al-Abdulrazzak et al., 2015). The biomass of spawning stock for several commercially important species is now less than 10% of its unexploited levels (EAD, 2021), and truncated size and age distributions suggest that replenishment of stocks by juveniles is being impaired (Grandcourt, 2012). Given that many commercially important species are also heavily reliant on coastal ecosystems for spawning, nursery, and foraging habitats (Buchanan et al., 2016; Grandcourt, 2012; Vaughan et al., 2019), the combined effect of fisheries pressure and ecosystem degradation has increased the risks to many commercially important fish species (Buchanan et al., 2019). Unfortunately, many parts of the Gulf do not have adequate fisheries management practices, law enforcement, or fisheries-related data collection to address these issues (Al-Abdulrazzak et al., 2015; Aljasmi, 2017; Siddeek et al., 1999).

Global climate change is exacerbating the effects of ecosystem degradation and overfishing. Frequent marine heatwaves have led to bleaching events that have substantially affected coral reefs across the Gulf (Burt, Paparella, Al-Mansoori, Al-Mansoori, & Al-Jailani, 2019; Riegl et al., 2018; Riegl & Purkis, 2015), reducing the total amount and complexity of coral in these habitats, which, in turn, affects reef-associated fish communities (Buchanan et al., 2016; Buchanan et al., 2019). Extreme temperatures are a physiological stressor that can affect the size (Brandl et al., 2020), growth (D'Agostino et al., 2021), fecundity (Howells et al., 2016), and susceptibility to disease (Howells et al., 2020) of marine organisms in the Gulf. As temperatures continue to rise, there will likely be further impacts on coastal ecosystems and their inhabitants.

Management Responses to Environmental Change in the Gulf

There have been increasing efforts in marine conservation and environmental management across the region in recent years in response to the growing awareness of the importance of coastal ecosystems and their vulnerable status (Grizzle et al., 2016; Hamza & Munawar, 2009; Khan, 2007; Lamine et al., 2020; Warren et al., 2016). At the national level, Gulf countries are increasingly establishing marine protected areas (Al-Cibahy et al., 2012; Van Lavieren & Klaus, 2013), adopting ecosystem-based management approaches (Burt et al., 2017; Mateos-Molina et al., 2021), developing policies towards more sustainable fishing practices (Grandcourt, 2012), strengthening environmental impact assessment processes and enhancing environmental regulations and laws (Naser, 2015). Gulf nations have also adopted various regional and international frameworks that seek to reduce environmental degradation and enhance sustainable development practices (Nadim et al., 2008), including the United Nations 2030 Sustainable Development Agenda. However, further cooperation between Gulf nations is necessary to achieve sustainability goals, particularly in fisheries management (Gulseven, 2020).

Artificial Reefs as a Tool for Marine Management in the Gulf

Better management and stronger regulations will help slow the decline of marine ecosystems going forward; moreover, the need persists for more active intervention towards habitat restoration and enhancement in response to past degradation (Alghunaim et al., 2020; Burt & Bartholomew, 2019; Erftemeijer et al., 2020; Hartig et al., 2019; Nithyanandan et al., 2018; Sen & Yousif, 2016). One such approach is the development of artificial reefs;

artificial reef programs have been widely adopted across the Arabian Gulf in recent years, including projects in Kuwait (Downing et al., 1985; Nithyanandan et al., 2018), eastern Saudi Arabia (Loughland et al., 2016), Bahrain (Erftemeijer et al., 2004; Maghsoudlou et al., 2008), Qatar (Abdel-Moati, 2006; Richer, 2008), Oman (Alhabsi, 2013; Burt et al., 2012), Iran (Azhdari et al., 2012; Mousavi et al., 2015) and the United Arab Emirates (Al-Cibahy et al., 2009; EAD, 2008; Hopkins, 2007; Mateos-Molina et al., 2020).

Artificial reefs have been deployed in the Gulf for a variety of reasons, including mitigating/compensating impacts to natural ecosystems, reducing coastal erosion (Abdel-Moati, 2006; Al-Saffar & Al-Tamimi, 2006; Azhdari, 2003; Hopkins, 2007; Maghsoudlou et al., 2008), providing recreation opportunities for diving and ecotourism (Al-Saffar & Al-Tamimi, 2006), or for aggregating commercially important fish and invertebrates for fisheries (Azhdari & Azhdari, 2008; Downing et al., 1985; EAD, 2008). However, in most cases, the management goals of Gulf artificial reef programs are not explicitly stated; there are no defined criteria for measuring success and, in almost all cases, they lack robust monitoring programs to determine whether the reef program meets its goals (Consultancy, 2017; Feary et al., 2011; Firth et al., 2020). Another problem with artificial reef programs in the Gulf region is that they usually do not account for possible unintended negative consequences that can result from reef construction, and so there are no efforts made to avoid these problems (Feary et al., 2011).

The following sections provide a review of the literature on artificial reef science from across the globe. The purpose of these sections is to summarize the benefits of developing artificial reef programs and highlight some of the unintended and negative consequences of the programs if they are not adequately designed and managed. We conclude the paper by synthesizing this knowledge into a series of policy recommendations for decision-makers considering developing artificial reef programs in the Arabian Gulf region. These recommendations will enhance the efficacy of these programs if they are adopted.

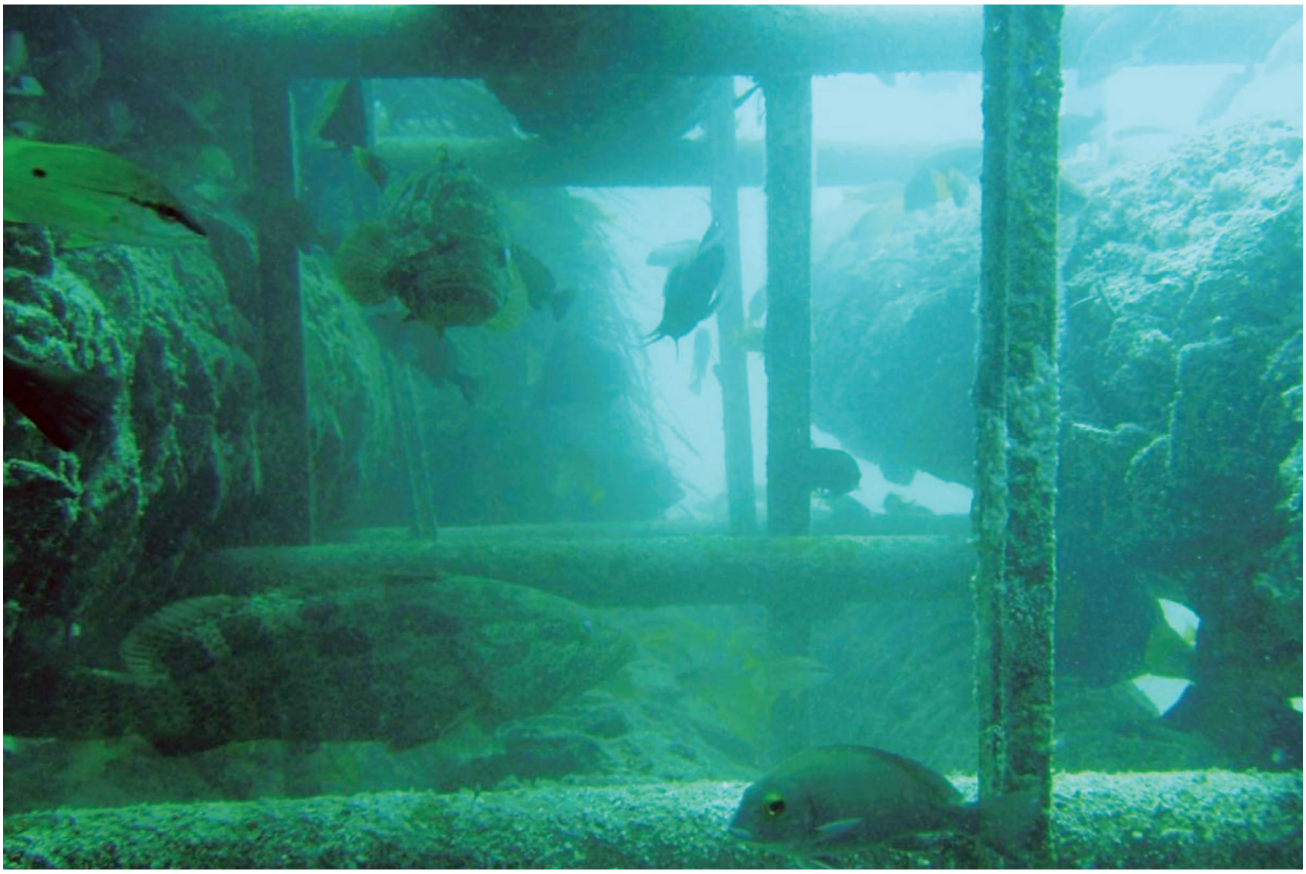
Purposes and Proposed Benefits of Artificial Reefs: A Global Perspective

Artificial reef programs have been used to support local economic interests in many countries around the world. They are often deployed to attract fish (Delmendo, 1990; Thierry, 1988) or to provide habitat for commercially important species (Charbonnel, 2002; Leitão et al., 2008), both of which can benefit local fisheries, at least in the short term (Bohnsack & Sutherland, 1985).

There is a long-standing debate over whether artificial reefs help produce new fish for local fisheries by increasing the total available habitat in an area or merely attracting existing fish from elsewhere, making them easier to catch (Bohnsack, 1989; Bohnsack et al., 1997). Arguably, most artificial reefs seem to attract fish rather than produce new biomass, and efforts to create artificial reefs that successfully produce fish are not well documented, in part because of the difficulty in demonstrating productivity changes on regional scales (Bohnsack et al., 1997; Pickering & Whitmarsh, 1997). However, there are examples where artificial reefs appear to have contributed to increased production due to a combination of creating novel habitat and design features of the reef. For instance, Claisse et al. (2014) reports that Californian oil platforms supported the highest secondary production (fish abundance) in marine habitats globally. The standard unit measured was seafloor surface area, which did not consider the vertical nature of the structures; moreover, such habitats do not exist in nature.

Artificial reefs may enhance local productivity through the following means: a) by providing breeding habitat (Kim et al., 2011; Pondella et al., 2002) and refuge habitat from predators (Eggleston et al., 1992; Folpp et al., 2020; Polovina & Sakai, 1989; Pondella et al., 2002; Leitão, 2019; Joyeux, 2011); b) by providing habitat for planktivorous fish that would not live in the area otherwise (Champion, 2015; Rilov & Benayahu, 2002; Smith et al., 2016); c) by increasing feeding opportunities leading to increased growth rates

Figure 3: An artificial reef built from palm reefs in 2006 in Khawr Bazim, Abu Dhabi



Note. For centuries, artificial reefs were built from palm tree trunks in the Arabian Gulf.

Image from A. Al-Cibahy (n.d)

(Cresson et al., 2014; Fabi et al., 2006; Love et al., 2007; Relini et al., 2002); d) by altering local circulation patterns to improve larval fish recruitment (Cenci et al., 2011); e) by providing settlement habitat to planktonic larvae that would otherwise die because there is no suitable natural habitat (Emery et al., 2006).

In addition to finfishes, artificial reefs are also widely used to support shellfish fisheries, such as oysters, lobsters, and mussels. Artificial reefs provide hard-bottom attachment sites that can increase the production of bivalves (Jensen, 2002; Lipcius & Burke, 2018; Macreadie et al., 2011; Steimle et al., 2002), and they can be designed to support the burgeoning invertebrate aquaculture industry (Fabi et al., 1989; Langhamer & Wilhelmsson, 2009; Xu et al., 2017).

Given the growth in human populations and concomitant fishing pressure, the use of artificial reefs as a tool to enhance fisheries will likely increase in the future (Becker et al., 2016). Improving their design may increase the likelihood that they produce fish for local fisheries rather than just attracting existing fish. Recommendations for this include creating vertically-oriented reefs (Rilov & Benayahu, 2002) and creating reefs with void spaces that are of an appropriate size to provide refuge spaces for fish, especially juvenile fish that normally have very high mortality rates (Burt & Bartholomew, 2019; Charbonnel et al., 2002; Hixon & Beets, 1993; Patranella et al., 2017). The co-location of fisheries and aquaculture with existing artificial structures such as those associated with energy extraction (e.g., offshore wind farms) (Airoldi et al., 2021; Ashley et al., 2014; Hooper & Austen, 2014) and the establishment of networks of artificial reefs have also been suggested (García-Gómez et al., 2015).

Aside from fisheries, artificial reefs can also provide recreational value and ecotourism benefits to local communities. Artificial reefs designed for coastal protection are also often constructed to act as surfing sites (Black & Mead, 2001; Herbert et al., 2017) or recreational fishing locations (Bohnsack, 1989; Keller et al., 2017; Whitmarsh et al., 2008). In addition, many artificial reef programs are designed to support dive tourism (Belhassen et al., 2017; Kirkbride-Smith et al., 2013; Shani et al., 2012), which is particularly useful in areas that lack natural reefs (Pears & Williams, 2005). Artificial reefs that attract tourism can bring substantial economic benefits to the local economy (Broughton, 2012; Rendle & Rodwell, 2014). Fishing and tourism on artificial reefs are generally incompatible activities, and tourism on these reefs can have a much greater economic impact than fishing (Brock, 1994). Artificial reefs can also be used to enhance awareness of marine environmental issues and promote marine education (Burt, Killilea, & Ciprut, 2019; Seidelin et al., 2018).

Besides economic benefits, artificial reefs have also been used to promote various ecological goals. They can provide attachment sites for ecologically important species of macroalgae, bivalves, and corals (Cummings et al., 2015; Endo et al., 2019; Fariñas-Franco & Roberts, 2014; Perkol-Finkel et al., 2012), increase biodiversity in the areas where they are constructed (Golani & Diamant, 1999; Hammond et al., 2020; Jackson et al., 2005; Perkol-Finkel & Benayahu, 2004; Raj et al., 2020), and support ecological services such as biofiltration to improve local water quality (Chojnacki & Ceronik, 1996; Hawkins et al., 2020; Hughes et al., 2005; Israel et al., 2017).

Moreover, artificial reefs have been successfully deployed to protect critical habitat from trawling (Lök et al., 2002; Relini et al., 2007), which can also protect fish stocks from overfishing (Polovina, 1991). Such concepts are also being applied to other artificial marine infrastructure such as renewable energy devices (Ashley et al., 2014; Inger et al., 2009; Thurstan et al., 2018). Ecological considerations have also been expanded to other common artificial infrastructure along the world's coastlines (e.g., seawalls, breakwaters), where so-called 'ecological engineering' principles are being used to support biodiversity goals by modifying coastal infrastructure (Airoldi et al., 2021; Dafforn et al., 2015; Firth et al., 2013; O'Shaughnessy et al., 2020; Perkol-Finkel & Sella, 2015). As the field of eco-engineering is relatively new, much can be learned from the older studies conducted on artificial reefs (Firth et al., 2020).

Artificial reefs have also been promoted as part of compensation strategies for loss or degradation of natural ecosystems through coastal development (Ambrose, 1994; Foster et al., 1994; Hueckel et al., 1989; Price et al., 2012) or major accidents (e.g., ship groundings) (Banks et al., 1998). The rationale for this approach is due to the perceived ecological benefits that artificial reefs can provide and their relatively rapid deployment compared with performing restoration (Elwany et al., 2011; Fariñas-Franco et al., 2013). Compensatory programs have shown that artificial reefs can develop communities with faunal abundances comparable to, or even exceeding, that of the natural habitats they were designed to replace (Foster et al., 1994; Hueckel et al., 1989). However, these programs can also displace resident organisms in the habitats where they are deployed (Hueckel et al., 1989) and typically support a mix of species that are reasonably distinct from surrounding natural habitats (Bulger, 2019; Walker & Schlacher, 2014), so their value as a compensation tool is limited.

The Dark Side: Unintended Consequences of Artificial Reefs

Artificial reefs are widely recognized for the potential positive impacts that they can provide to local economies and ecology. However, there is growing awareness that without appropriate planning and management, the construction of artificial reefs can have serious negative consequences. Here, we summarize some of the current knowledge of these issues to highlight the unintended consequences that may result if artificial reef construction proceeds without scientific guidance during their design and deployment.

Fisheries

Enhanced attraction and production of fish for fisheries is one of the most common goals for artificial reef programs worldwide. Commercial fishes and invertebrates are certainly attracted to these structures (Pears & Williams, 2005). This can enhance short-term gains for commercial and recreational fishers (Azhdari et al., 2012; Chou, 1997; Kasim et al., 2013; Keller et al., 2017; Kim et al., 1994; Lin & Su, 1994; Santos & Monteiro, 1998), but concentrating fishes and fishing activity on artificial reefs will unfortunately only exacerbate overfishing over the long-term (Grossman et al., 1997; Polovina, 1991; Roa-Ureta et al., 2019; Watanuki & Gonzales, 2006; Whitmarsh et al., 2008). Consequently, in regions where artificial reefs are constructed for fisheries purposes, there is little evidence that catch rates increase after an initial short-term bump (Polovina & Sakai, 1989; Sun et al., 2017). Instead, boat traffic is often higher at artificial reefs than natural sites (Keller et al., 2016); such pressure likely contributes to overfishing at regional scales (Bohnsack, 1989; Chou, 1997; Simon et al., 2011), even leading to declines in regional fisheries income (Islam et al., 2014).

Paradoxically, the only solution to this overfishing issue is to ban or heavily manage fishing activities around artificial reefs that are often built for this explicit purpose, which is unlikely to occur. Even if fishing bans could be applied as a strategy, most artificial reefs are well-known to fishers and easily accessible (Keller et al., 2016; McGlennon & Branden, 1994; Watanuki & Gonzales, 2006), meaning that enforcement of such regulation will be a challenge, particularly in less economically developed nations (Islam et al., 2014; Watanuki & Gonzales, 2006).

Ecology

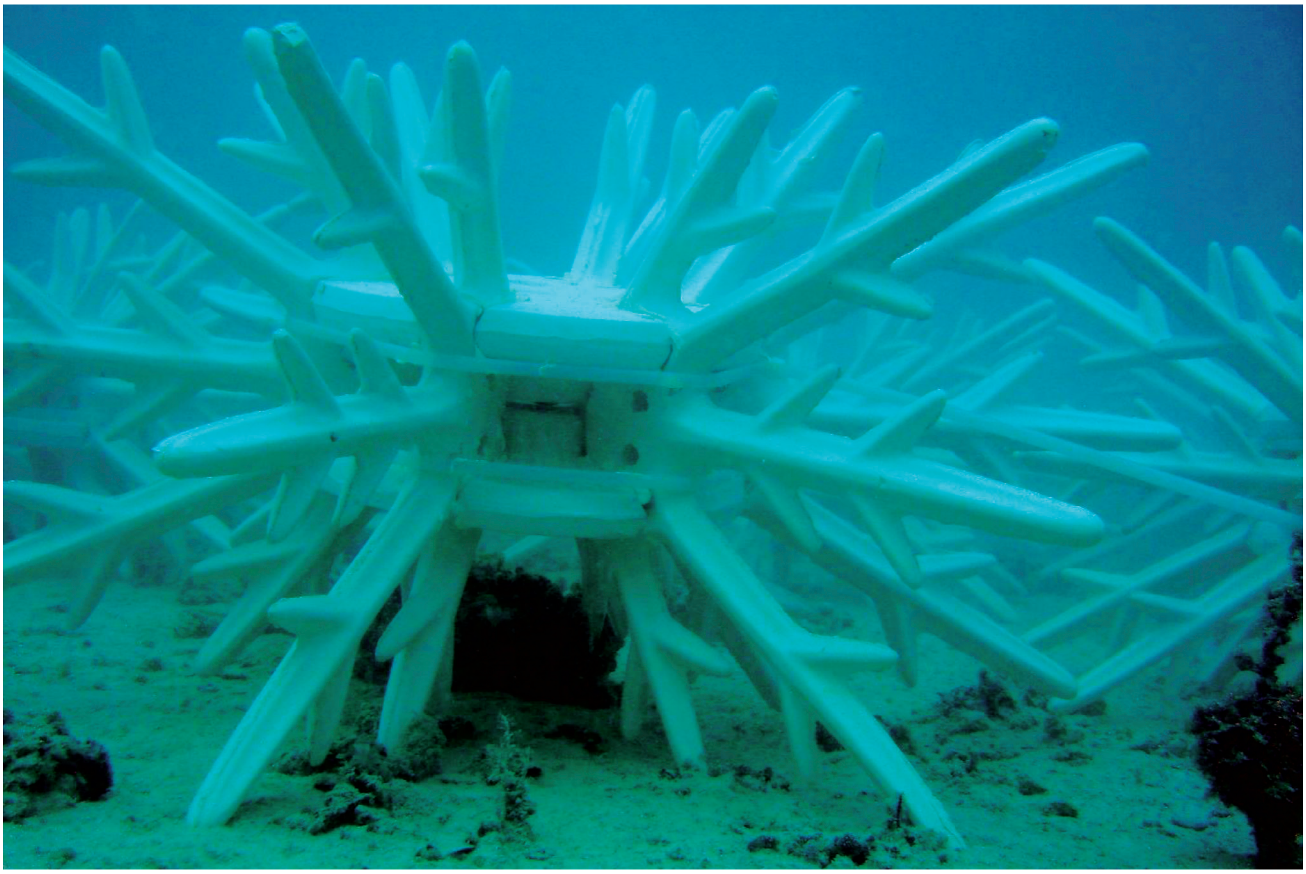
Artificial reefs can also have unintended ecological consequences at local and regional scales. On a relatively localized scale, artificial reefs usually support different biological communities than their surrounding habitats. They also alter local hydrodynamics. These actions can create a 'halo effect' of altered habitat around the reef (Herrera et al., 2002). High densities of fishes on artificial reefs can alter the biological communities around reefs through feeding on prey (Bortone et al., 1998; Herrera et al., 2002; Reeds et al., 2018) or vegetation (Edelist & Spanier, 2009), and by nutrient enrichment of surrounding sediments (Alevizon, 2002; Dewsbury & Fourqurean, 2010). Given that artificial reefs tend to attract large predatory fishes (Paxton et al., 2020), they may also act as ecological traps by serving as a 'wall of mouths' that prevents the establishment of juvenile fish and impacts existing prey communities (Folpp et al., 2011; Herrera et al., 2002; Leitão et al., 2008; Swearer et al., 2021).

Local hydrodynamic changes caused by the artificial reefs can also lead to erosion or deposition of sediments, further affecting surrounding soft-sediment communities (Danovaro et al., 2002; Herrera et al., 2002; Raineault et al., 2013). On larger scales, artificial reefs attract adult fish from nearby areas, leading to decreased abundance and shifts in community structure in natural habitats (Matthews, 1985; Simon et al., 2011). They may also act as 'sinks' for fish larvae if the larvae settle on the artificial reef rather than settling in natural nursery habitats (Carr & Hixon, 1997).

Additionally, it is increasingly recognized that artificial reefs often serve as 'stepping stones' that facilitate the range, extension, and spread of invasive species across biogeographic boundaries (Adams et al., 2014; F. Bulleri & Airoldi, 2005; Dong et al., 2016; Firth et al., 2016; Keith et al., 2011). These constructed reefs are often the only hard-bottom habitat in areas typically dominated by muds and sands, enhancing the establishment and spread of non-native rock-dwelling species (Airoldi et al., 2015; Mineur et al., 2012; Sheehy & Vik, 2010). Thus, artificial reefs can also facilitate invasion of rocky areas by providing 'novel' habitats (Bulleri et al., 2020) that are particularly attractive to invasive species with fast growth and high reproductive rates, but often with poor ability to compete with resident species (Broughton, 2012; Dafforn et al., 2012; Glasby et al., 2007; Simkanin et al., 2012).

Managers and policymakers should consider ecological factors in the design of artificial reefs and where they are deployed. Designs that feature low profiles, that seek to limit hydrodynamic and biological impacts on surrounding habitats, and that

Figure 4: Destruction of an artificial reef by shamal winds



Note. While artificial reefs may provide several benefits, they can also have unintended consequences. This artificial reef was destroyed by *shamal* winds during a winter storm, breaking and scattering debris across surrounding habitats.

mimic existing natural habitats would likely have less negative impacts (Bohnsack, 1991; Pearce et al., 2011; Vivier et al., 2021). The use of natural materials (e.g., shell or natural rock) that could be "seeded" with native species soon after construction also has the potential to limit the establishment of non-native species (Dafforn, 2017; Ferrario et al., 2016; Firth et al., 2016).

Impact Compensation

While artificial reefs are sometimes promoted as a means to mitigate or compensate for human impacts on coastal ecosystems, it is well known that they are very poor surrogates for natural habitat, both in terms of the biological communities they support and the ecological functions that they provide (Burt et al., 2009; Burt et al., 2013; Firth et al., 2013). Although artificial reefs usually develop large and diverse communities of organisms, they are novel habitats that support communities of invertebrates (Becker et al., 2016; Perkol-Finkel & Benayahu, 2005; Svane & Peterson, 2001; Thanner et al., 2006; Walker & Schlacher, 2014) and fishes (Bulger et al., 2019; Clark & Edwards, 1999; Hackradt et al., 2011; Jones et al., 2020; Koeck et al., 2014; Komyakova et al., 2019; Thanner et al., 2006) that are quite distinct from those of the surrounding natural ecosystems.

Given their unique ecology, artificial reefs thus provide little in the way of mitigating or compensating for the loss of natural habitats and are, at best, only poor surrogates. While it is correct that artificial reefs could be considered a tool for habitat enhancement since they develop their own, unique communities (Chou, 1997; Lemoine et al., 2019), a far more appropriate management strategy would be to direct efforts and funding towards conservation of natural ecosystems, rather than 'greenwashing' negative impacts on natural habitats by constructing artificial reefs as compensation (Firth et al., 2020).

Other Considerations

Aside from the issues described above, there are also practical issues of scale and cost to factor in when considering whether to develop artificial reefs. Most artificial reef programs are minimal in size (<100 m2), which is too small to create any meaningful ecological or economic benefits beyond the immediate vicinity of the reef, regardless of the intended goals (DeMartini et al., 1989; Pitcher et al., 2002). They are also costly and time-consuming to create and deploy (Bayraktarov et al., 2019; Pioch & Doumenge, 2011; Sutton & Bushnell, 2007). This suggests that the time, effort, and money spent on artificial reefs would usually be better spent on protecting, restoring, or enhancing natural habitats (Airoldi et al., 2021; McCreless & Beck, 2016; Morris et al., 2018).

This is particularly true for projects that are little more than waste disposal, where structures such as cars, planes, trains, and decommissioned oil rigs are sunk to create artificial reefs (Chou, 1997; Firth et al., 2020). Such programs are often promoted by industries that stand to gain from cost savings relative to using traditional disposal (Broughton, 2012). Moreover, there have been numerous examples of such materials leaching pollutants (Collins et al., 2002; Frease & Windsor, 1991) or degrading natural habitats when these 'artificial reefs' are pushed onto natural habitats during storms (Broughton, 2012; Morley et al., 2008). As such, it is recommended that such 'waste disposal' reef programs be avoided.

Gaps in Policy and Management

The above sections show that with appropriate planning and consideration of challenges, artificial reefs may serve as valuable tools for marine management in coastal areas. However, clearly defined policy objectives and careful data collection are required to assess whether artificial reefs effectively meet their intended goals. Unfortunately, few studies have described the purpose, criteria for assessment, or monitoring results for artificial reefs in the Arabian Gulf (Feary et al., 2011). Such deficits in overarching program policy are widespread in artificial reef programs worldwide (Becker et al., 2018; Seaman & Jensen, 2000).

Spieler et al. (2001) and Seaman (2007) both stress the need to establish measurable objectives as the starting point for artificial reef projects in combination with developing a robust monitoring program to assess whether the project was successful in meetings these objectives. Unfortunately, in many cases, the specific objectives for constructing artificial reefs are not explicit, and there are no defined criteria to assess whether the reef should be considered a success. If criteria are described at all, they are often listed as loosely defined benefits rather than specific, quantifiable changes in ecological characteristics, making assessing the success or failure of projects difficult (Becker et al., 2018). In addition, few systematic attempts have been made to conduct the long-term monitoring necessary to determine the effectiveness of artificial reefs in meeting their intended goals (Pears & Williams, 2005). Communities of organisms on artificial reefs undergo natural ecological succession and thus change rapidly for several years after their construction (and even for many decades depending on the organisms) (Becker et al., 2018; Nicoletti et al., 2007; Perkol-Finkel & Benayahu, 2005), but many monitoring programs are conducted over short time-frames or with limited continuity, if they are conducted at all (Baine, 2001; Vivier et al., 2021). These broad gaps in policy have meant that it has been impossible to assess the performance of most artificial reef programs in meeting their intended goals (Pears & Williams, 2005).

Recommendations for Improved Artificial Reef Policy in the Arabian Gulf

The Gulf nations are well recognized internationally for rapidly developing ultra-modern, cosmopolitan cities under forward-looking leadership that seeks to position their nations for the future competitively. Part of this future includes a strong focus on sustainability and enhancing the effectiveness of environmental management. We provide six recommendations that policymakers and marine managers should adopt in order to enhance the effectiveness of future artificial reef programs in the Arabian Gulf:

1. Avoid 'greenwashing' with artificial reefs

While artificial reefs can be developed in ways that provide numerous economic and ecological benefits, they should not be considered a tool that can compensate for current or future impacts on natural ecosystems from coastal development projects. Artificial reefs develop communities of marine organisms that are typically very distinct from those of natural habitats and function differently. As such, they are not surrogates for natural ecosystems and cannot adequately compensate for the destruction or degradation of natural habitats. Policies that promote the preservation, restoration, and enhancement of natural ecosystems will not only be less costly but are far more likely to be successful in supporting sustainable management objectives.

2. List explicit goals for the artificial reef program

The development of objectives and goals in creating an artificial reef is one of the most critical aspects of developing an evaluation program, as these objectives underpin all subsequent activities and the assessment of the effectiveness of the overall program. Generally, the creation of these goals and objectives are guided by the perceived benefits that marine managers want to enhance (e.g., enhance dive tourism opportunities), although these objectives may also include reference to problems that managers want to avoid (e.g., reduction in trawling damage to reefs). Programs may have multiple goals, but it is crucial to consider compatibility (e.g., diving and fisheries-related goals are likely incompatible). Goals should be concise and listed individually so that each goal can be assessed independently.

3. Define quantifiable criteria for assessing performance in meeting each goal

The criteria for evaluating success in meeting goals should be laid out clearly for each individual goal. For example, it is important to indicate not only that an increase in fish density is desired but to specify a measurable quantity of fish. It is only with the assignment of such a quantitative indicator of success that the artificial reef goals become testable and allows the determination of whether or not it has met its purpose (Seaman, 2007; Spieler et al., 2001).

Multiple criteria may support each goal. For example, if a goal is enhanced ecotourism opportunity, criteria may be metrics related to fishes, corals, number of visitors, etc. As long as they are clearly defined and measurable, they can each serve as evidence in assessing performance in meeting the intended goal. The development of such measurable criteria should be given priority before initiating any artificial reef program and should be re-evaluated through stakeholder engagement before moving on to later phases (Pears & Williams, 2005).

4. Design artificial reefs towards their intended goals

A limitless range of configurations, sizes, materials, and other features can be considered in designing artificial reefs, but only a subset of these will support the project›s intended goals. Likewise, artificial reefs can be deployed in many different marine environments, but specific environmental and hydrodynamic conditions are most likely needed to enhance target marine species while limiting nuisance species and other negative consequences. It is recommended that decision-makers consult with multiple stakeholders in the design stage of artificial reef programs, including experienced marine ecologists, marine engineers, and any end-users of the constructed reefs (e.g., fishers, divers, etc.) if the goals include human benefits. Such engagement is considered critical to ensuring that all stakeholders feel included in the planning process, and such dialogue should happen iteratively to allow revision and refinement of the design to maximize both biological and social benefits from the program.

5. Develop a robust monitoring program to assess criteria in meeting goals

Despite their widespread use, there are few published accounts of the results of monitoring programs conducted following the construction of artificial reefs in the Arabian Gulf (Burt et al., 2012; Feary et al., 2011). However, monitoring data is essential in determining the effectiveness of artificial reefs in meeting their intended goals. It is highly recommended that marine

Table 1: A summary of the six key recommendations

Key Recommendations
Avoid ‹greenwashing› with artificial reefs
List explicit goals for the artificial reef program
Define quantifiable criteria for assessing performance
Design artificial reefs towards their intended goals
Develop a robust monitoring program
Evaluate the artificial reef program and share lessons learned

Note. Policymakers and marine managers should adopt these recommendations when considering the development of artificial reef programs

managers consult with professional marine ecologists in designing such a program. Factors such as the sampling design (e.g., Before-After, Control-Impact, BACI), replication and extent of sampling in space and time, use of reference sites, specific methods for monitoring different fauna, and subsequent data analyses approaches each need to be considered in-depth to ensure that the monitoring program is sufficiently robust to assess changes caused by the reef, both statistically and conceptually. Without such a monitoring program, it will be impossible to validate whether or not the reef program is meeting its intended goals. Given the high cost of constructing and deploying most artificial reefs, monitoring represents a relatively modest expense that should be considered a good return on investment in the scheme of the overall program.

6. **Evaluate the artificial reef program and share lessons learned**

The final stage in any artificial reef program should be to evaluate the effectiveness of the artificial reef and then share the lessons learned to guide the creation and management of future artificial reef programs across the Arabian Gulf and beyond. Data from an appropriately designed long-term monitoring program can be used to assess the criteria established early on in the program›s design, allowing an understanding of whether the program was effective in meeting its overarching goals. This is particularly true in the Gulf region that serves as a 'natural laboratory' and early warning system for the impacts of climate change. It also allows decision-makers to identify areas of weakness so that future programs can avoid mistakes that were previously overlooked or unanticipated. By sharing this information publicly through workshops, conferences, or publications, marine managers can demonstrate their commitment to promoting environmental sustainability while also supporting the development of future artificial reef programs across the region.

Summary

Artificial reef construction has proliferated in the Gulf in recent decades. As the populations of Gulf nations continue to grow and the urbanization of coastlines continues to expand, it is likely that policymakers will increasingly turn to artificial reefs as one of the tools that they can employ for marine management. This survey of the literature has shown that artificial reefs can provide substantial economic, social, and ecological benefits; however, it also shows that they represent a 'double-edged sword' that needs to be carefully planned and implemented to ensure that these benefits are maximized, and unintended adverse effects are limited. Our synthesis of the global and regional literature on artificial reefs is condensed into six key recommendations for policymakers and marine managers considering adopting artificial reef programs. Implementation of these recommendations will help ensure the success of ongoing projects while also guiding future sustainable artificial reef programs across the Arabian Gulf.

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