BLUE ECONOMY
COOPERATIVE RESEARCH CENTRE

FINAL PROJECT REPORT

# IDENTIFYING THE POTENTIAL OF ARTIFICIAL FLOATING BENTHIC ECOSYSTEMS TO UNDERPIN OFFSHORE DEVELOPMENT

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# | EXECUTIVE SUMMARY

**Artificial structures such as fish traps have been used to attract and support harvesting of marine life for thousands of years.**

Marine life is also known to aggregate on and around structures such as shipwrecks and breakwater walls, and floating structures (e.g. fish aggregating devices) have been used to attract fish for ease of capture. More recently, artificial structures have been used to enhance recreational (e.g. fishing and diving) activities, increase biodiversity and for restoration of marine habitats.

However, with the majority of marine infrastructure (including purposefully built artificial reefs) being located in fragile coastal environments, concerns have been raised regarding negative impacts associated with these structures and the need to preserve natural habitats and nurseries.

Therefore, there is increasing interest in taking some of the commercial marine activities (e.g. aquaculture and energy production) offshore.

This report focuses on examining feasibility of floating artificial reefs to address a range of ecosystem services, with a primary focus on food production and twin-functioning with energy installations.

**In this scoping study, floating artificial reefs are defined as man-made structures that mimic the natural reefs in terms of biotic communities they support, such as plant or animal species that are being commercially cultured for food, marine products, and/or environmental benefits.**

Unlike natural reefs and traditional artificial reefs that occur as benthic systems, offshore floating artificial reefs are suspended from the surface to depths that are still within the photic zone, generally between 5 and 40 metres.

The Blue Economy CRC aims to perform world class, collaborative, industry focused research and training that underpins the growth of the Blue Economy through increased offshore sustainable aquaculture and renewable energy production. The project “Identifying the potential of floating artificial reefs to underpin offshore development” provides the first evaluation of the feasibility of development and deployment of floating artificial reefs.

***With natural reef systems providing Australia's most valuable seafood exports, floating artificial reefs provide an opportunity to compliment these markets for enhanced supply while reducing negative impacts.***

With the increased interest in seaweed aquaculture for food, nutraceuticals, pharmaceuticals and carbon sequestration, floating artificial reefs provide opportunities to target these emerging markets. As floating artificial reefs simulate ecosystems that are responsible for nutrient recycling in natural systems, these artificial systems can assist in the recycling of excess nutrients from both their own activities as well as other adjacent aquaculture activities through innovative system design.

Development of novel floating artificial structures that serve as farms and marine habitats in the offshore environments provides additional opportunities, such as the possibility to create refugia for threatened species, redirect fishing efforts from coastal zones and access points for a range of renewable energy sources (e.g. wind and wave power).

To date, no data exists on the functioning of floating artificial structures as marine habitats, as no such structures have been developed, deployed and monitored for the purposes of provision of ecosystem services, other than recreation, or as small scale fish aggregation devices.

While there is limited research on floating artificial reefs, this report engages with the extensive research on artificial infrastructure in the marine environment, and the evaluation of the impacts of such infrastructure over many decades, with some of the earliest research published half a century ago.

This provides a baseline for the development of effective and sustainable solutions for artificial habitat creation in the offshore environment.

***The report considers the state-of-the-art knowledge in these areas and some of the challenges that these ventures may need to consider for deployment of floating artificial reefs in Australian waters.***

Decisions on the floating reef size would be dictated by the primary goal of the deployment, reef utilisation (e.g., method of harvesting or monitoring) and targeted species. Floating artificial reef designs that aim to provide conservation, habitat restoration or nutrient recycling services need to address greater reef complexity and diversity of refugia. Designs of floating artificial reefs that are focused on the production of specific commercial species need to mimic the most favourable habitat characteristics and geometry used by the species across the size ranges being cultured, as well as habitat characteristics advantageous to growth and reproduction of their preferred food sources.

The type of material used in the construction of artificial reefs is a major consideration. A wide range of materials have been used to create artificial reefs, including rocks, tyres, ropes, nets, fibreglass and geotextiles. Concrete has been the most extensively used in recent decades and improvements in manufacture by the incorporation of, for example, mussel shells or recycled materials, is improving the environmental reputation of this product.

Different mooring configurations (e.g., taut, tensioned leg and catenary) should be explored in terms of their suitability for floating artificial reefs; this should include several aspects such as footprint, fairlead connection points, cost, intact and damage scenarios. Materials for mooring lines can vary to include wire ropes (steel), synthetic fibre ropes, and chains (steel).

Regulatory voids due to the novelty of offshore floating artificial reefs provide new challenges with respect to floating reefs that are more than "fish aggregating devices", and it is recognised that social acceptability for proposed floating artificial reefs is a key consideration.

The report includes a research plan for ongoing development on floating artificial reefs to meet the multiple opportunities they can provide in future offshore aquaculture development and marine stewardship.

MARINE ENVIRONMENTS

PROVIDE **60%** OF THE WORLD'S VITAL ECOSYSTEM SERVICES

**45%** OF STOCKS ARE CONSIDERED AS OVERFISHED

MANY SPECIES ARE **EITHER EXTINCT OR** UNDER SEVERE RISK OF **EXTINCTION**

# 1. INTRODUCTION

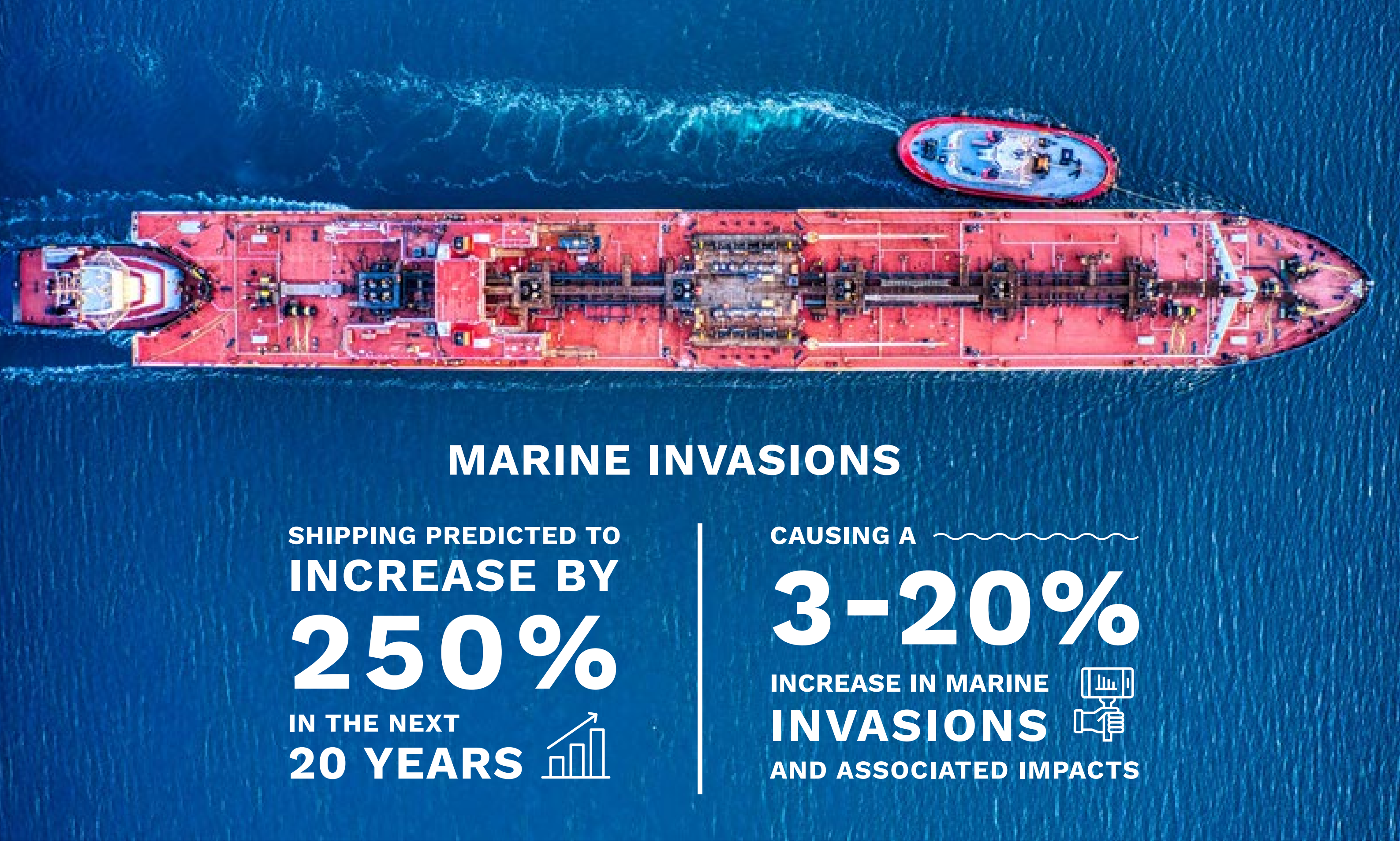
**Marine environments provide us with 63% of the world's vital ecosystem services, such as carbon sequestration, oxygen production, weather regulation, production of a variety of resources for human consumption (e.g., food, pharmaceuticals, construction materials), as well as transport and culturally important artefacts and locations (Box 1) (Falkowski, 2012, Gruber et al., 2019, Mora et al., 2011, Pauly and Zeller, 2016, Riser and Johnson, 2008).**

Mistakenly thought to be highly resilient, marine environments have been experiencing intensifying impacts from anthropogenic activities since before industrialisation (Halpern et al., 2008, McCauley et al., 2015, Andrello et al., 2022, Halpern et al., 2019).

Historical overexploitation has led to ecosystem collapses and local species extinctions (Jackson et al., 2001). These impacts have only increased in the recent decades, with 45% of stocks being considered as overfished and many species either going globally extinct or under severe risk of extinction (Dulvy et al., 2003, Dulvy et al., 2021, Yan et al., 2021, Foundation, 2021). Chemical pollution, eutrophication, introduction of invasive species and spread of infectious diseases, due to poor technologies or historical lack of appropriate management, have led to loss of biodiversity and creation of marine "dead zones" (Mack et al., 2000, Piola and Johnston, 2008, Ogburn et al., 2007, Molnar et al., 2008, Macko, 2018, Bailey et al., 2020).

***Shipping, the primary pathway of marine invasion, has been predicted to increase by over 250% in the next couple of decades, likely causing a 3-20% increase in marine invasions and associated impacts (Sardain et al., 2019).***

The plague of the recent decades is undoubtably a range of impacts associated with anthropogenic climate change. Marine environments are threatened by predicted increase in extreme weather events (e.g., cyclones), marine heatwaves (Bloemendaal et al., 2022, Jacox et al., 2022, Smith et al., 2021), and the spread of range shifting species (Pinsky et al., 2020).




Adding to historical pressures that continue to be exacerbated and ever rising climate change impacts, marine environments also face new threats in the 21st century, such as a range of novel types of pollutions (e.g., noise, light and microplastic pollution), that have been linked to significant ecosystem and human health impacts (Komyakova et al., 2020, Komyakova et al., 2022, Beloe et al., 2022, Wootton et al., 2021, Miller et al., 2020); and extensive replacement of natural habitats with artificial infrastructures (Bugnot et al., 2020, Floerl et al., 2021). The majority of these impacts are particularly severe in fragile and ecologically important coastal areas (Floerl et al., 2021, Bugnot et al., 2020, Halpern et al., 2008, Williams et al., 2022, Clark et al., 2021).

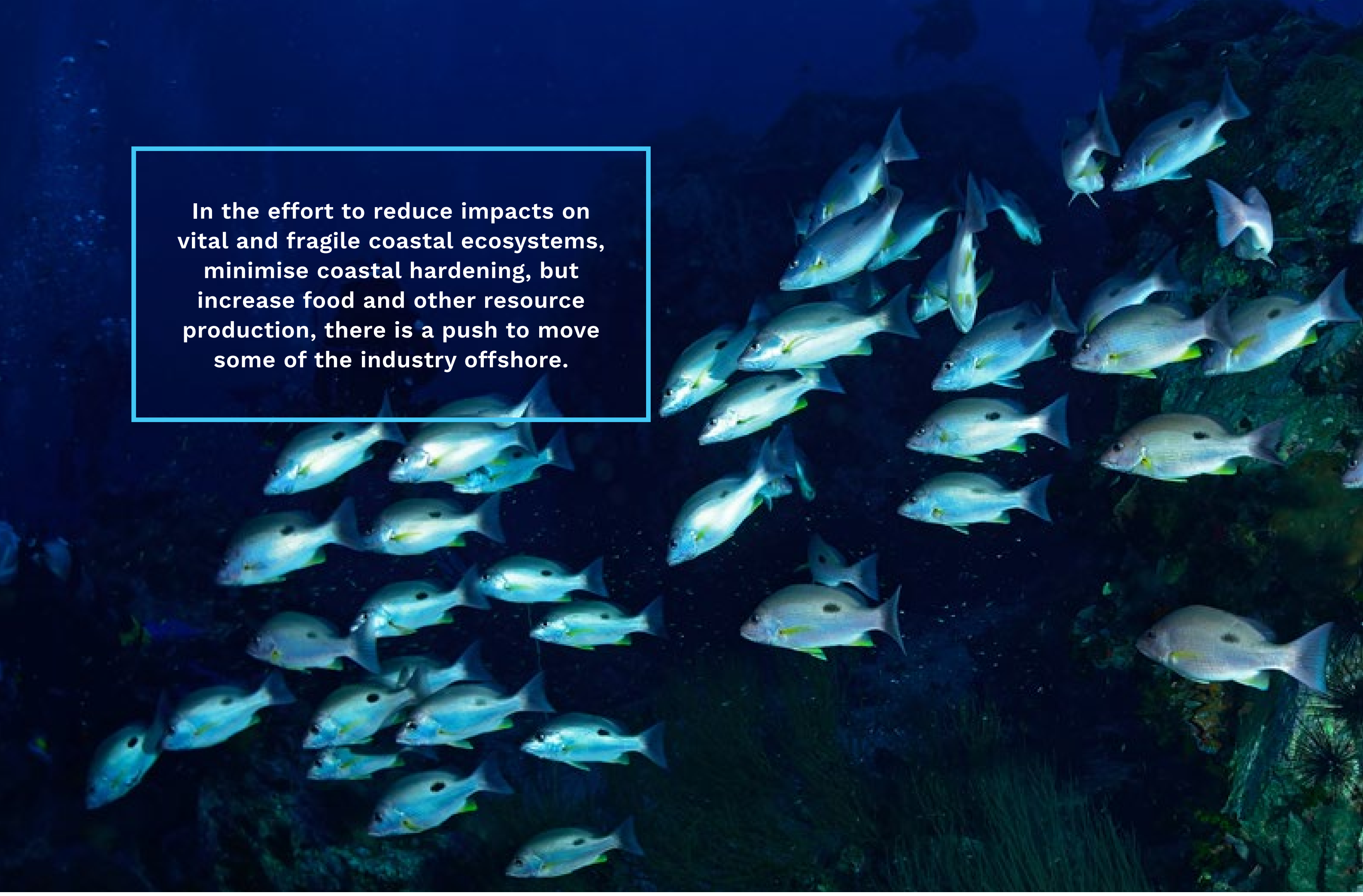
**Many of the stressors described above have accumulative and additive impacts, including leading to extreme habitat declines with over 70% of habitats being lost in many locations**

(e.g., coral and oyster reefs, seagrasses, mangroves and kelp forests) (Butler et al., 2020, Lotze et al., 2006, Morais et al., 2020, Beck et al., 2011). Extensive loss of habitats has been linked to dramatic phase-shifts and declines in habitat associated fish species, including pelagic species with habitat associated juvenile stages (Jones et al., 2004, Hughes, 1994, Lotze et al., 2006, Yan et al., 2021, Das, 2017). In fact, habitat loss is the second largest cause of marine animal extinction after overexploitation (Dulvy et al., 2003). These effects of habitat loss on fish populations are not surprising, as habitats provide vital resources, such as food and shelter, and influence outcomes of animal interactions, such as predation and competition (Jaxion-Harm and Speight, 2012, Hixon and Menge, 1991, Beukers and Jones, 1998, Ford and Swearer, 2013, Ford et al., 2016).

A range of habitat variables, such as complexity, diversity and vertical relief have been linked with high fish abundance and diversity (Komyakova et al., 2013, Chabanet et al., 1997, Parsons et al., 2016, Wilhelmsson et al., 2006). Complex and diverse habitats allow for niche and resource partitioning and hence lead to diversification (Willis et al., 2005, Connor and McCoy, 2001, Sueiro et al., 2011).

They reported that vegetated coastal ecosystems, including algal reefs, provide the largest value for provisioning services and nutrient cycling (support services) and could be worth as much as $120 billion per year or $17,608 per hectare per year (Gaylard et al., 2020). In tropical regions, the Great Barrier Reef in north eastern Australia has been valued at $6.4 billion per year and most of this is attributed to cultural (mainly recreational and icon) values of the reef.

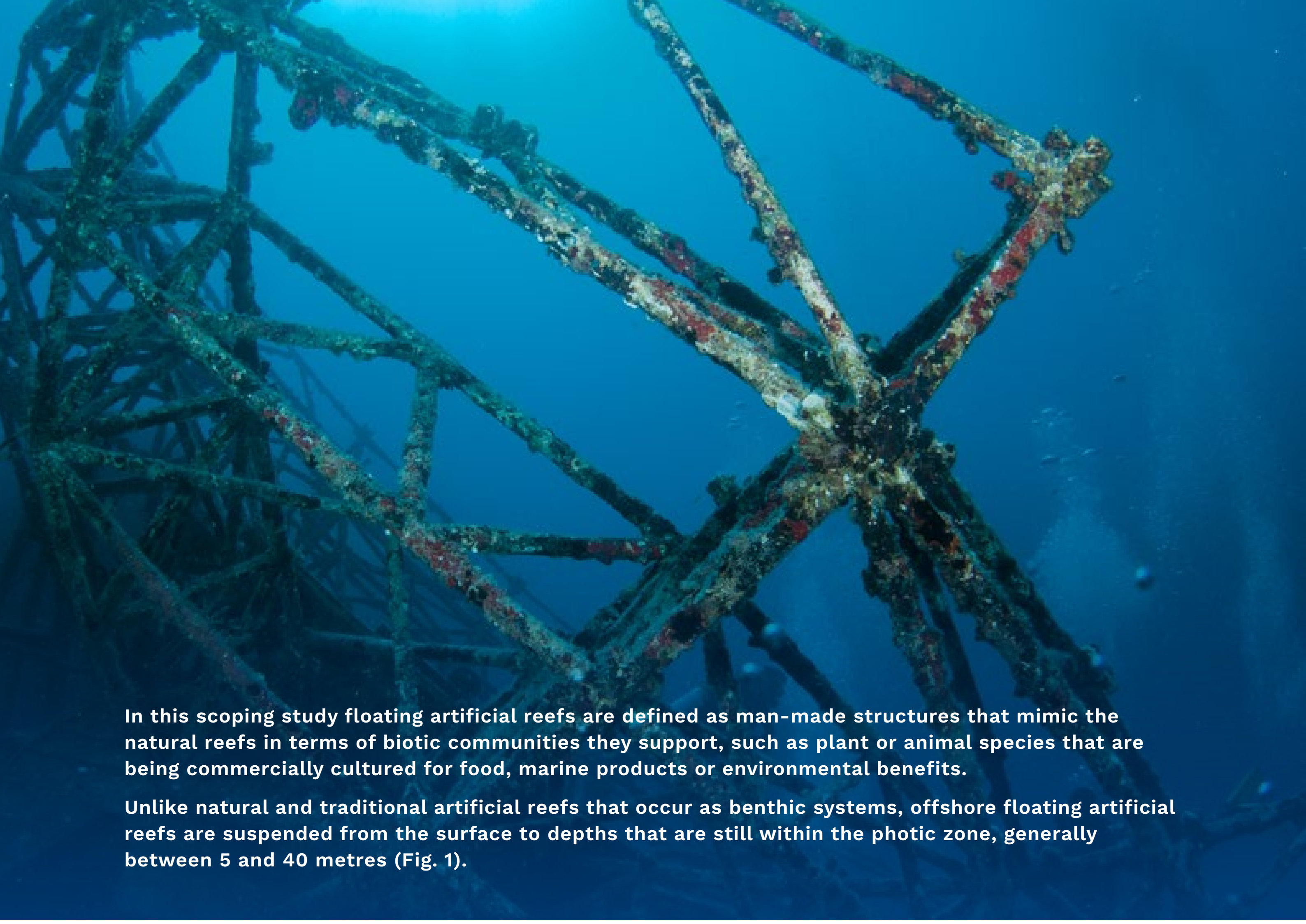
Other ecosystem services such as storm and erosion protection, food provisioning (primarily fishing) and provision of nursery sites for 25% of all marine animals highlight the importance of tropical reefs (What is the economic value of the Great Barrier Reef?).




This push leads to the need to examine opportunities, challenges and risks associated with the artificial habitat development and deployment in offshore environments. Reef system productivity is fuelled by sunlight and the associated photosynthesis in shallow coastal waters. For example, kelp forests are rarely found deeper than 40m (Krause-Jensen et al., 2019, Kvile et al., 2022, Marzinelli et al., 2015). As such, productivity declines as reefs extend offshore below the photic zone (Gattuso et al., 2006). Thus, to move offshore and provide the ecosystem services associated with inshore reef systems, artificial reefs need to be maintained within the photic zone.

Development of novel floating artificial structures, that serve as farms and marine habitats, in the offshore environments provide additional opportunities, such as the possibility to create refugia for threatened species, redirect fishing efforts from coastal zones and access to a range of renewable energy sources (e.g. wind and wave power) (See Section 2 for details). These and other opportunities may be further enhanced through development of multifunctional artificial habitats, that can address a range of human and ecosystem needs. To date, no data exists on the functioning of floating artificial structures as marine habitats, as no such structures have been developed and deployed for the purposes of provision of ecosystem services, other than tourism. However, extensive research has been conducted evaluating impacts associated with artificial infrastructure in the marine environment (Komyakova et al., 2022, Heery et al., 2017) (see Section 3 for the details) and successful attempts to improve infrastructure functioning as marine habitats have been documented around the globe (Komyakova et al., 2022, Dafforn et al., 2015, Evans et al., 2021, Dafforn, 2017, Strain et al., 2018). Furthermore, research examining functionality of natural habitats spans many decades, with one of the earliest published research being half a century old (Risk, 1972). Learnings from these earlier experiments and observations can provide a baseline for the development of effective and sustainable solutions for artificial habitat creation in the offshore environments.

**Here, we explore some of the state-of-the-art knowledge in these areas and some of the challenges that developers of offshore artificial reef deployments may need to consider and address and, provide the first evaluation of the feasibility of development and deployment of floating artificial reefs (FARs) to address a range of ecosystem services (Box 1 and Table 1), in particular focussing on food production, as part of the Blue Economy CRC.**



**In this scoping study floating artificial reefs are defined as man-made structures that mimic the natural reefs in terms of biotic communities they support, such as plant or animal species that are being commercially cultured for food, marine products or environmental benefits.**

**Unlike natural and traditional artificial reefs that occur as benthic systems, offshore floating artificial reefs are suspended from the surface to depths that are still within the photic zone, generally between 5 and 40 metres (Fig. 1).**

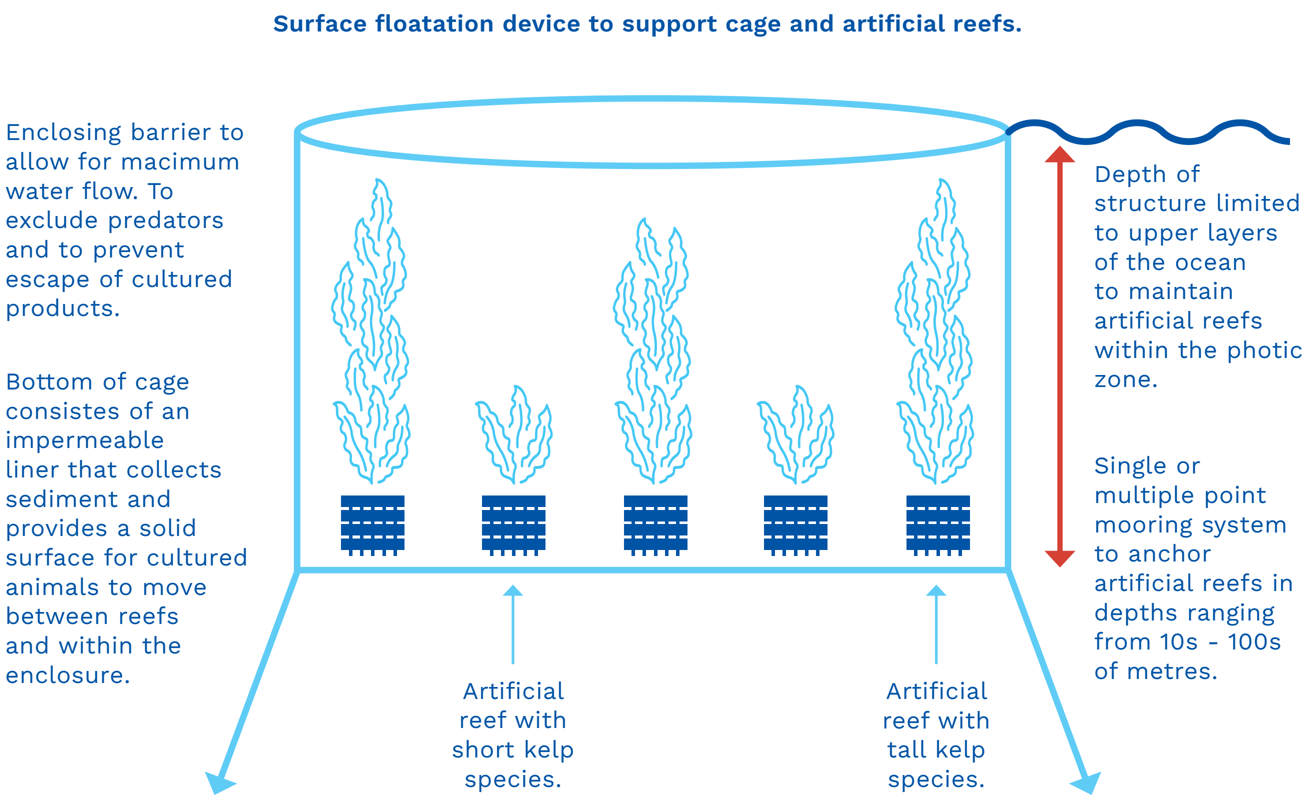



Figure 1. Conceptual representation of floating integrated aquaculture ecosystem artificial reef.

# 2. FLOATING ARTIFICIAL REEF SERVICES AND THEIR ASSESSMENT

**We undertook a simple SWOT (Strengths, Weakness, Opportunities and Threats) approach as a useful initial 'environmental scan' to assess the ability to achieve these services, noting that STRENGTHS refer to matters where there is robust evidence and OPPORTUNITIES are matters that need to be tested but have a certain level of assurance that there is a potential.**

## Ecosystem Services

**Ecosystem services are those services provided by the natural world which are linked to life on earth (Constanza et al. 1997).**

Ecosystem services are defined as 4 groups: provisioning services are the goods produced or provided by ecosystems and include food, timber, fuel etc. Regulating services are the benefits humans receive from regulation of ecosystem processes such as climate regulation, pest regulation, pollination etc.

Support services are the factors necessary for producing ecosystem services such as nutrient cycling, primary production, soil formation etc. Cultural services are the nonmaterial benefits from ecosystems and include spiritual, recreational, aesthetic and educational (Millennium Ecosystem Assessment, 2005).

### Floating artificial reef systems expected to provide a range of services:

**Food provisioning:** marine products, freshwater, raw materials, biochemical and genetic resources, species, products including biotechnology products from targeted marine plants and animals.

**Regulatory services:** climate regulation (including carbon sequestration) as well as waste and disease regulation and buffer zones.

**Supporting services:** primary production, nutrient cycling, biologically mediated habitats, release of pressure from additional inshore activities (e.g. food production).

**Cultural services:** includes science, conservation and education, inspirational aspects, recreation and tourism.

Table 1. Strengths, Weakness, Opportunities and Threats – First Pass Analysis of Floating Artificial Reefs

| | | |
|---|---|---|
| **S – STRENGTHS** | **MARINE EXPORT PRODUCTS** | Offshore FARs can supplement the existing export markets for high-priced marine products (e.g. rock lobsters, abalone). |
| | **NUTRIENT RECYCLING** | Ability for the reef to undertake nutrient recycling for both itself and other adjacent operations. |
| | **FOOD BIO-TECHNOLOGY PRODUCTS** | Provides a substrate for food (flora and fauna) and biotech products (e.g. algae for pharmaceutical products). |
| | **POLLUTANT EXPOSURE** | Marine products can be grown in (relatively pristine) Southern Ocean waters, away from coastal pollutants, runoff from agriculture or urban centres. |
| | **DEVELOPMENT OPPORTUNITIES** | If proven successful, as the developer of this concept, local companies would have first mover advantage and access to developments, patents etc. and a research workforce to continue at the cutting edge. |
| | **PROTECTION FROM EXTREME EVENTS** | Reduced impact from extreme events (e.g. freshwater runoff and high sediment loads associated with flooding; cyclones and associated storm surges (including tsunamis)). |
| | **REDUCED COST OF DEVELOPMENT** | Potentially lower costs due to the competing demands for coastal real estate. |
| **W – WEAKNESSES** | **ECOLOGICAL PRODUCTS** | Unknown impacts on wild populations (e.g. fish aggregating device (FAD) effect, eco-trap effect on migration patterns, light/noise pollution). Many of these have similar impacts to other aquaculture and/or offshore platforms in general. |
| | **ENGINEERING CHALLENGES** | Engineering aspects associated with construction, deployment, monitoring and removal of offshore FARs are unknown. |
| | **POLICY/ MANAGEMENT** | Currently a dearth of policy and management knowledge regarding offshore FARs, including gaps in legal frameworks. Both policy and management need to work across Australia's state and federal jurisdictions. |
| | **KNOWLEDGE GAPS** | As offshore FARs are novel, research is required across a range of scales (from basic research to pilot studies at small and commercial scale) to address a range of knowledge gaps. |
| | **ECONOMIC FEASIBILITY** | Currently there is no existing economic information or cost-benefit analysis for offshore FARs. |
| | **COMMERCIAL VALUE** | It may be difficult to mimic and maintain coastal reef ecosystems in offshore environments. This could have impacts ont he nutritional value of reef based food chains and subsequent growth of commercial product. |

| | | |
|---|---|---|
| **O** OPPORTUNITIES | **KELP PRODUCTION** | Likely to be more robust for offshore kelp production (especially bull kelp) than existing inshore culture methods. |
| | **SOCIAL ACCEPTABILITY** | FARs are a form of ecosystem aquaculture which could attract greater social acceptability, as evidenced by farming practices that adopt ecosystem approaches. |
| | **CONSUMER PREFERENCE** | Through the culture of a multitute of species providing an ecosystem framework, the system closely resembles a marine permaculture system that may attract consumer preference similar to agricultural goods. |
| | **CONSERVATION** | Could serve as areas for protection of threatened, engangered or prtected species (TEPs), especially those being impacted by climate change. This could be enhanced through breeding programs that assist in restoration. |
| | **MARINE SYSTEM PROTECTION** | FARs, especially those supporting dence algal cultures, can dampen current and wave activity and provide protection to infrastructure on their leeward side. |
| | **OFFSHORE FOOD PRODUCTION** | Global food demand is rising due to an increasing global population, and seafood production is expected to play a key role in future provisioning. Offshore food production systems focused on Australian products can assist in redirection of pressure from increased use of coastal environments. |
| | **DISEASE TRANSFER** | As FARs are seperated from inshore coastal reefs, there is decreased opportunity for within species disease transfer. Coastal disease threats such as harmful algal blooms are less likely to occur offshore. |
| | **REEF DEVELOPMENT** | By-products from the FARs, such as calcareous encrusting organisms can be used in a concrete mix for further reef development. |
| | **COASTAL MANAGEMENT** | Reduced concerns over environmental degradation due to impacts on natural coastal systems. |
| **T** THREATS | **BIOSECURITY** | FARs could attract and harbour invasive species of diseases (this threat would also need to be considered for all offshore infrastructure). |
| | **SERVICING/ MONITORING** | Unlike traditional aquacultire, the servicing and monitoring of multispecies associated with complex marine habitats is unknown and may require technical innovation. |
| | **OFFSHORE IMPACT** | s with all offshore developments, there will be concern over the impact that these developments have on the offshore marine environments. For FARs, this could include pollution from lost or damaged gear. |
| | **STOCKING FEASIBILITY** | FARs are reliant on the supply of juveniles/seed for stocking and some species, such as rock lobsters, are still in their infancy in seed production. |

# 3. RISK ANALYSIS OF THE POTENTIAL IMPACTS OF FLOATING ARTIFICIAL REEFS

Table 2. Risks and potential impacts of Floating Artificial Reefs (FARs) (some discussed/reviewed in Heery et al. (2017) and Komyakova et al. (2022))

| EFFECT TYPE | CHANGE/ EFFECT | SCALE | POTENTIAL IMPACT | REFERENCES |
|---|---|---|---|---|
| **Biosecurity** | FARs may act as 'stepping stones' and attract/ harbour invasive species (either naturally or via vessels used for servicing/ monitoring) | Unknown, but potentially 10s to 100s of kilometres (installation and maintenance of structures could increase dispersal distance) | Ecological - May alter FAR community composition and seascape connectivity; changes to nutrient and energy transfers; potential ecological or economic risk; increased disease risk | Adams et al. (2014), Airoldi et al. (2015), Consoli et al. (2013), Fernandez-Gonzalez et al. (2021), Fitridge et al. (2012), Layman et al. (2016) |
| **Biosecurity** | Introduced disease/ infection to FAR (particularly from biofouling organisms, which act as reservoirs and amplifiers of pathogens) | Unknown | Ecological - Production losses, reduced product quality | Costello et al. (2021), Fitridge et al. (2012) |
| **Bottom-up limitation** | Increased predation from reef-associated predators | Metres to 10s of metres | Ecological - Unknown (but potential ecological trap) | Davis et al. (1982), Frazer et al. (1991), Posey et al. (1992), Nelson et al. (1988) |
| **End user conflict** | Conflict arising between end-users relating to type, use, location and management of FARs | Unknown | Sociological – could threaten the effectiveness of the FAR | Pears and Williams (2005) |
| **Governance** | Potential lack of acceptance to FAR by local/ state/national policies | Unknown | Sociological – could limit scale/ effectiveness of FAR | Knapp and Rubino (2016) |

| EFFECT TYPE | CHANGE/ EFFECT | SCALE | POTENTIAL IMPACT | REFERENCES |
|---|---|---|---|---|
| **Navigational hazard** | Submerged obstacle | Dependent upon size and depth of FAR/mooring | Ecological - Entanglement of marine species Sociological - damage to vessels and FAR structure; production losses | Benjamins et al. (2014), Fabi et al. (2015) |
| **Organic enrichment** | Organic enrichment/site-specific reduction in sedimentary oxygen | <2 m | Ecological - May alter meiofaunal community composition | Fricke et al. (1986), Danovaro et al. (2002), Wilding (2014) |
| **Pollution** | Potential loss of/ damage to gear associated with FAR | Unknown | Ecological - damage to coastal ecosystems from objects washed ashore; potential for invasive species movement via lost gear; threat to marine organisms (entrapment/ entanglement, ingestion) | Skirtun et al. (2022), Werner et al. (2016) |
| **Pollution** | Nutrient loading/ discharge | Unknown | Ecological - potential impacts (e.g. reduced production, hypoxia) could depend on background dissolved nutrient levels, degree of upwelling, hydrodynamics; potential impact to deep sea ecosystem (e.g. reduced assimilative capacity of sediments) | Buck et al. (2018), Troell et al. (2003) |
| **Pollution** | Light/noise/ | Unknown | Sociological – could threaten the effectiveness of the FAR | Pears and Williams (2005) |
| **Social acceptability** | Public opposition to FAR/negative public perception of FAR | Unknown | Sociological – could threaten the operation and effectiveness of the FAR | Bacher (2016), Kraly et al. (2022), Knapp and Rubino (2016), Froehlich et al. (2017) |

# 4. VARIABLES IN THE ASSESSMENT OF FLOATING ARTIFICIAL REEFS

## 4.1. CONSTRUCTION MATERIALS

The type of material, used in the construction of artificial reefs (ARs) is a major consideration.

A wide range of materials have been used to create artificial reefs, including rocks (e.g. graywacke, sandstone), tyres, ropes, nets, fibreglass and geotextiles (Lima et al., 2019).

It has been estimated that approximately 40% of ARs around the world have been constructed from concrete, 20% from steel, 15% from rock, 10% from rubber and the remainder from materials such as ash, ceramic, shell, fibreglass and brick (Ramm et al., 2021).

Most studies investigating the ecological impacts of artificial reef materials have examined near-shore artificial reefs located on the seafloor. In an analysis between artificial and natural reefs, (Dodds et al., 2022) found that species richness did not significantly vary among material types (although these studies were generally short and therefore didn't consider long-term effects, e.g. initial opportunistic species eventually out-competed/replaced with more species-rich communities).

Other studies have found the effects of material type is greater for sessile species, as they interact directly with the reef substrate (Dobretsov et al., 2013, Sedano et al., 2020).

### 4.1.1. Concrete

Concrete is the most commonly used material in artificial reef construction (Lima et al., 2019), owing to its chemical composition (which is similar to natural coral limestone), availability and durability.

Importantly, concrete has been found to support greater abundances of species than other artificial substrates (Dodds et al., 2022). While the micro-texture of concrete is generally more homogeneous compared to natural materials such as rock or wood (Coombes et al., 2015), concrete artificial reefs display high fixation rates and high levels of colonisation by sessile invertebrates (Baine, 2001, Mos et al., 2019, Sempere-Valverde et al., 2018, Vivier et al., 2021).

This may be attributable to the leaching of calcium hydroxide, which acts as a settlement cue for calcifying organisms such as bivalves, barnacles and corals (Mos et al., 2019, Anderson, 1996). Concrete artificial reefs may even support similar species abundance as natural reefs (Dodds et al., 2022).

Standard concrete may contain toxic metals as additives to improve strength or resistance to chemical attack (Snelson and Kinuthia, 2010). Leaching of heavy metals into the surrounding water column can occur as a result (McManus et al., 2018, Müllauer et al., 2015), although the impact of this will likely be lessened in environments with high water exchange, such as large floating systems (Becker et al., 2020). Standard forms of concrete may also have a higher pH than seawater (Perkol-Finkel and Sella, 2014). Portland cement, which is a major construction material used in marine concrete artificial structures (McManus et al., 2018), has a much higher pH (~13) compared to seawater (~8) (Sella and Perkol-Finkel, 2015). Thus, its use in concrete structures can create communities dominated by alkotolerant taxa such as barnacles (Dennis et al., 2018, Guilbeau et al., 2003, Dooley et al., 1999). However, this alkaloid effect has been reported to be largely short-term (3-6 months) (Dooley et al., 1999). Therefore, concrete remains an acceptable material for use in marine environments.

The concrete used in artificial reef is generally a high-strength marine-grade concrete which returns a sufficient level of rugosity, and by adding micro silica, it can have a balanced pH (Florisson, 2018a, Industries, 2018, China, 2010, Dodds et al., 2022). Integration of concrete and steel can also add to the benefits of artificial reefs (Florisson, 2018a).

***Within recent years, eco-friendly concrete alternatives have begun to be used within artificial reef structures.***

Eco-friendly concrete attempts to provide some form of ecological enhancement (Sella and Perkol-Finkel, 2015), either by varying the chemical properties of concrete (e.g. reducing pH) (Hsiung et al., 2020), or incorporating natural materials into the concrete matrix (Vivier et al., 2021).

***An important factor determining the longevity of concrete structures is the extent to which seawater can permeate the material.***

The efficacy of changing the chemical composition of concrete for ecological enhancement appears to be dependent on the concentration of natural additives, with higher concentrations of additives resulting in increased settlement (Lee et al., 2009, Neo et al., 2009). Importantly, utilising eco-friendly concrete may reduce colonisation of artificial reefs by non-target species, while increasing target species richness (Sella and Perkol-Finkel, 2015, Dafforn, 2017).

Indeed, one study found that using specially-formulated concrete compared to standard concrete in marine structures reduced invasive species richness by as much as 50%, while native species richness was increased by almost 45% (Sella and Perkol-Finkel, 2015). Albeit more recent studies have reported limited benefits from alterations of concrete chemistry (Dodds et al., 2022).

Developing biogenic concrete from marine products such as oyster shells can be considered a solution to increase the richness and abundance of species (Dodds et al., 2022, Vivier et al., 2021). The European RECIF project suggested incorporating crushed seashells of the queen scallop, (Aequipecten opercularis), into the substrate of concrete blocks (Vivier et al., 2021). Similarly, blue mussels' shells are used for their calcium carbonate in the production of Blue Mussel concrete (Vergés, 2014).

Despite some success in the development of eco-friendly and biogenic concrete mixtures, studies report that altering the surface complexity/ rugosity appears to have greater positive impacts on abundance in settling communities than altering the chemical properties of concrete (Dodds et al., 2022, Potet et al., 2021, Hayek et al., 2022), as it provides more area for attachment, greater refuge from predators, and reduced impact from competition and other environmental stressors (Bulleri and Chapman, 2010, Strain et al., 2018, Loke and Todd, 2016).

**An important factor determining the longevity of concrete structures is the extent to which seawater can permeate the material.**

Typically, surface coating and chemical buffering are used to stop seawater infiltrating the structure (Yi et al., 2020), thereby slowing corrosion. However, corrosion inhibitors can also negatively impact the biocolonisation of concrete AR structures.

Interestingly, biofouling by some encrusting organisms (such as barnacles, oysters, annelid worms and molluscs) may confer some degree of protection against corrosion and leaching of concrete (Pioch et al., 2018). For example, barnacles attached to concrete structures have been shown to reduce saltwater ingress and crystallisation below the concrete surface (La Marca et al., 2014).

Growth of such organisms on concrete may also increase the strength of the structure, as it has been reported that coastal breakwaters dominated by oyster growth showed a ten-fold increase in strength two years post deployment (Risinger, 2012).

### 4.1.2. Steel

Metal and steel are often introduced in the marine environment as part of anthropogenic structures, such as oil rigs, jetties, and artificial reefs.

Metal structures are common in AR construction as the material is very stable, durable and can adopt complex forms. While various metals used in steel structures are toxic to certain marine species (e.g. Ni, Cr) (Aslam and Yousafzai, 2017, Dodds et al., 2022), iron ions released during oxidation can be utilised by algae and subsequently increase primary productivity (Layman et al., 2016, Muñoz-Pérez, 2008, Lima et al., 2018). However, in some iron-poor environments (with low or non-existant iron inputs), shipwrecks have been shown to cause a phase shift in the coral reef community, moving from a coral-dominant community to one characterised by high benthic cover of turf and macroalgae, cyanobacterial mats and corallimorphs (Kelly et al., 2012, Work et al., 2018). To prevent turf and macroalgae dominance around steel structures, the mineral application technique (MAT) (Box 2) can be applied to metal structures to enhance coral recruitment, survival, and growth (Hylkema et al., 2021).

**Mineral Application Technique (MAT)**

The MAT technique exposes the metal structure to a low voltage electrical current, which causes seawater electrolysis and accretion of calcium carbonate.

This method was also named the low-voltage mineral deposition technology (LVMD) and can be applied to metal structures to grow underwater limestone on metal frames of any shape and size in the sea. This method has been shown to have stimulatory impacts on different types of marine life.

LVMD can be sped up by increasing the voltage and allowing the precipitation of the Magnesium Hydroxide (Brucite) rather than the calcium carbonate, making a structure whose strength is comparable to or even superior to concrete (Margheritini et al., 2021).

### 4.1.3. Wood

Despite wood being an inexpensive, renewable, biodegradable and non-toxic option for marine construction, it is a not commonly used in benthic artificial reefs.

This is largely due to its low durability and stability within marine environments, particularly in areas of strong current or wave action (although it can be used in conjunction with concrete to increase its stability) (Yamamoto et al., 2014, Yu et al., 2015).

Wood is a preferred material for use in floating structures such as marinas; however, the material is highly hydrophilic and most woods can be degraded by biological organisms and the impact of waves, wind and sand (Treu et al., 2019, Filgueira et al., 2021). To protect against wood-degrading organisms, wood is typically treated with paints and coatings that may contain heavy metals (e.g. zinc, copper), or organic compounds that are toxic to both biofouling organisms as well as non-target organisms that colonise wooden structures (Filgueira et al., 2021).

Subsequently, there has been a recent push to develop more environmentally friendly treatments for wooden marine structures (Filgueira et al., 2021, Callow and Callow, 2011). Non-biocide antifouling treatments generally use hydrophobic compounds, such as silicon, that interfere with the adhesion of marine microorganisms (Filgueira et al., 2021, Brady, 1999, Callow and Callow, 2011). However, these treatments would likely inhibit colonisation of wooden FAR structures by reef-associated organisms. As such, wood is unlikely to be suitable for long-term use within FARs.

### 4.1.4. Plastic & related polymers

Plastic artificial reefs commonly support lower abundances of species and have a higher environmental impact compared to reefs constructed with concrete or natural materials (Dodds et al., 2022, Vivier et al., 2021, Zhang et al., 2020).

Plastics often poorly mimic natural surfaces owing to low micro-surface complexity, and are therefore generally less attractive to most marine organisms (Becker et al., 2020). Moreover, plastics themselves are often hydrophobic and have low wettability, which can further limit settlement; however, some species of algae and invertebrates which are able to settle on such surfaces may benefit from reduced competition (Encinas et al., 2010). This may be particularly true for invasive species.

Crucially, plastic artificial reefs can release micro- and nano-plastics particles (Zhang et al., 2020), which can be ingested by marine organisms across a wide range of trophic levels and negatively impact feeding behaviour, growth, development, reproduction and lifespan (Alfaro-Núñez et al., 2021, Gallo et al., 2018, Kawasaki et al., 2003, Botterell et al., 2019, Wright et al., 2013b, Anderson et al., 2016).

Additionally, plastics may contain chemical additives and contaminants which can have deleterious impacts on marine species at extremely low concentrations, such as persistent organic pollutants and endocrine disruptor chemicals (Gallo et al., 2018, Anderson et al., 2016, Andrady, 2011).

Despite extensive concerns associated with the use of plastic in the marine environment, it has been proposed that some polymers may be suitable for marine infrastructure.

High-density polyethylene (HDPE) is a polyethylene thermoplastic made from petroleum and is one of the most commonly produced plastic polymers (Mazur et al., 2020, Kumar et al., 2011).

HDPE has been used in some small-scale artificial reef experimental studies (Hong et al., 2019; Lokesha et al., 2013; Angel and Spanier, 2002), and is frequently used in aquaculture due to its versatility, chemical and biological stability (Koutny et al., 2006), resistance to UV degradation, high level of recyclability (recycling code 2) and low cost (Lusher et al., 2017, Kumar et al., 2011). It also has a longer degradation time than other forms of polyethylene, varying from tens of years for plastic bottles, to thousands of years for heavier industrial forms such as pipes (Chamas et al., 2020).

Despite longer degradation time, HDPE micro particles are often present in the marine environment, where filter feeders such as bivalves may be particularly susceptible to ingestion (Browne et al., 2008, Wright et al., 2013a). HDPE micro particles can be taken up into the cells of the blue mussel (Mytilus edulis L.) and can cause significant effects at the tissue and cellular level (von Moos et al., 2012). Similarly, Pacific oyster (Crassostrea gigas) embryos exposed to HDPE micro particles experienced negative impacts to development and locomotor activity (Bringer et al., 2020).

Indeed, when considering the probability of exposure (factoring in global waste generation, mean density and degradability), HDPE is found to be one of the most significant polymers with regards to the potential risk to human health from food chain exposure routes in marine waters (Yuan et al., 2022).

As with all petroleum-based plastics, HDPE production is strongly link to climate change issues (1.75kg of petroleum produces 1kg of HDPE) (Lavers et al., 2022, Ford et al., 2022).

**The benefits of clay are that the material itself is inert, robust, sustainable, has a low production cost and organisms adhere well to it.**

Due the concerns associated with environmental pollution, climate change and sustainability concepts, scientists are investigating alternative methods of producing HDPE, such as using sugar cane and other non-petroleum products (dos Santos Jr et al., 2018)(although sugarcane production has its own environmental impacts (El Chami et al., 2020)).

There may be opportunity for innovation in the use of plastics by using recycled plastics that are encased in a calcareous substance that fully protects leakage of micro- and nano-plastics into the marine environment. The calcareous casing provides the outer surface complexity, and the recycled plastic provides additional ecosystem benefits by locking up existing plastics.

However, concerns raised by communities and Government regarding marine plastic pollution may result in all plastic products being prohibited for use in the marine environment.

### 4.1.5. Ceramic and Clay

Ceramic is becoming an attractive alternative material to concrete or steel in marine construction (Baumeister, 2022).

Ceramic materials are non-toxic, pH neutral and can be built in various designs using 3D printing (Muliawati et al., 2022). Clay is a natural option for use within artificial reefs.

The benefits of clay are that the material itself is inert, robust, sustainable, has a low production cost and organisms adhere well to it.

Furthermore, ceramic materials can stimulate coral metamorphosis and are favoured by coralline algae, which is known to have a positive impact on increasing the settlement of corals and other benthic organisms (Levy et al., 2022). This can also lead to fish more promptly colonising ceramic reefs compared to concrete reefs (Santos et al., 2011). Despite these benefits, clay remains an underutilised option for artificial reef construction (Trilsbeck et al., 2019).

Table 3. Assessment of FAR material suitability, considering environmental and engineering factors

| MATERIAL | BIOGENIC[1] | COMPLEXITY[2] | LONGEVITY[3] | STRENGTH[4] | OTHER CONSIDERATIONS: BUOYANCY5 |
|---|---|---|---|---|---|
| Ceramic | Green | Green | Orange | Green | Grey |
| Concrete (standard) | Orange | Green | Green | Orange | Grey |
| Concrete (eco-crete) | Green | Green | Green | Orange | Grey |
| Plastic (HDPE) | Red | Orange | Green | Orange | Green |
| Steel | Orange | Red | Orange | Green | Red |
| Wood | Red | Orange | Red | Orange | Green |

**Green** – strong evidence of positive effect or high performance.

**Orange** – discrepancies in the results with both positive and negative impact equally common; limited evidence of positive effects.

**Red** – strong evidence of negative impacts or poor performance, Grey – insufficient information available.

[1]**Biogenic** – experimental studies have demonstrated limited negative impacts on marine biodiversity and a range of positive relationships with biodiversity variables.

[2]**Complexity** – defined as an ease of incorporating small scale complexity to the designs.

[3]**Longevity** – defined as maximum life span with life span of over 50 years identified as highly durability, 50-10 – as of moderate durability and >10 as poor durability.

[4]**Strength** – estimate based on combination of compressive and tension strength (MPa) of material, with <10 MPa identified as low strength, 10-150 MPa as moderate strength, and >150 MPa as high strength.

[5]**Buoyancy** – defined as ease of creating buoyancy within material.

## 4.2. REEF DESIGN

**Documented sampling design-based research into marine habitat functionality and specific habitat characteristics that drive plant and animal communities is over half a century old (Klopfer, 1969, Risk, 1972, Gorman and Karr, 1978, Luckhurst and Luckhurst, 1978).**

The evidence that humans used observations of nature and enhanced their fishing strategies using artificial installations dates back thousands of years with Australian Indigenous communities employing various fish trap designs (Rowland and Ulm, 2011, Stockton, 1982, Colhoun and Piper, 1982).

Japanese records that mention the use of artificial reefs for enhancing fisheries output are at least 300 years old with the development of artificial marine habitats for fisheries management gaining widespread attention in Japan and Europe in the last 80 years Fabi et al., 2011, Grove et al., 1991, Thierry, 1988).

In that time a large variety of artificial reef designs have been deployed around the world, from accidental and purposeful shipwrecks to experimental small-scale units to specially designed large-scale installations (Fig. 2).

This plethora of experiences and data provides solid foundation for the development of innovative floating designs.

Some decisions regarding reef design characteristics would be driven by primary purposes of the reef deployment (e.g., aquaculture, conservation, fisheries enhancement, habitat restoration), targeted species, as well as locations of deployment from the perspective of wave exposure, depth, surrounding habitats and vicinity of the natural reef (Blount et al., 2021, Komyakova et al., 2019a). However, there are broad habitat design characteristics that should be considered regardless of the targeted variables. The primary parameters of importance are reef size, geometry, complexity, diversity of refugia, vertical relief and module configuration. Apart from these, stability and strength must also be evaluated during the design.


Figure 2. Examples of the variety of artificial reef designs employed around the world. a. Various designs of Reef Ball® reefs in a five-point dice arrangement deployed off Frankston pier in Victoria, Australia. Photo courtesy of Valeriya Komyakova; b. Lobster enhancement reefs designed by Greg Paige from Southern Blue Reefs deployed in Tasmania, Australia. Photo courtesy of Simon Talbot c. Artificial small scale experimental installation at Yanaka Isl., Fiji. Photo courtesy of Kerry Borgula; d. Shipwreck in Thailand. Photo courtesy of Tom Coughlin.

### 4.2.1. Reef Size, Surface Area and Volume

Location, purpose of the reef (e.g., surf reef, fishing reef) and targeted fish species dictate most suitable reef size leading to variability in recommendations on optimal size (Becker et al., 2019, Bowen et al., 2020).

For instance, 5700 m3 has been disputed both as the minimum and maximum size for a reef (Bowen et al., 2020, Turner et al., 1969). In Japan, the optimal size recommended is 3000 m3/km2 (Sato, 1985), while in Australia, a minimum of 800 m3 has been suggested (Diplock, 2010). For natural habitats, it has been demonstrated that larger habitats tend to support greater total abundances (Komyakova et al., 2018, Holbrook et al., 2002b). However, the results of the experimental artificial reef studies are not fully consistent. Some studies showed that small reef patches tend to have greater fish densities, while larger patches support greater biomass density due to the presence of larger individuals but in lower abundances (Bohnsack et al., 1994).

Other investigations demonstrated that increased reef size does lead to greater fish abundance and species richness (Jordan et al., 2005, Jones et al., 2020, Shelamoff et al., 2020). Some studies advised that increase in fish abundance and richness with increase in habitat size was linear (Jones et al., 2020), while other reported non-linear change (Jordan et al., 2005).

Studies have also shown that fragmented natural and artificial reef habitats with multiple smaller habitat patches can support greater fish abundance and diversity than single large reefs, potentially due to increased edge effect and facilitation of reef associated and reef visiting species (Bohnsack et al., 1994, Jordan et al., 2005, Bonin et al., 2011, Jones et al., 2020). However, some positive effects of fragmentation observed for fish communities, may not translate to other organisms, with some studies demonstrating that fragmentation of kelp habitats can lead to reduction or failure of kelp recruitment (Layton et al., 2020).

*Generally speaking, the size of an artificial reef needs to be large enough to have valuable ecological production yet small enough to ensure economic value without a plateau of production concerning the* size (Bohnsack and Sutherland, 1985). Furthermore, scientific modelling suggests that a smaller reef is more effective for long-term production for low nutrient waters with low food supply.

**Identifying minimum reef size that facilitates production and reef functionality as habitat is important; however, reef functionality as habitat is dependent on other structural factors and these factors may also determine the absolute minimum reef size.**

As the size of a reef increases, there is more demand for nutrients in the water meaning more primary producers need to be available to form a new ecological community (Champion et al., 2015, Bowen et al., 2020).

With the majority of marine organisms undergoing a pelagic larvae stage (Kingsford et al., 2002), larger reefs are often considered to be more detectable by the recruiting larvae (Shelamoff et al., 2020, Komyakova and Swearer, 2019). However, in areas far removed from source populations with limited overall habitat availability, isolated reefs may become highly attractive (i.e., as an oasis). There is evidence that isolated reefs tend to support greater fish abundance and richness regardless of reef size (Jordan et al., 2005, Jones et al., 2020). Floating artificial reefs deployed off-shore would likely be impacted by these trends.

**Identifying minimum reef size that facilitates production and reef functionality as habitat is important; however, reef functionality as habitat is dependent on other structural factors and these factors may also determine the absolute minimum reef size.**

For example, surface area may differ for reefs of the same size, and the higher the surface area available for the settlement of algae and invertebrates, the greater source of food for other levels of the reef community and, therefore, the greater productive capacity (Florisson, 2018b). Increasing surface area within a reef would lead to better reef performance regardless of size.

Furthermore, reef quality can influence its functionality, with poor reef quality undermining benefits of larger size. For example, a two-year study that examined fish community structure through abundance, richness and composition measures demonstrated that while large, continuous natural reefs support greater fish density in comparison to small patchy artificial reefs, it is only true when the natural reef is healthy and complex. In areas where natural reefs were largely low-lying boulder reefs, artificial reefs with greater vertical reef and small-scale complexity supported greater fish biomass (Komyakova et al., 2019a).

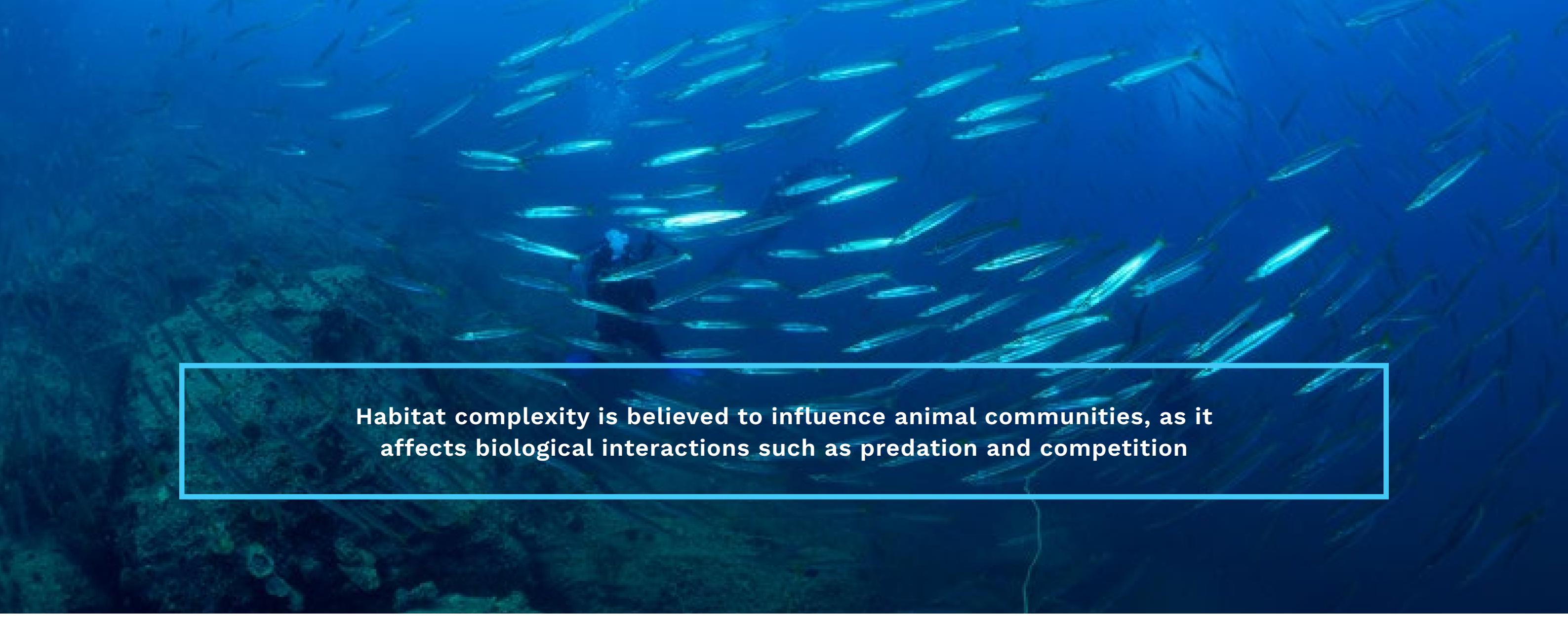
A study comparing fish recruitment on different sized artificial reef patches with transplanted kelp of varying density found that while recruitment did scale with patch size, it was twice as high on patches with high kelp density compared to low kelp density (Shelamoff et al., 2020). Similarly, studies examining change in coral reef fish community variables with changes in coral patch size have demonstrated a general increase in fish abundance and species richness with increasing in colony size; however, corals of higher complexity were shown to support significantly higher abundances and species richness than coral with lower complexity at all colony sizes (Komyakova et al., 2018, Holbrook et al., 2002b). This suggests that other factors, such as cover of habitat forming organism or habitat complexity, may play a significant role in driving fish-habitat relationships.

## Recommendations:

Decisions on the floating reef size will be dictated by the deployment region, the primary goal of the deployment (e.g., aquaculture vs twin-functioning as habitat for floating energy installations), reef utilisation (e.g., method of harvesting or monitoring) and targeted species. Apart from biological variables, size would also influence feasibility and stability considerations. For example, larger reef size can reduce the risk of failure due to sediment transport or extreme wave actions (Bohnsack and Sutherland, 1985), but may also create challenges from a logistical perspective for deployment and monitoring. Multiple smaller reefs may be more economically feasible. Wave and current velocity will impact the height to base ratio although additional infrastructure could be used to counter these forces (e.g., stays).

For FARs, where the species of commercial interest is added for on-growing, the size of the reef can become a trade-off between the stocking density, the naturally available food and the acceptable amount of added food.

The current state-of-knowledge suggests that there is a fine balance between habitat size, fragmentation and isolation that impacts certain organisms differently and will require careful consideration when constructing reefs for different purposes. However, overall, we recommend examining optional reef size from a logistics perspective, using suitable modelling approaches and in-lab testing (e.g., wave tanks), designing reef installations as fragmented habitats with patch distance calculated based on reef goals and species, and designing reefs that maximise surface area available (Appendix D).




### 4.2.2. Reef structural characteristics

#### Complexity

On natural habitats, habitat complexity has been associated with increased fish abundance and species richness across multiple studies (Komyakova et al., 2013, Risk, 1972, Darling et al., 2017).

While some discrepancies in the results do exist (e.g., Bergman et al., 2000, Gratwicke and Speight, 2005, Jimenez et al., 2012), the majority can be explained by species targeted, measures of the complexity and employed methodology. That is, habitat complexity can operate at multiple scales and the scale of habitat complexity can influence different species in different ways. At a large scale, habitat complexity is often referred to as rugosity and is likely to be important for larger, mobile fish species (Sale, 1998, Harborne et al., 2012).

In contrast, rugosity was found to have little effect on small, site attached individuals. At a smaller scale (e.g., individual coral colonies), habitat complexity is more likely to impact individuals that live in close association with the substratum (Richardson et al., 2017, Sale, 1998, Harborne et al., 2012). However, at very small-scales, patchy distribution of individuals may influence detection of fish-habitat complexity relationships (Ault and Johnson, 1998, Hewitt et al., 1998). For example, a study that investigated how the scale of measurement and the complexity of coral colonies may influence fish variables demonstrated that relationships detected appeared stronger at larger scales of measurement (i.e., 2 x 2 m2) (Komyakova et al., 2018). Nevertheless, the same study reported that more complex corals tend to support more diverse and abundant fish communities (Komyakova et al., 2018).

Similar results have been seen for experimental artificial reef studies (Hunter and Sayer, 2009, Bowen et al., 2020). For example, a study that examine differences in fish community variables between artificial reef blocks with different number of holes (refugia, used as a complexity measure) determined more complex blocks supported greater species richness overall and greater abundance for at least 30% of the species recorded (Hackradt et al., 2011). Another study that manipulated complexity of wave power foundations reported a 5-fold increase in crab abundance on complex foundations (Langhamer and Wilhelmsson, 2009), an effect that remained consistent through time for over 10 years (Bender et al., 2020).

Habitat complexity is believed to influence animal communities, as it affects biological interactions such as predation and competition (Almany, 2004, Hixon and Beets, 1993, Hixon and Menge, 1991). It is generally accepted that with increased complexity of the reef, the interstices created provide refuge for the fish, which will assist the species in escaping from predators and provide a habitat for procreation (Hackradt et al., 2011, Bowen et al., 2020, Kawasaki et al., 2003). A study examining mortality of a small reef-associated fish species (Trachinops caudimaculatus) between different artificial reef designs and natural reefs, has reported nine times greater mortality rates for individuals occupying less complex artificial reefs, in comparison to more complex artificial reefs and healthy natural reefs (Komyakova et al., 2021). Similar results have been shown for invertebrate communities, where seeded oysters' survival was greater on tiles with complex surfaces compared to flat tiles (Strain et al., 2020).

Furthermore, habitat complexity, incorporated into artificial reef design, has also been linked with increased productivity of suspension feeders (Rouse et al., 2020). One study reported that productivity of Flustra foliacea (Linnaeus 1758) was 2.4 times greater on complex artificial reef installations. These findings were attributed to differences in current regimes and food accessibility (Rouse et al., 2020).

Despite these findings, it is important to note that habitat complexity has been shown to correlate with other habitat variables, such as cover of habitat forming species and habitat diversity in terrestrial and marine ecosystems (Komyakova et al., 2013, Kristan III, 2007, Richardson et al., 2017, Fukunaga et al., 2020). Therefore, it is difficult to tease apart specific influences of these variables. A tropical study that examined multiple habitat variables in terms of their relationships with fish variables (abundance and species richness) found positive associations for fish species richness but not fish abundance with habitat complexity (Komyakova et al., 2013).

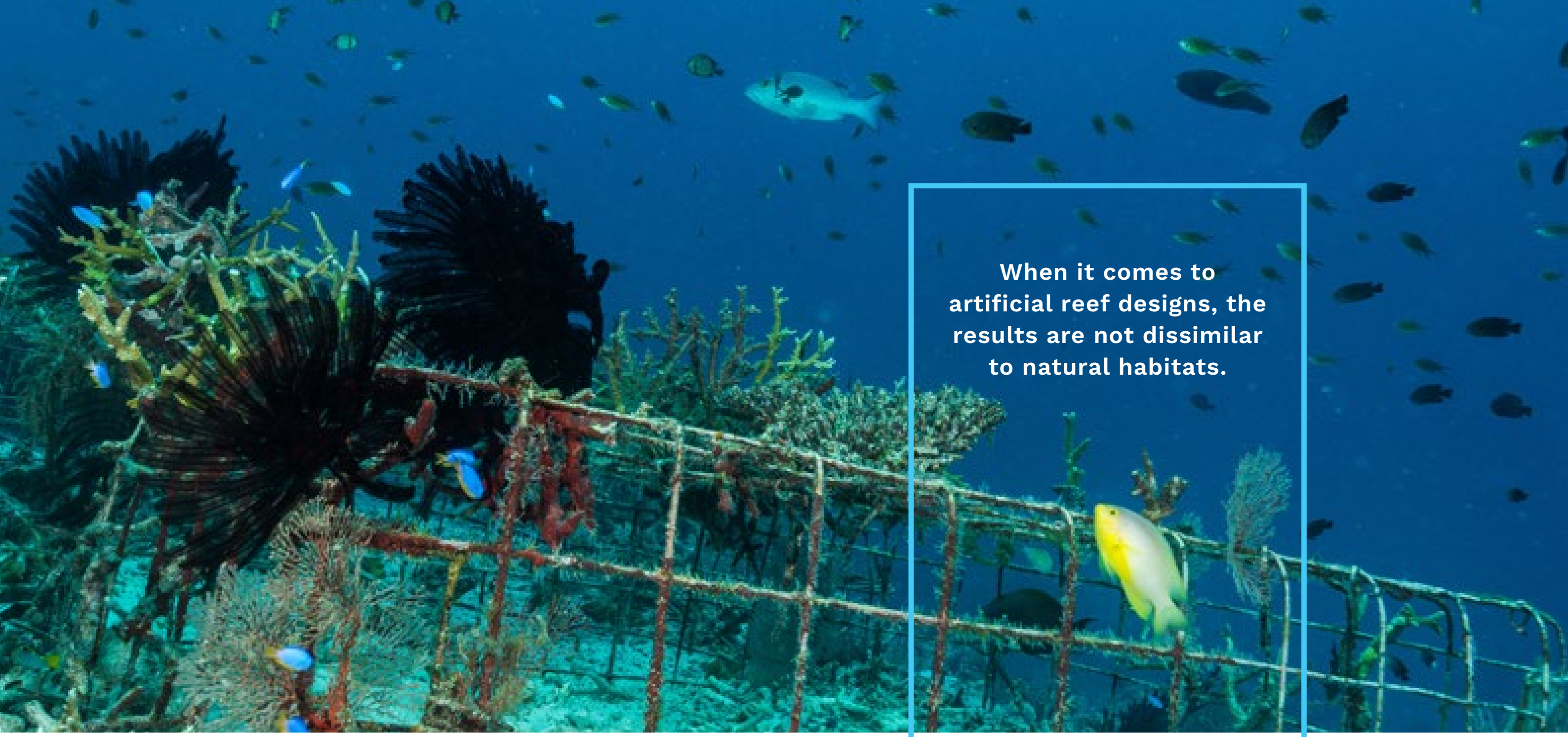
However, positive relationship with fish species richness was quite weak, with hard coral cover and coral species richness explaining the majority of the variation in fish variables (fish abundance 25.5%; fish species richness 70.5%) (Komyakova et al., 2013), suggesting that other structural characteristics may play a vital role in habitat functionality apart from habitat complexity.

## Diversity

Marine organisms tend to use shelter that is closely matched to their body size (Hixon and Beets, 1993, Holbrook et al., 2002a).

Therefore, complex habitats with replicated morphology, such as monotypic coral stands (e.g., branching Acropora spp. (Fig. 3a)) may rate high on a complexity scale but not offer diversity of refugia due to repetitive and limited number of refugia sizes, while habitats that contain diversity of different habitat types would rate high on complexity scale as well as provide a variety of refugia options (Fig. 3b) (Komyakova et al., 2013, Komyakova, 2009).

Increased variety of refugia is directly linked to the increased microhabitat availability, allowing increased resource sharing and niche partitioning (St. Pierre and Kovalenko, 2014, Willis et al., 2005, Bishop et al., 2022).




For example, large openings would provide passages for large cods and pelagic species swimming inside the reef, while cryptic species prefer a more complex reef with smaller voids and openings (Recfishwest, 2017). Moreover, species diversity is generally higher at small body sizes, hypothesised to be driven by opportunities to specialise in specific elements of a reef's mosaic (Munday and Jones, 1998), further enhancing the importance of diversity of those elements. High levels of specialisation have been observed for several small bodied fish families, with some species exhibiting high levels of habitat overlap and others showing strong habitat partitioning (Apogonidae (Gardiner and Jones, 2005) and Gobiidae (Munday et al., 1997, Doll et al., 2021)).

Generally, species may be associated with very specific habitats for food, as found for corallivores fish species (Pratchett et al., 2013, Russ and Leahy, 2017) or herbivorous specialists (Hay et al., 1990, Gollan and Wright, 2006). Some fish species also display specialised shelter requirements, having strong preferences for particular morphologies or even specific species of habitat forming organisms (Apogon leptacanthus and Sphaeramia nematoptera are only found on Porites cylindrica (Gardiner and Jones, 2005)). For coral reef fish, while only 10% have been estimated to have direct dependencies on live corals (e.g., food, specific species associations) (Munday et al., 2007), over 75% show a negative response to coral decline, suggesting complex habitat dependencies (Jones et al., 2004, Pratchett et al., 2012). These studies showcase the importance of diverse habitat types from diversity of refugia sizes to diversity of habitat forming organisms.

Furthermore, habitat partitioning and specialisation occurs even within fish families that are considered to be habitat generalists through ontogenetic habitat preferences and habitat shifts (Komyakova et al., 2019b). For example, it has been demonstrated that juveniles of damselfish species tend to prefer plate corals during early life stages and move on to branching corals, soft corals or other reef habitats at later stages (Komyakova et al., 2019b). On a larger scale, while only 10% of coral reef fishes have been shown to associate with live corals at adult stages, over 65% demonstrated preferential recruitment to live corals (Jones et al., 2004). Therefore, availability of several habitat types that support early and late life stages for such species is paramount for species survival.

When it comes to artificial reef designs, the results are not dissimilar to natural habitats. Studies suggest that artificial reef success is dependent on the suitability of the void space for the target species (Bowen et al., 2020, Frijlink, 2012), with the availability of suitable interstices impacting the number and size of fish supported by the reef (Sherman et al., 2002). Additionally, a reef's void space, considered a shelter, can also impact the species' attraction (Kawasaki et al., 2003) and should be designed based on the targeted species (Blount et al., 2021). Therefore, artificial reefs that incorporate diversity of habitats are more likely to support greater biodiversity or be more effective as habitat for particular targeted species.

## Geometry

In terms of importance of artificial reef geometry on reef performance, the only currently available study that examined this question through a meta-analysis has suggested that cylindrical or cubic designs were most affective, but the authors also concluded that material of construction was a stronger factor (Vivier et al., 2021).

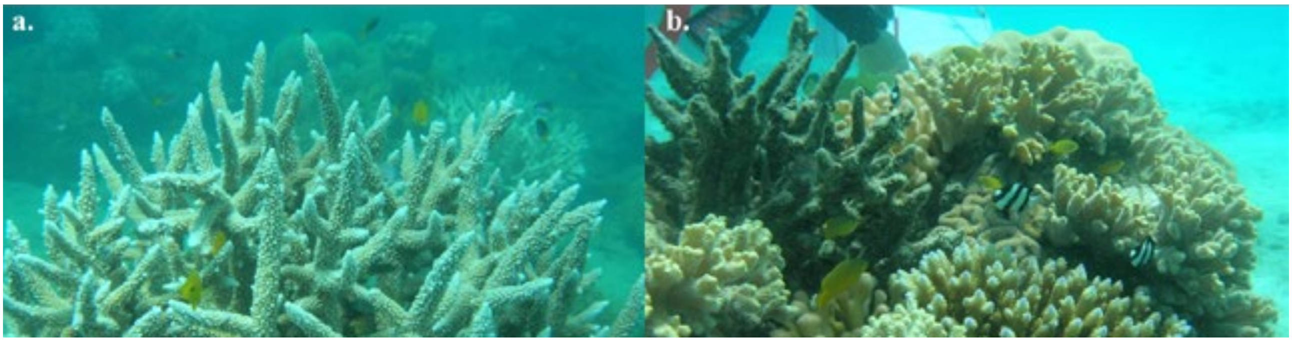



Figure 3. Habitat complexity and diversity. Habitat complexity and diversity. a. Monotypic branching Acropora spp. patch representing high complexity but low diversity habitat; b. Multi-coral species patch of coral species with a range of morphologies (branching, plate, massive etc.) representing a high diversity and high complexity habitat. Photo courtesy of Valeriya Komyakova. Photo location: Great Barrier Reef, QLD, Australia.

## Other factors

Apart from specifics of artificial reef designs, such as complexity, habitat diversity, vertical relief and material of construction, a large variety of other factors plays a role in determining reef functionality (e.g., geographic deployment, location, depth, surrounding habitats, proximity to natural reefs and  reef shape).

However, studies that have attempted to tease apart specific influences of these factors are highly limited and these influences would be dictated by the overall goal of the reef and targeted species. Small scale experimental studies examining differences in artificial reef designs in terms of reef performance as fish habitat in comparison to adjacent natural reefs have reported that reef design is particularly important for dictating fish species diversity and community composition, while location may be driving patterns in fish abundance (Komyakova et al., 2019b). On a large scale, in a recent review of artificial and natural reefs performance as fish habitats, it was reported that subtropical regions generally support greater biomass and species richness, while temperate and sub-arctic areas support greater fish densities at any given habitat (Paxton et al., 2020).

Considering depth of deployment, some studies have suggested that deeper artificial reefs may support greater fish densities (Santos et al., 2013), however depth preferences have also been shown to change with ontogeny (Jaxion-Harm and Szedlmayer, 2015) and impact energy allocations in some species (Hoey et al., 2007). It is likely that depth selection would need to be based on reef goals, species and feasibility (Blount et al., 2021).

## Recommendations:

Based on current state of knowledge of habitat functionality, our broad recommendations for floating artificial reef designs that aim to provide conservation, habitat restoration or nutrient recycling services would be to target greater reef complexity, habitat diversity and vertical relief, aiming to enhance habitat characteristics that promote flora and fauna that provides these roles.

For FARs that are focused on the production of specific commercial species, the design needs to mimic the most favourable habitat characteristics and geometry used by the species across all size ranges being grown as well as habitat characterises favourable to growth and reproduction of their preferred food source.

Today, advanced 3D printing technologies exists that allow artificial habitat development that can closely mimic and amplify natural habitat features (Levy et al., 2022, Evans et al., 2021). Similarly, advanced quantitative techniques exist to explore reef functioning in virtual space and determine their potential (Rogers et al., 2014, Komyakova et al., 2022). These technologies and tools should be employed during the planning stages of any artificial reef project.

### 4.2.3. Configuration of Modules

**The distribution and number of modules can alter the diversity and biomass of species on an artificial reef (Protocol/UNEP, 2009). Design, spacing and positioning of reef modules can be variable, and affect species abundance and richness.**

The optimal size of a reef is dependent upon specific requirements of the reef. While some reefs can consist of a single large structure, a common approach is to deploy numerous structures or modules, which together make up a reef "field" (Becker et al., 2019) and increase the effective footprint of the reef (Blount et al., 2021). Increasing the number of reef modules has been shown to increase fish abundance and species richness (Jordan et al., 2005).

Determining the distance at which species associate with a reef is a key consideration to ensure reef modules are appropriately spaced (Jordan, Gilliam and Spieler 2005; Scott et al. 2015). It is therefore necessary to consider what species will be using the reef, and their foraging behaviours (Blount et al. 2021). This is particularly important to avoid creating "foraging haloes" around reef structures – areas where modules are placed too close together and foraging overlaps, leading to a depletion of prey (Blount et al. 2021; Campbell et al. 2011; Frazer and Lindberg 1994; Lindberg, Frazer and Stanton 1990; Reeds et al. 2018). While offshore FARs are unlikely to impact the benthic community in this way (unless the reef modules themselves contain a false "bottom" suitable for benthic species to inhabit), increased predation pressure may still be experienced by demersal (reef-associated) species if there is insufficient area between reef modules. Indeed, it has been shown that isolation of reef modules can have a positive effect on both abundance and species richness at the patch and cluster scale (Jones et al. 2020; Jordan, Gilliam and Spieler 2005; Smith et al. 2017). This may be partly attributed to the decreasing predation impact with increasing distance between reefs, as there is some evidence that transient predators are more likely to visit (and spend more time at) aggregated reefs (Belmaker, Shashar and Ziv 2005; Belmaker, Ziv and Shashar 2009; Jones et al. 2020; Jordan, Gilliam and Spieler 2005; Overholtzer-McLeod 2006).

While increasing distance between modules can have a positive effect on abundance and richness, it is also important to consider the point at which species' association with reefs declines, in order to create an assemblage that remains sufficiently connected. The optimum distance between reef modules will vary due to species- and class-specific differences in responses (Jordan, Gilliam and Spieler 2005). In benthic studies, the distance at which species tend to associate with artificial reefs appears to increase with increasing depth (Boswell et al. 2010; Smith et al. 2017) (Table 3), although reef configuration and bottom type may also impact species responses (Boswell et al. 2010).

Alternatively, if reef modules are set up to be independent, disconnected assemblages (e.g. to facilitate harvesting of certain species from each module), knowing the density dependence of key species is key to arranging reef modules at a distance that minimises movement between clusters. In the case of coastal reefs, this knowledge can also be used to minimise movement of species to ARs from nearby natural reefs (Jones et al. 2020).

Ensuring reef clusters are appropriately spaced will also facilitate important hydrological effects around the reef (such as upwellings, vortices, eddies and slipstreams), which enhance habitat, move nutrients and improve feeding opportunities within the reef space (Blount et al. 2021). Modules placed too close together can impact water flow and negatively impact reef occupation (Kim et al. 2008).

Table 4. Studies where artificial reef association distance varies with depth

| STUDY | DEPTH | SPACING | REEF TYPE | ENVIRONMENT |
|---|---|---|---|---|
| **Jones et al. (2020)** | 4-12 m | Reef patches were 70 m away – designed to minimise movement between natural habitat and reef clusters | Ecological - Entanglement of marine species Sociological - damage to vessels and FAR structure; production losses | Benjamins et al. (2014), Fabi et al. (2015) |
| **Jordan et al. (2005b)** | 8 m | Reef modules in clusters of varying distance – (0.33 m, 5 m, 15 m, 25 m). Clusters discontinuous at 35 m | Concrete reef modules (1 m3) | Sand bottom (Ft Lauderdale, Florida, USA) |
| **dos Santos et al. (2010)** | 9 m | Greater association 0-50 m from reef than 300 m | Concrete reef balls® (1 m3) | Flat, homogeneous sand/mud bottom (Rio de Janeiro coast, Brazil) |
| **Rosemond et al. (2018)** | 10-18 m | 60 m buffer zone between reefs (90% of species won't move) or 120 m (99% won't move) | Reef plots (containing a mixture of natural rocky reef and artificial reef structures e.g. concrete pipes, metal ships) | Natural rocky reef and sand flats (Onslow Bay, North Carolina, USA) |
| **Becker et al. (2019)** | 30 m | Reef modules still contiguous at 50 m, fish association significantly reduced 100 m from reef | Concrete modules (9 m3) | Flat, sandy bay (Shoalhaven, NSW, Australia) |

## 4.3. MOORING AND ANCHORING SYSTEMS

### 4.3.1. Mooring Systems

**Different mooring configurations (e.g., taut, tensioned leg and catenary) should be explored in terms of their suitability for offshore FARs; this should include several aspects such as footprint, fairlead connection points, cost, intact and damage scenarios.**

**Materials for mooring lines can vary and may include wire ropes (steel), synthetic fibre ropes, and chains (steel). Environmental aspects should also be considered when optimising the performance of mooring systems. There are a few software tools available to conduct mooring analysis, examples include Orcaflex and ANSYS AQWA.**

### 4.3.2. Anchoring Systems

Anchors are likely to be gravity-based structures which may also act as bottom-mounted ARs. However, other types of anchors should be explored. Geo-tech data is vital to select and analyse a proper anchor system. It is appreciated that such data is site dependent and scarce and most likely would require site survey and core sampling. Although it is site dependent, scour protection/mitigation strategies should be developed as part of the anchor design.

**Five types of commonly used offshore anchors include:**

- Drag anchors
- Vertical Loaded Anchors (VLAs)
- Suction pile anchors
- Driven pile anchors
- Deadweight anchors

Offshore Standards and Recommended Practices (such as API and DNV) developed originally for the Oil & Gas industry would be useful for designing offshore FAR systems, and adaptation of these systems maybe warranted. On-bottom stability checks for the anchors (sliding, bearing, and overturning) would require coupled analysis with hydrodynamic loading and response models, mooring modelling as well as soil models.

**Design standards and guidelines:**

- ABS (2013). Offshore Anchor Data for Preliminary Design of Anchors of Floating Offshore Wind Turbines. Houston, Texas, USA.
- API (2008). API-RP-2SK Design and Analysis of Station-keeping Systems for Floating Structures. American Petroleum Institute.
- DNV (2015). DNVGL-OS-E302 Offshore mooring chain - Rules and standards
- DNV (2018). DNVGL-OS-E301 Position mooring - Rules and standards

Considerations of the effect of floating support structure types, soil properties, and maximum line tension ranges should be included in the design. Anchor manufacturers such as Vryhof and Bruce provide extensive information about anchor specs and design charts. ASTM D-2488 and BS CP-2004 standards provide recommended methods and definitions for soil types and properties for the purpose of initial anchor sizing for the preliminary/conceptual design. However, actual soil properties should be obtained from site assessment and used in detail designs.

# 5. GOVERNANCE FRAMEWORK – FLOATING ARTIFICIAL REEFS

**Proposals to develop floating artificial reefs need to navigate a complex governance framework, recognising that research and development activities, in general, are treated differently (in the sense of permitting or licensing) to commercial or full scale-development. This framework includes Australia's commitment to international agreements and Australian and State government legislation, regulation, and policy.**

## 5.1. INTERNATIONAL AGREEMENTS

London Convention/ Protocol (Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 1996 Protocol).

The purpose of the London Convention is to control all sources of marine pollution and prevent pollution of the sea through regulation of dumping into the sea of waste materials. A so-called "black- and grey-list" approach is applied for wastes, which can be considered for disposal at sea according to the hazard they present to the environment. For the blacklist items dumping is prohibited.

Dumping of the grey-listed materials requires a special permit from a designated national authority under strict control and provided certain conditions are met. All other materials or substances can be dumped after a general permit has been issued.

The purpose of the Protocol is similar to that of the Convention, but the Protocol is more restrictive: application of a "precautionary approach" is included as a general obligation; a "reverse list" approach is adopted, which implies that all dumping is prohibited unless explicitly permitted; incineration of wastes at sea is prohibited; export of wastes for the purpose of dumping or incineration at sea is prohibited.

Extended compliance procedures and technical assistance provisions have been included, while a so-called transitional period allows new Contracting Parties to phase in compliance with the Protocol over a period of five years, provided certain conditions are met. (IMO 2022) water outside Tasmania's jurisdiction.

## 5.2. AUSTRALIAN INTERGOVERNMENTAL FRAMEWORK

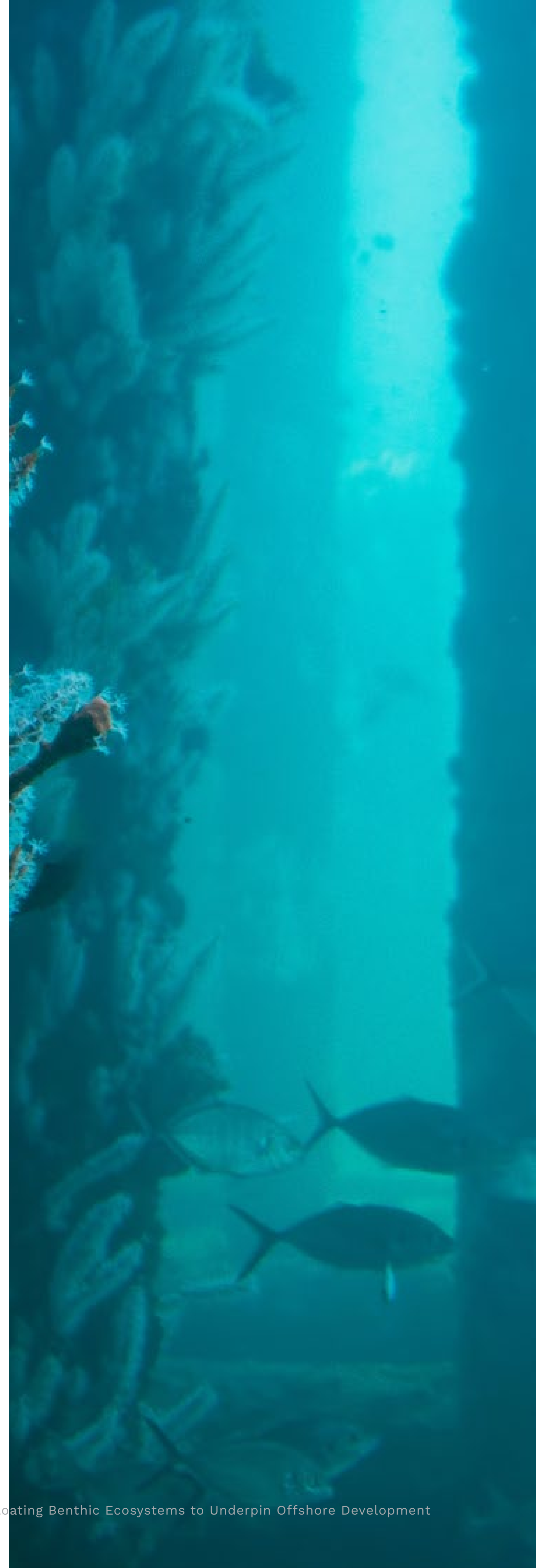
### 5.2.1. The Offshore Constitutional Settlement (OCS)

A key element in assessing and supporting the development and long-term viability of offshore artificial reefs centres on the policy and regulatory framework under which such actives are managed.

Activities within state waters (within three nautical miles from low water mark or from agreed offshore baselines) under the Offshore Constitutional Settlement (OCS) are governed by state law.  The baseline is in most cases the low water mark, but in some areas closing lines across bays means that the baseline is many miles offshore, for example, Spencer Gulf, Gulf St Vincent and Kangaroo Island in South Australia, and in Storm Bay and the south east coast in Tasmania  (see Seas and Submerged Lands (Territorial Sea Baseline) Proclamation 2016 (F2016L00302)).

The OCS framework established “Agreed Arrangements” in the fisheries and oil and gas sectors. These arrangements varied but were designed to provide efficient and effective management in offshore resources sectors recognising state capacity and capability, while maintaining Australia’ international obligations. Agreed Arrangements allowed the establishment of Joint Authorities to manage activities across jurisdictions, and these arrangements themselves have evolved over time.

The most recent iteration is the MOU related to offshore aquaculture in Bass Strait, negotiated between the Commonwealth and the Tasmanian Government in 2021-22, to govern research and development in water outside Tasmania’s jurisdiction.



## 5.3. COMMONWEALTH LEGISLATION

Commonwealth legislation impact on, or are likely to impact on, the regulation and management of floating artificial reefs, in particular the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) (Table 5).

Table 5. Commonwealth Legislation relating to Floating Artificial Reefs (FARs).

| | |
|---|---|
| **ENVIRONMENT PROTECTION AND BIODIVERSITY CONSERVATION ACT 1999 (EPBC ACT)** | » Provide legislative base to the Australian government environmental interests, and mandate processes where activities impact on or potentially impact on "matters of national environmental significance" (MNES):<br>» World heritage properties<br>» National heritage places<br>» Wetlands of international importance<br>» Nationally threatened species and ecological communities<br>» Migratory species<br>» Commonwealth marine areas<br>» The Great Barrier Reef Marine Park<br>» Nuclear actions (including uranium mining)<br>» A water resource, in relation to coal seam gas development and large coal mining development<br>» Proposals for activities outside state waters may also need to address Key Ecological Features (KEFs) under the EPBC Act (DAWE, 2022a) |
| **ENVIRONMENT PROTECTION SEA DUMPING ACT 1981 (SEA DUMPING ACT)** | » Regulates the loading and dumping of waste at sea and the placement of artificial reefs within Australian Waters" (DAWE, 2022a)<br>» The Act applies to all vessels, aircraft and platforms in Australian waters, and to all Australian vessels and aircraft in any part of the sea. The disposal of waste and other matter at sea is prohibited, except for some controlled materials which require a permit. Permits are most commonly issued for:<br>» The disposal of dredge material<br>» The creation of artificial reefs<br>» The dumping of vessels, platforms or other manmade structures<br>» Burials at sea<br>» The Act does not apply to operational discharges from ships, such as sewage and galley scraps |
| **SEA INSTALLATIONS ACT 1987** | » Provides a legislative base to manage artificial structure in the marine environment. "A sea installation is defined as any man-made structure that can be used for an environment related activity, either when in physical contact with the seabed or whilst floating." (DAWE, 2022a). Examples provided of sea installations are tourism pontoons, artificial islands, fish aggregating devices. Fishing and aquaculture, Oil platforms, drill ships or defence installations are specifically excluded from the ambit of the Sea Installations Act 1987. The Act does not apply to the area under State jurisdiction from low water mark to the three mile boundary. |
| **UNDERWATER CULTURAL HERITAGE ACT 2018** | » Gives effect to Australia's obligations under the International Convention on the Protection of the Underwater Cultural Heritage (2001). The legislation updated and replaced the Historic Shipwrecks Act 1976 that was developed to address specific aspects of underwater heritage, specifically 'treasure' from sunken ships. The Historic Shipwrecks Act, along with the Great Barrier Reef Marine Park Act 1975 was incorporated into the OC framework in 1979 (Haward, 1989). |
| **NAVIGATION ACT 2012** | » Provides a major reform of and contemporary focus to the (much amended) Navigation Act 1912. |

## 5.4. COMMONWEALTH POLICIES AND PLANS

### 5.4.1. Plastics in Artificial Reefs Policy 2022

The current policy guidance notes that the Australian government's "preferred environmental outcome is that artificial reefs avoid the use of plastic fibres and instead utilise traditional steel reinforcement or other natural fibres as a concrete reinforcement."

- The department considers the use of plastic fibres in artificial reef modules to be unsuitable due to:
  - the lack of long-term studies and therefore scientific uncertainty about the breakdown of artificial reef modules containing plastic fibres over their design life
  - the department's concern about the feasibility of monitoring the exposure, breakdown and release of plastic fibres from the artificial reef modules over the life of the permit
  - the department's concern about the feasibility of removal of artificial reef modules if monitoring identifies that release of plastic fibres has occurred or is likely to occur
  - concern for consequent impacts on the marine environment if plastic fibres are released.
- The department is unlikely to recommend the granting of sea dumping permits for artificial reefs which include plastic fibres in their designs.

**The Plastics in Artificial Reefs Policy 2022 is directly linked to the Threat Abatement Plan for the Impacts of Marine Debris on the Vertebrate Wildlife of Australia's Coasts and Oceans (2018) and the Australian Government's National Plastics Plan (2021).**

**The Threat Abatement Plan "incorporates actions needed to abate the listed key threatening process, particularly actions to develop understanding about microplastic impacts and the potential role of new technologies in waste management.**

**The actions are intended to be feasible, effective and efficient, as required by the EPBC Act. The plan binds the Commonwealth and its agencies to respond to the impact of marine debris on vertebrate marine life, and identifies the research, management and other actions needed to reduce the impacts of marine debris on affected species." (DAWE, 2022b)**

## 5.5. State Legislation and Policies

To date, at least 150 artificial reefs have been deployed in Australian waters and they are one of the most common types of aquatic infrastructure deployed for fisheries enhancement (Recfishwest, 2017). Floating structures tend to be focused solely on Fish Aggregation Devices to assist in development of recreational fisheries (e.g. in Tasmania).

## 5.6. Community Interests

Floating artificial reefs are likely to generate interest among various stakeholders with diverse and conflicting values; therefore, it is crucial to identify and understand the stakeholders' opinions and values (Sutton and Bushnell, 2007).

A key here will be providing sufficient information to the community on the scale and scope of the proposal in the development phase of any project. Among different stakeholders the local community should be considered from different perspectives. Site selection issues related to floating artificial reefs differ from those issues relate to fixed benthic or bottom reefs. For example, local users' opinions and expectations should be included in the project deployment to gain local people's support and ensure the project's success.

# 6. IMPLEMENTATION CHALLENGES & LIMITATIONS

**This review has identified a number of key implementation challenges in the development and deployment of floating artificial reefs.**

**Challenges include, for example, reef design, including materials and engineering; moorings or anchoring; management and monitoring, regulatory approval, costs and financing, sites and target species and social acceptability.**

**While the Australian Government has introduced policy guidance on artificial reefs, regulatory challenges remain with respect to floating reefs that are more than "fish aggregating devices". In addition to legislative and regulatory measures, financing and social acceptability are also key factors influencing development of floating artificial reefs.**

# 7. CONCLUSION

**This report has addressed the opportunities and constraints related to the development and use of floating benthic artificial reefs, defined for our purposes as "manmade structures that mimic the natural reefs of the plant or animal species that is being commercially cultured for food, marine products or environmental benefits, suspended from the surface to depths that are still within the photic zone, generally between 5 and 40 metres".**

As this review has found, there is limited literature on floating artificial reefs with much analysis focused on fixed or benthic reefs. To-date, artificial reefs have not been used for the provision of commercial seafood or other marine products through aquaculture.

While there are many challenges, floating artificial reefs can provide significant benefits in the provision of quality high priced export marine products, the provision of nutrient recycling and carbon sequestrations ecosystem services and buffering services for other offshore developments. As with all innovative and novel systems, multiple challenges need to be researched to develop and/or ascertain the benefits that can be accrued. Given these potential multiple benefits, we have provided a roadmap to provide the necessary information to support future decision making in the development of floating artificial reefs.

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# | APPENDIX A – PROJECT SYNOPSIS

## PROJECT LEADER

Marcus Haward, University of Tasmania.

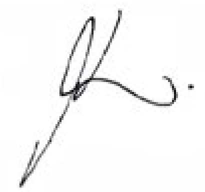
## PROJECT LEADER

- Valeriya Komyakova, University of Tasmania.
- Brigette Wright, University of Tasmania.
- Stewart Frusher, University of Tasmania.
- Saeed Mohajernasab, University of Tasmania.
- Ali Shakourloo, University of Tasmania.
- Nagi Abdussamie, University of Tasmania.
- Marcus Haward, University of Tasmania.

## DATE REPORTED TO THE BE CRC

October 2022

## APPROVED BY THE BE CRC



Dr John Whittington, BE CRC CEO

## PROJECT TEAM

- Valeriya Komyakova, University of Tasmania.
- Brigette Wright, University of Tasmania.
- Stewart Frusher, University of Tasmania.
- Saeed Mohajernasab, University of Tasmania.
- Ali Shakourloo, University of Tasmania.
- Nagi Abdussamie, University of Tasmania.
- Marcus Haward, University of Tasmania.
- Brian von Herzen, Climate Foundation.
- Kristien Veys, Blauwe Cluster, Belgium.
- Gregory Page, Southern Blue Reefs.
- Adam Brancher, Southern Ocean Carbon Company.
- Frances Huddlestone, Oysters Tasmania.
- Sven Frijlink, Department of Natural Resources and Environment Tasmanian Government.
- Simon Clark, Macquarie University.
- Rouzbeh Abbassi, Macquarie University.
- Fatemeh Saleh, Macquarie University.
- Ehsan Arzagh, University of Tasmania.
- Til Baalisampang, University of Tasmania.
- Vikram Garaniya, University of Tasmania.

## PROJECT OBJECTIVE(S)

- Identify the potential for floating benthic artificial systems to support marine products.
- Assess the current state of knowledge on environmental and economic (market and non-market) benefits of incorporating artificial ecosystems into the design of integrated offshore developments.
- Assess current design opportunities and constraints in the construction of floating artificial benthic ecosystems suitable for offshore developments. Assess alternative mooring/anchoring systems.
- Identify current regulatory and policy issues with respect to development, deployment and operation of artificial ecosystems, and how these systems can assist in demonstrating responsible management of offshore developments.

## BE CRC MILESTONES

- RP1.1.2 Commercial-ready designs and sub-systems for offshore aquaculture cages in a high-energy environment.
- RP1.1.2 Commercial-ready designs and sub-systems for offshore aquaculture cages in a high-energy environment.
- RP2.1.2 Advanced understanding of, and industry-ready knowledge to- improve fish biology in offshore environments.
- RP2.2.2 A framework for integrating production and engineering technologies that advances overall productivity of seafood marine products.
- RP2.3.2 Platform to underpin the value and promotion of seafood from new aquaculture systems.

## BE CRC MILESTONES

- RP4.1.1 Multi-criteria regional marine spatial planning tool for the identification of regional areas that would be feasible (technically and economically) for integrated multiple-use platforms.
- RP4.2.1 Framework for assessing proposed offshore activities & supporting specific site selection.

## UTILISATION/COMMERCIALISATION OPPORTUNITIES

- Development of research map to guide development of a prototype floating artificial reef.
- Outline of current regulatory and policy issues with respect to development, deployment and operation of artificial reef systems.

## INTELLECTUAL PROPERTY

- N/A

## CONFIDENTIALITY

Does this report include confidential information? Yes – or No X

# | APPENDIX B – SHORT SCIENCE SUMMARY

A short science summary for this project is provided on the following page(s).

BLUE ECONOMY
COOPERATIVE RESEARCH CENTRE

Australian Government
Department of Industry, Science and Resources

AusIndustry
Cooperative Research Centres Program

# SHORT SUMMARY

## 5.21.002
## Identifying the Potential of Artificial Floating Benthic Ecosystems to Underpin Offshore Development.

## KEY POINTS

» Reefs are common benthic systems throughout Australia's extensive coastline and provide significant ecosystem services, many of which can be provided by artificial reef systems.

» Floating of artificial reefs to maintain them within the photic zone is a way to extend these ecosystem services beyond inshore waters and throughout Australia's Exclusive Economic Zone.

» Floating of artificial reefs is a novel and blue skies concept and current knowledge is reliant on artificial reefs position on the seabed in coastal environments.

» As a novel concept, significant advantages in leading developments in his area, including patents and first mover advantages can be achieved. Disadvantages include the unproven design, untested economic viability and lack of regulatory frameworks.

» A research roadmap is presented to address these disadvantages and develop the substantial opportunities which floating artificial offshore reefs can provide to the Australian economy.

## THE CHALLENGE

To-date artificial reefs have been confined to coastal systems where they are placed on the seabed. Floating artificial reefs so that they can be suspended in the photic zone and anchored in all water depths has never been attempted. This scoping study brought together the existing knowledge and expertise on existing artificial reef construction and designs to develop a roadmap for the development of floating artificial reefs.

## THE OPPORTUNITY

Australia's most valuable seafood exports are reef based species and floating artificial reefs provide an opportunity to build on these products. They also provide opportunities to recycle nutrients from their own and other food production systems, to produce products for carbon sequestration, to provide buffering of oceanic sea conditions and assist in restoration of coastal systems. By being based on ecosystem principles, floating artificial reefs are likely to be more socially accepted than other traditional aquaculture systems.

## OUR RESEARCH

This scoping study aimed to provide a summary of the existing knowledge on floating artificial reefs and develop a roadmap for development of floating artificial reef systems.

Floating artificial reefs are defined as artificial reef systems that are suspended from the surface to depths that maintain the reefs within the photic zone so that primary production is maintained. This is considered to be in depths from 5m to 40m.

As floating artificial reefs are a new approach to aquaculture systems, there was no literature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# SHORT SUMMARY

## 5.21.002
## Identifying the Potential of Artificial Floating Benthic Ecosystems to Underpin Offshore Development.

available and information regarding their design and construction was reliant on literature pertaining to artificial reefs used in the coastal zone and positioned on the seafloor.

Natural reef systems are one of the most dominant coastal ecosystems in Australia and provide substantial ecosystem services including provisioning of food and other marine products, cycling of nutrients, carbon sequestration, buffering of coastal foreshores and cultural services for traditional first nations peoples. Artificial reefs can supply many of these ecosystem services as well as providing restoration opportunities for degraded reef systems.

Artificial reefs that more closely replicate natural systems in rugosity of surface material, three dimensional shape including different sized voids and crevices have proven to be provide more diverse biological communities.

Concrete has been the major building material to-date and advances in improving the ecological footprint of concrete are encouraging. Other products including ceramics and recycled HDPE plastic are also worthy of consideration.

As a novel concept, design considerations in the structures for support of floating artificial reefs, containment of culture products and moorings need to be developed although some information can be obtained from the oil and gas industry and offshore fish aggregation devices. A schematic of a conceptual design identifying some of the key considerations is provided in Figure 1.

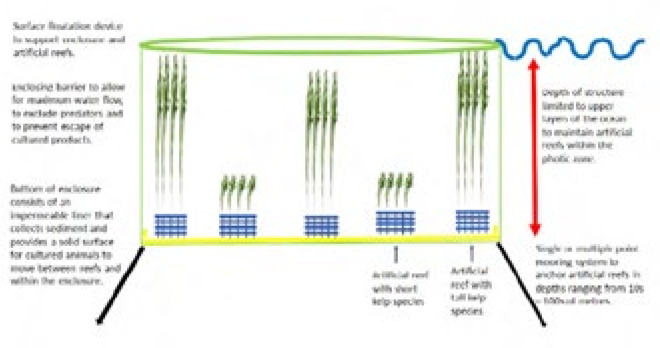

***Figure 1. Schematic of a hypothetical floating artificial reef design highlighting design considerations***

As an innovative concept, floating artificial reefs will require engineering and technology research into materials, mooring and anchoring systems, stability, structural analysis, monitoring technologies and installation techniques. Ecological design will focus on complexity for both commercial species, nutrient recycling species and carbon sequestration and ocean dampening species. Biological considerations include the species mix, their stocking densities to minimise external food inputs and maintain high growth rates. Key Australian species for temperate regions included rock lobsters, abalone, bull and giant kelps and urchins.

Although there is current legislation and international agreements on offshore structures and dumping at sea, new or adapted regulations are likely to be needed for the development of floating offshore artificial reefs. These are likely to also encompass other offshore infrastructure such as platforms. Societal understanding and expectations of what floating artificial reefs are,


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# SHORT SUMMARY

## 5.21.002
Identifying the Potential of Artificial Floating Benthic Ecosystems to Underpin Offshore Development.

how they work and the benefits and impacts of their use need to be transparently accessed throughout their development.

## OUTCOMES

A roadmap, identifying the research needs from the BECRC's Offshore Engineering and Technology, Seafood and Marine Products; Environment and Ecosystems; and Sustainable Offshore Developments programs, was developed that would culminate in a floating offshore artificial reef prototype for industry consideration and adoption.

## NEXT STEPS

The next step is the development of an integrated project that addresses the research outlined in the roadmap. This will provide greater certainty in the structural integrity and biological productivity of thesystem to determine economic viability, including market and non-market values.

## PROJECT TEAM

- Valeriya Komyakova, University of Tasmania.
- Brigette Wright, University of Tasmania.
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- Ali Shakourloo, University of Tasmania.
- Nagi Abdussamie, University of Tasmania.
- Marcus Haward, University of Tasmania.
- Brian von Herzen, Climate Foundation.
- Kristien Veys, Blauwe Cluster, Belgium.
- Gregory Page, Southern Blue Reefs.
- Adam Brancher, Southern Ocean Carbon
- Company.
- Frances Huddlestone, Oysters Tasmania.
- Sven Frijlink, Department of Natural Resources
- and Environment Tasmanian Government.
- Simon Clark, Macquarie University.
- Rouzbeh Abbassi, Macquarie University.
- Fatemeh Saleh, Macquarie University.
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