Exploring the Potential of a Novel Breakwater Material:

Creating Coastal Habitat at Iona Island

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All illustrations by Emma Gosselin unless otherwise indicated.
Cover image: background photo via Metro Vancouver, proposed breakwater illustration by Emma Gosselin.

TABLE OF CONTENTS

"We can't build single-purpose infrastructure anymore. We're making…a structure that supports life."

-Pippa Brashear, SCAPE Studio

Photo Credit: Virginia Sea Grant, Flickr
https://bit.ly/3gXoTOg

INTRODUCTION

Metro Vancouver is planning an upgrade to the Iona Island Wastewater Treatment Plant (IIWWTP) from primary to tertiary level treatment (Metro Vancouver 2022). Part of this upgrade will include a series of proposed ecological restoration projects and active rehabilitation of the region to promote returning salmon and other marine and estuarine species (Metro Vancouver 2022).

Shoreline resilience and infrastructure protection are also critical components of concern for the Metro Vancouver wastewater treatment system upgrade due to rising sea levels, winter storm surges and coastal erosion due to climate change (Metro Vancouver 2022). Conventional methods for hardening coastal infrastructure for erosion protection such as placement of concrete or quarried rock result in significant embodied carbon dioxide (CO_2) emissions and contribute to climate change. Metro Vancouver has proposed a dual-function “living breakwater”; a structure for both infrastructure protection and for coastal habitat enhancement. The intent of the breakwater is that it is designed to support marine species that colonize or benefit from rocky tidal and subtidal substrates.

Biorock, a mineral accretion technology, represents a potential net carbon sequestration solution (Hilbertz 1992) for reinforcing shorelines against erosion from wave action (Goreau et al. 2017). Additional benefits include augmented subtidal habitat for marine organisms and consequent increases in biodiversity and ecosystem function. Biorock, sometimes called “seament” or “seacrete”, is a cement-like engineered material that is produced by low-voltage, direct current electro-chemical precipitation (accretion) of calcium carbonate from seawater onto a metal scaffold frame. The advantages of Biorock scaffolds over conventional breakwaters include lower weight for transportation and superior maneuverability during installation which allows the use of Biorock in ecologically sensitive areas, in close proximity to existing infrastructure such as outfalls, and in high traffic areas, where rubble breakwater material would otherwise be placed with less control. These are common concerns in riprap repair. The modularity and macroscopic design flexibility of Biorock may provide an opportunity to promote specific species, including juvenile fish, seagrasses, kelp, and shellfish.

The sustainability of Biorock breakwaters in comparison to conventional materials and opportunities for design considerations which promote positive ecological impacts for Biorock are scarcely documented for coastal BC waters. While there are few built examples on the use of Biorock structures as habitat in Canada, several studies in other locations have been carried out that focus on species that are applicable at Iona Island. Thus, using Biorock as both a breakwater material and a structure for marine habitat presents a potential opportunity to meet both of Metro Vancouver’s goals of protecting the Iona Island foreshore from coastal erosion and creating habitat.

SITE CONTEXT

Photo via Metro Vancouver

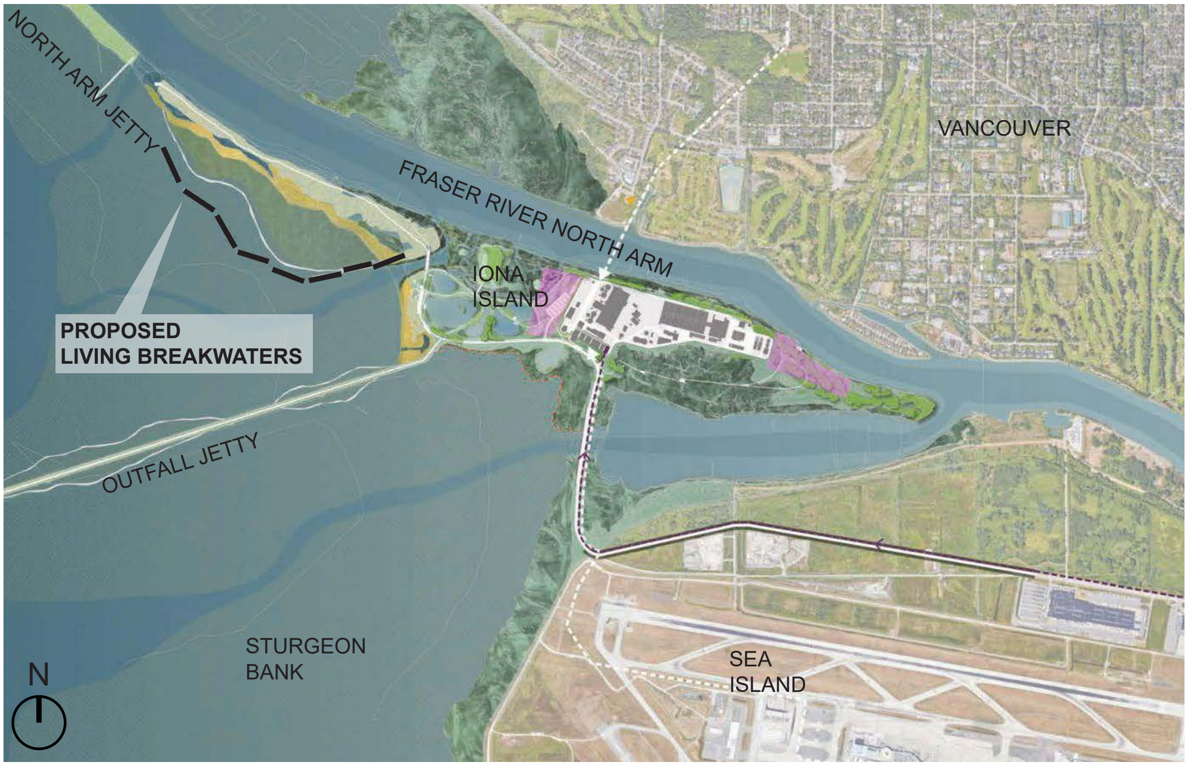

Figure 1. Location of proposed living breakwaters at Iona Island in Richmond, BC. Modified from proposed concept plan from Metro Vancouver.

Iona Island is located at the north of Sturgeon Bank in Richmond, British Columbia, where the Fraser River Estuary meets the Salish Sea (Metro Vancouver 2020). In 1914, construction began on the North Arm Jetty, permanently altering the deposition of sediment and freshwater at the outfall of the Fraser River (Atkins et al., 2016). The Iona Deep-Sea Outfall Jetty ("outfall jetty" or "Iona jetty") was constructed in 1961 to convey treated wastewater from the IIWWTP to the Strait of Georgia.

Roberts Bank and Sturgeon Bank are characterized by shallowly-sloped sediments forming an intertidal area of 158 km² that includes tidal marshes, mud flats and sand flats (Hutchinson, 1988; Luternauer et al., 1995).The proposed site for the living breakwater is situated in the interjetty area, consisting of tidal mudflat as well as sandflat that is both subtidal and intertidal (Metro Vancouver 2020). The two jetties consist of rock riprap, while the rest of the interjetty area is devoid of hard substrate and is relatively low in biodiversity (Dave Scott, personal communication 2022). The subtidal area is 3-6m below low tide, while the intertidal area has a 2m depth range between high and low tide (Metro Vancouver 2020). In the interjetty area, water salinities range from 14-28 Practical Salinity Unit (PSU) under freshet conditions and from 25-30 psu under non-freshet conditions (Metro Vancouver 2021). These brackish salinity ranges limit the viability of saltwater species in the area, and potentially reduce the efficacy of Biorock accretion.

The tidal marsh habitat adjacent to Iona Island is an important nursery habitat for juvenile Chinook salmon migrating through the north arm of the Fraser River (Balke 2017). The Fraser River is a migration route for approximately 50% of BC's adult salmon (Ashley 2006). Other fish species that are found in the foreshore include Pacific herring, Pacific sand lance, surf smelt, and three-spine stickleback (Metro Vancouver 2020). Oolichan and sturgeon are also found near Iona Island but less common than they were historically (Metro Vancouver 2020). The mud and sand flats areas are also important for shorebirds, clams, and many other invertebrates (Metro Vancouver 2020).

The north jetty and outfall jetty are likely concentrating wave energy in the interjetty area, impeding successful establishment of tidal habitats (Metro Vancouver 2020). The wide flat expanse of the Fraser River Delta foreshore may also exacerbate wave energy and contribute to greater flooding with sea level rise if wave energy is not mitigated (Metro Vancouver 2020). Off-shore living breakwaters may help create lower-energy nearshore conditions that reduce jetty erosion, allow sediment build-up in preferred areas, and protect coastal wetlands by attenuating concentrated wave energy (Metro Vancouver 2020).

Thus, the interjetty area may benefit from offshore breakwaters to improve the health of tidal habitats and increase resilience to sea level rise. Constructing a living breakwater made from Biorock may present an opportunity to increase biodiversity and ecosystem services in the area by diversifying available habitat types with the addition of a novel hard substrate material.

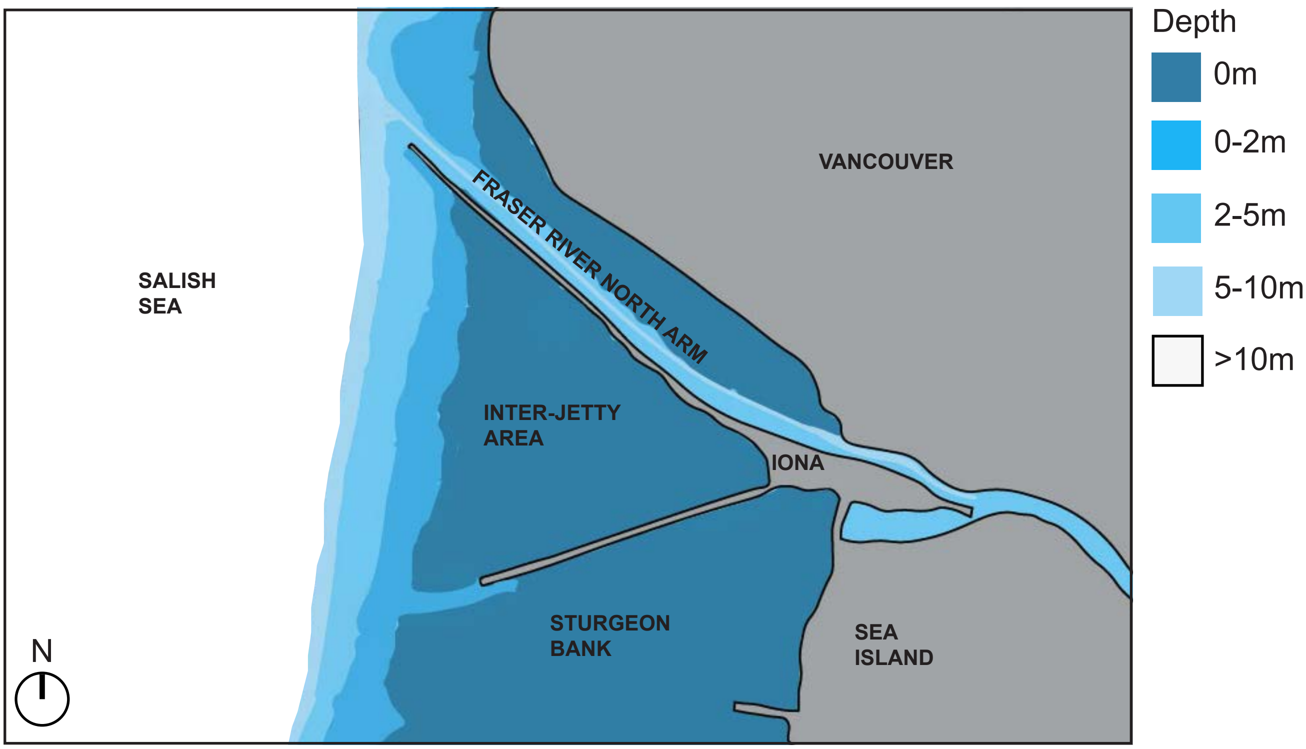

Figure 2. Map of water depth relative to sea level in Iona Island shore zone. Modified from Navionics Chart Viewer, 2022.

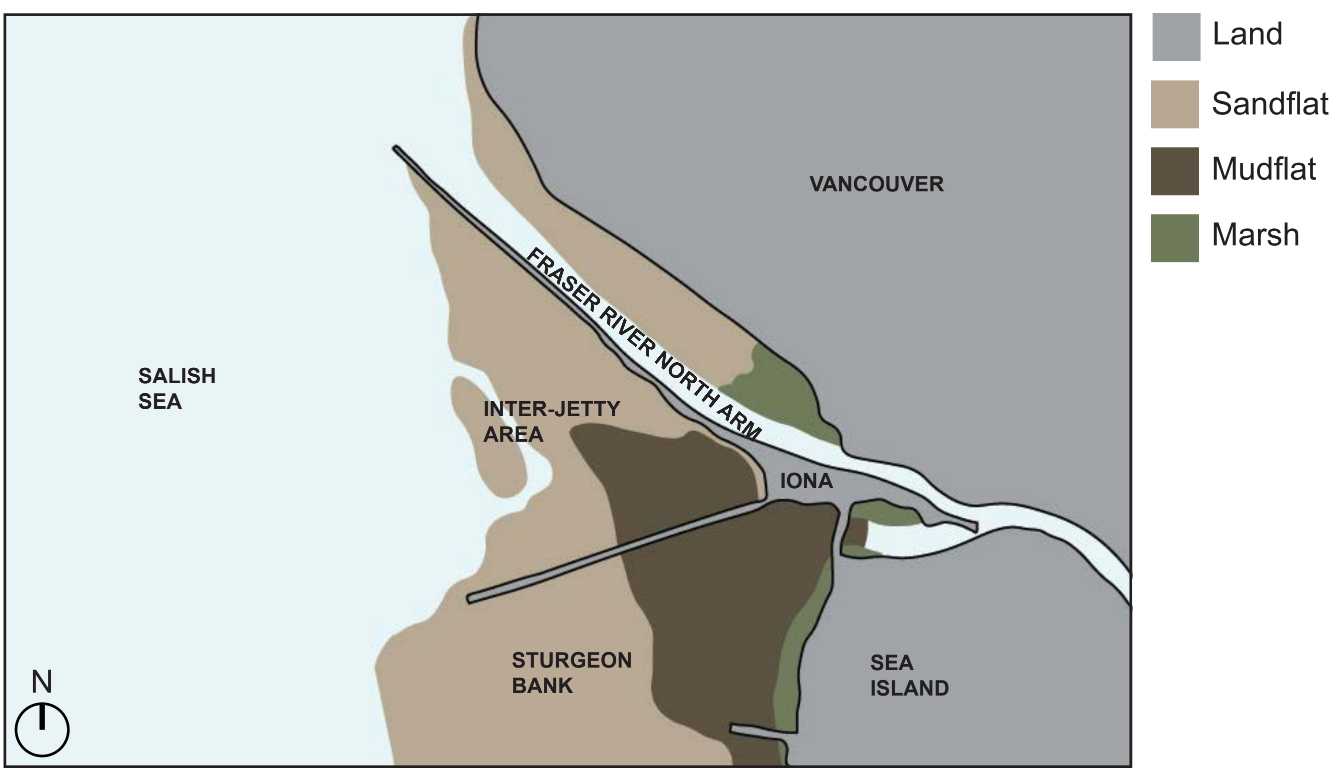

Figure 3. Map of habitat classifications in Iona Island shore zone. Modified from Fraser River Estuary Management Program Habitat Atlas (Community Mapping Network 2013) and from Catherine Berris and Associates 2010.

OBJECTIVES

This project seeks to determine the ecological considerations for the design of a living breakwater made from Biorock to increase biodiversity and the availability of marine habitats. The specific objectives of this study included the following:

1. Understand the potential of Biorock as a more sustainable breakwater material in comparison to conventional materials for protecting Metro Vancouver's ocean-facing infrastructure at Iona Island Outfall Jetty.

2. Identify which species are prevalent in the area, their preferred habitat, and determine if Biorock structures can be designed to promote these species and their habitat requirements.

3. Determine Biorock design considerations to incorporate habitat creation in a Biorock demonstration unit to promote positive ecological impacts in coastal BC waters.

4. Determine the capacity of Biorock for habitat and ecosystem generation.

5. Identify opportunities for active habitat creation or restoration through manual transplantation projects.

RESEARCH METHODOLOGY

To provide recommendations and direction for design considerations for a Biorock habitat structure, this report seeks to synthesize knowledge and ideas by:

1. Conducting a review of seagrass, kelp, shellfish and fish found near Iona Island and determining their habitat requirements.

2. Conducting literature reviews of grey and white literature to inform Biorock habitat design considerations for seagrass, kelp, shellfish and fish. Topic searches included Biorock habitat studies, architectural design precedents, artificial reef design precedents, habitat restoration and species transplantation techniques, regenerative aquaculture techniques, ecologically engineered seawalls, living shorelines and living breakwaters.

3. Conducting informal interviews with disciplinary experts in marine biology and conservation, architecture, and mineral accretion technology (Biorock) to inform the selection of focal species for this research, to advise on species-specific habitat requirements and to give direction for habitat design and species transplantation techniques.

4. Creating graphic renderings to explore visionary, schematic design options.

REVIEW OF BREAKWATER MATERIALS

With climate change, coastal areas will be exposed to more frequent and intense hazards including flooding and coastal erosion (Eyquem 2021). A conventional method for hardening coastal infrastructure as protection against erosion is the use of submerged offshore breakwaters, or coastal structures that protect shorelines from waves and strong currents (Hindle 2018). Coastal erosion protection strategies can also involve a range of materials, often classified on a spectrum from "grey" to "green" infrastructure (Morris et al. 2018).

GREY INFRASTRUCTURE

Based on a review of the literature, scarce local examples exist of the ecological effects of different breakwater materials in the Pacific Northwest. Looking at the broader literature base (without restricting searches to local geography), some of the most commonly used conventional breakwater materials include rubble mound, riprap and concrete tetrapods, which can be classified as grey or "hard" infrastructure (Narayan et al. 2016, Eyquem 2021, Bridges et al. 2021). From an ecological standpoint, one of the main disadvantages of these structures is that they are not typically designed for habitat or biodiversity, and are lacking in habitat heterogeneity and structural complexity as compared to natural rocky structures (Hindle 2018). For example, a UBC study in Burrard Inlet showed that the uniform, small size and steep slope of riprap supported few intertidal species and recommended larger boulders with more rugged surfaces for greater stability and complexity as well as shallower slopes to increase intertidal rock area (Walton et al. 2019). Concrete tetrapods have been shown to have negative impacts on subtropical benthic species and corals as their high wave reflectivity exacerbated coastal erosion (Masucci et al. 2020). Additionally, the transport and emplacement of concrete or quarried rock can result in significant CO_2 emissions, which contribute to climate change.

GREEN INFRASTRUCTURE

On the "green" and "soft" end of the spectrum of coastal infrastructure, natural habitats can also function as coastal defense, including saltmarshes, oyster reefs, seagrass and kelp beds, providing various benefits including fish production, carbon sequestration, protection from storm events and reduction in coastal erosion via wave attenuation (Narayan et al. 2016). Saltmarshes in particular have shown the highest potential among these for reducing wave heights and are significantly cheaper than submerged breakwaters (Narayan et al. 2016). Saltmarshes in Boundary Bay show high carbon sequestration potential, with total carbon stocks of approximately 10 million kg-C for 140 ha of marsh (Gailis et al. 2021). Natural materials such as bagged oyster shells have been used to construct breakwaters in Alabama and helped reduce shoreline retreat, erosion rates and showed an increased abundance in fish communities (Scyphers et al. 2011). Placement of large woody debris on beaches has also been effective in reducing wave reflection as a nature-based coastal protection strategy in the Pacific Northwest (Falkenrich et al. 2020).

HYBRID INFRASTRUCTURE

More recent breakwater materials have been developed using a multi-functional approach known as hybrid infrastructure; hard materials are used to design structures that provide habitat. For example, concrete reef balls used in Alabama were successful in supporting mussels and small juvenile fish, and Atlantic Croaker, Red Drum, Seatrout were five times more abundant compared to mudflat control sites (Scyphers et al.

2015). However, the reef balls were less successful in supporting larger fish species. Another study in Florida showed that adding concrete blocks inside reef balls increased reef fish species abundance and diversity by increasing habitat complexity (Sherman et al. 2002). Another novel breakwater material is the ECOncrete habitat block, a concrete mixture that structurally resembles coral and rock in texture and composition, which was used in the Living Breakwaters project in New York by SCAPE Studio (Ido and Perkol-Finkel 2015). It is designed with surface texturing and crevices for habitat complexity and heterogeneity for finfish and shellfish and configured with complex “reef streets” for reef fishes (Hindle 2018). Biorock is another material that falls within the grey-green spectrum of coastal infrastructure. It presents the potential to function as another hybrid form of coastal infrastructure as it can function as habitat for species and as a wave-attenuating structure (Goreau et al. 2017).

BIOROCK

Biorock, sometimes called “seament” or “seacrete”, is a mineral accretion technology that precipitates limestone (primarily calcium carbonate) in seawater (Hilbertz 1979). Biorock is formed by applying a low-voltage electric current to a submerged metal mesh scaffold, which induces the deposition of solid calcium carbonate from dissolved carbon dioxide and calcium in seawater, similar to how seashells are formed (Goreau 2012) (Figure 1).

One of the uses of Biorock is to provide coastal erosion protection by attenuating waves (Goreau et al. 2013, Goreau et al. 2017). A benefit of this open mesh structure is that it allows sediment to build up around the structure to build back eroded beaches (Goreau et al. 2017). A main advantage of Biorock over conventional rock or concrete shore protection materials is its reduced carbon footprint since it can be produced in-situ rather than being transported from off site. Biorock also sequesters carbon in the limestone that is formed, and may further sequester carbon by providing habitat for marine vegetation (Hilbertz 1992).

Thus, Biorock may offer a potential net carbon sequestration solution for reinforcing shorelines against erosion from wave action. The Biorock scaffold advantages over conventional breakwaters also include lower weight for transportation and superior maneuverability during installation. This allows the use of Biorock mineral accretion in ecologically sensitive areas, in close proximity to existing infrastructure such as outfalls, and in high traffic areas, where rubble breakwater material would otherwise be placed. Biorock is also self-repairing; when Biorock material breaks off the scaffold it can grow back as long as an electric current is supplied (Goreau 2012). The limestone coating that forms also protects the interior metal scaffolding from corrosion, preventing its deterioration (Goreau 2012).

Biorock can also be used to create habitat for marine organisms. The modularity and macroscopic design flexibility of Biorock to create customizable shapes may provide an opportunity to promote specific species, including juvenile fish, seagrasses, kelp, and shellfish.

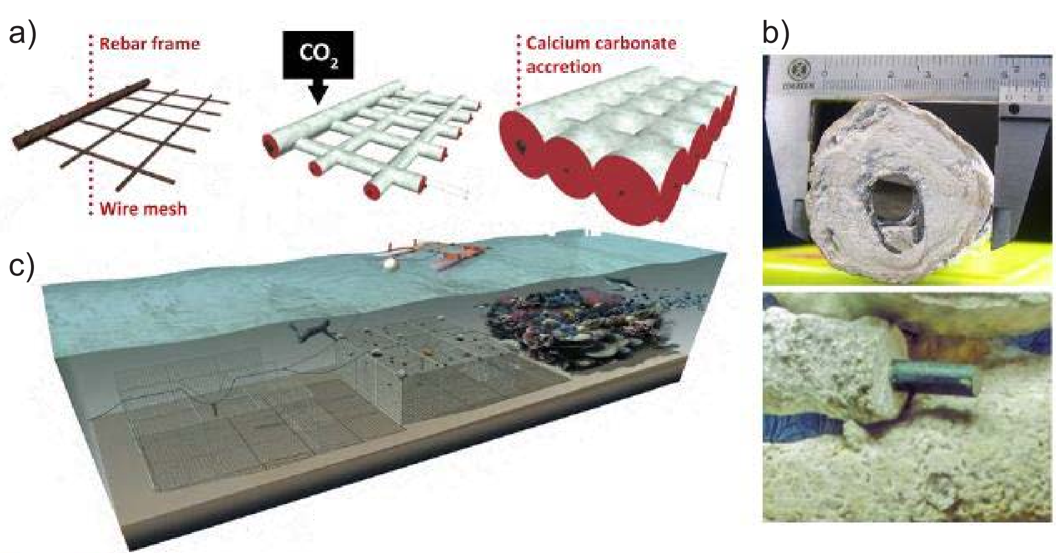

Figure 4. Biorock formation process: a) Progression of accretion of $CaCO_3$ on metal scaffold (Image credit: Knight 2012), b) Thickness of Biorock on 10 mm rebar after 18 months (Image credit: Global Coral Reef Alliance, https://bit.ly/3P11Oqz), c) Biorock life cycle in tropical regions for coral reef formation (Image credit: Knight 2012).

Since it is made from calcium carbonate, Biorock has also been shown to facilitate the growth of calcifying organisms such as oysters and hard-bodied corals that use calcium carbonate in shell formation (Hilbertz and Goreau 1996).

In the Pacific Northwest, there have been no Biorock studies to date except for a cursory study in which blue mussels appeared to grow on Biorock in the Strait of Georgia (Goreau 2020). While most studies on Biorock have been conducted in tropical environments, a few studies on the Biorock formation process have been conducted in cold-water regions, including Denmark (Margheritini et al. 2019, Margheritini et al. 2020) and Sweden (Strömberg et al. 2010).


Photo Credit: Dante Aguiar,Flickr https://bit.ly/3FoNXqM

Figure 5. Coral reef growing on biorock in Indonesia.

REVIEW OF BIOROCK AS A HABITAT STRUCTURE

The focal organisms in this study include shellfish, juvenile fish, seagrasses and kelp. Of these, there is literature on Biorock and its compatibility with seagrass, shellfish and fish. The following section describes examples of organisms relevant to this study that have been observed using Biorock as habitat.

BIOROCK AND OYSTERS

In a field experiment in Indonesia, it was shown that the biorock process stimulated growth of juvenile pearl oysters, in which oysters were attached to biorock rearing panels suspended in water (*Pinctada maxima*) (Karissa et al. 2012). Another study in the Hudson River estuary in New York tested the growth of eastern oysters on Biorock (*Crassostrea virginica*) (Berger et al. 2012). Since oysters cannot naturally sustain themselves without old shells or other hard substrate to attach to, the source of minerals was artificially produced using the biorock process, and oysters were initially glued to the submerged steel structures. This experiment showed increased growth rates and survival rates of oysters, and it was speculated that biorock can help jump-start the shell formation of calcifying organisms and accelerate their growth (Shorr et al. 2012, Goreau 2022). Specifically, this is hypothesized because accreted calcium carbonate becomes more bioavailable to shellfish on the metal structure, which may allow them to increase efficiency of metabolic processes and save energy for shell growth (Shorr et al. 2012, Goreau 2022). Another study tested restoration of eastern oysters in the East River estuary using biorock, which also resulted in increased oyster growth and survival despite suboptimal water quality conditions (Shorr et al. 2012). The design included steel helical-shaped structures in the intertidal with oyster bags attached. This design allows the free flow of water through the structure such that oysters receive food and nutrients while waste can be flushed out (Haseltine 2012). A study in Florida showed that using the Biorock process with steel mesh mats promoted eastern oyster recruitment at a rate comparable to conventional plastic mats, offering a more sustainable material option (Hunsucker 2021). As few published studies on mineral accretion for oyster restoration exist, further research is needed to test oyster recruitment and growth using biorock in estuarine settings (Hunsucker 2021).

While the Eastern oyster species studied here are not local to Iona Island, these findings show that there is potential to promote the growth of calcifying species in estuarine environments and would be interesting to test on local oysters such as the Pacific oyster (*Crassostrea gigas*). For example, species local to Southern BC, such as Pacific oyster or Olympia oyster (*Ostrea lurida*), which currently aren't found at Iona Island, could potentially be grown at the site if a hard calcareous substrate were provided.

BIOROCK AND MUSSELS

One example of biorock being deployed in Canadian waters was the spontaneous settlement of blue mussels (*Mytilus edulis*) on Biorock in Sechelt Inlet (Eric Vanderzee, personal communication). A biorock experiment proposal was also created for blue mussels in Nova Scotia, which outlined technique involving the placement of adult blue mussels into wire mesh bags and attaching them to biorock scaffold structures (Miller 2020). The opening mesh bag design allows the free flow of water from all directions, allowing the mussels to feed and rid their waste. Field observations of mussels growing on Biorock have also been reported in tropical environments (Goreau 2020).

BIOROCK AND FISH

Numerous field observations have shown that mobile marine species used biorock structures as shelter. For example, Biorock structures have been designed using suitable sizes and shapes to provide shelter for juvenile sea bream fish against predation in tropical regions (Lecaillon 2012). Structures built in Jamaica, Mexico and Panama were also built to provide shelter of the right size and shape for lobsters (Goreau and Hilbertz 2008). While these studies were carried out in the tropics, other studies have shown how different types of artificial reefs have successfully promoted groundfish local to the Pacific Northwest. These artificial reef examples will be discussed in a later section.

BIOROCK AND SEAGRASS

An observational study carried out in Italy showed that Mediterranean neptune grass (*Posidonia oceanica*), established amongst two-dimensional grids of biorock (Vaccarella et al. 2012). It is speculated that biorock formation may have helped secure plants by stabilizing their roots from wave action while they were establishing in sediment. The exact mechanism behind Biorock's beneficial effect on marine plants is not yet understood and requires further research.

SUMMARY

In summary, the vast majority of the research on Biorock as a species-supporting structure appears to be focused on rehabilitating coral reefs in tropical environments, and on growing Eastern oysters on the Southern and Eastern coasts of the United States, with scarce biorock studies carried out in cold water, estuarine or Pacific Northwestern environments. The existing Biorock habitat research consists mainly of observational studies on the growth and survival of aquatic organisms on Biorock, and there appears to be scarce information on design considerations for Biorock structures to accommodate species-specific habitat needs. Given these research gaps, as well as the scarcity of examples of living breakwaters in the Pacific Northwest, it was necessary to broaden the literature searches and look to other disciplines for landscape architecture design precedents, artificial reef design precedents, habitat restoration and species transplantation techniques, regenerative aquaculture techniques, ecologically engineered seawalls, living shorelines and living breakwaters. These diverse interdisciplinary approaches to creating marine habitat are explored in the following section to inform recommendations for a range of options and design considerations for a Biorock habitat structure that could function as a living breakwater. Examples of habitat creation that were local to the Strait of Georgia were used where possible.

ECOLOGICAL OPPORTUNITIES AND DESIGN CONSIDERATIONS

The following sections describe the compatibility of Biorock as a habitat structure for selected species of seagrass, kelp, shellfish and fish. In this study, compatibility means the species benefits from using biorock as habitat in either subtidal or intertidal environments, either as a refuge, as a substrate for surface growth or as a material to aid in the calcification of shells. The criteria for selecting focal species within these organism groups were based primarily on the availability of information of known geographically relevant techniques for habitat creation that showed promise, and based on whether the species were known to occur at Iona Island or nearby. Species distributions were determined from literature searches and iNaturalist. Upon reviewing the literature, it was determined that available information on local coastal species at Iona Island is limited to intertidal species, and there is a data gap on species found in the subtidal area adjacent to the island. Due to this data gap, subtidal species information from a nearby reference site at Roberts Bank was used.

Each section that follows reviews and synthesizes examples of landscape architecture design precedents, artificial reef design precedents, habitat restoration and transplantation techniques, regenerative ocean farming techniques, ecologically engineered seawalls, living shorelines and living breakwaters based on studies found from grey and white literature reviews that showed success in creating or restoring habitat, using examples that were relevant to the focal species and also local to the Pacific Northwest where possible. Opportunities for habitat creation and design considerations are summarized in each section to inform the design of a Biorock habitat structure. Further information about the focal species can be found in Appendix 2.

OYSTERS

Focal species: Pacific oyster

Background

Pacific oysters (*Crassostria gigas*) are an introduced species found in the intertidal and subtidal zones throughout the Strait of Georgia, and are tolerant of a wide range of salinity and temperatures (Fisheries and Oceans Canada 2022). While the native Olympia oyster (*Ostrea lurida*) is in greater need of restoration since they are a Blue listed species (a species of special concern), Pacific oysters are tolerant of the lower salinities found near Iona Island and may be more successfully grown with future climate change due to their preference for warmer temperatures (Amelia Hesketh, personal communication). Based on iNaturalist species observations, Pacific oysters are also much more prevalent in the area than Olympia oysters. In an oyster's life cycle, free swimming larvae develop into spat (juveniles), which then settle and cement themselves onto hard surfaces where they grow into adults and can form oyster reefs (Harbo 1997). They can also attach to muddy or sandy substrates when hard structures are scarce, and larvae prefer to settle on the shells of adults (Harbo 1997). Oysters tend to prefer substrates with high rugosity, irregularity and convex shapes (Amelia Hesketh, personal communication). They are considered ecosystem engineers as they provide a complex three-dimensional structure that attracts diverse marine species (Smaal et al. 2019). Oysters can improve water quality by uptaking nitrogen, phosphorus and carbon and can also provide shoreline protection and erosion control (Smaal et al. 2019). This may be of heightened benefit due to the proximity of anthropogenic nutrient discharges from wastewater treatment and industrial sources from the Fraser River.

Design Research

There are many techniques used in oyster restoration and aquaculture for generating oyster reefs. These include placing spat on a provided substrate (adult shells or other constructed materials), “remote setting” (releasing free-swimming larvae in tanks on site with a provided substrate) and installing gabions filled with oyster shells as an attachment substrate (Bohn et al. 1995). When there is a lack of existing oysters to support reef growth on site, oyster restoration projects often use the remote setting technique to boost populations (Miller et al. 2015).

Various designs for built structures have been tested to serve as substrates for oyster growth. In an experiment testing constructed substrates for oysters in Sidney, British Columbia, concrete Reefballs (hollow concrete domes with several circular openings) were seeded with native Olympia oysters and then placed on a mudflat (Carolsfeld et al. 2019). ECOncrete “oyster castles” were also tested, where concrete structures made from a mix of cement and pozzolans (siliceous and aluminous materials) were used as substrate (Carolsfeld et al. 2019). Results showed low recruitment rates, though it was suspected that sedimentation was the cause of adult mortality (Carolsfeld et al. 2019). However, reef balls have shown success in generating Olympia oyster reefs in San Francisco (Boyer et al. 2017). A study from the Billion Oyster Project in New York also found that Eastern oysters successfully grew on reef balls and in gabion baskets filled with oyster shell, and showed that gabions filled with shells provided greater surface area for larvae compared to reefballs, resulting in higher oyster abundance (Smith 2017). In and experiment in Israel, ECOncrete blocks with complex surfaces including holes, crevices and rough textures showed higher abundances of oysters compared to on smooth blocks made from portland cement (Ido et al. 2015). A study on oyster reef design recommended using an open lattice structure to allow larvae to access and grow from all surfaces of the structure and that on-bottom culturing of bags of oysters could lead to sedimentation issues (Wellman et al. 2022). In the Pacific Northwest, multiple studies have shown that heavier, high-relief structures such as reef balls sank into soft mud, and concluded that substrates should be placed on firmer bottom substrate (Ridlon et al. 2021). Growing oysters such that they are suspended from the bottom can also help prevent sedimentation (Eric Vanderzee, personal communication 2022).

Design Considerations

An off-bottom approach should be used by growing out spat in raised or suspended mesh Biorock cages to prevent smothering from silt and to protect oysters from any benthic predators. Since oysters require an open structure for flow and flushing of nutrients and waste, a porous Biorock mesh seems to be suitable. As a rugose substrate, Biorock may provide a suitable surface texture for oysters. Using a hollow, dome-shaped, porous design similar to reef balls could be suitable as they prefer convex surfaces. Since Biorock is comparatively lighter than concrete reef balls, it may be more suitable on mud flats. Future experiments should determine which weights are compatible with the bottom substrates found on site to prevent sinking. Providing Biorock gabion baskets filled with adult shells could be supplied as an additional substrate for larvae settlement to help increase the success of larval recruitment. A remote-setting experiment could also be conducted to test if larvae released on site will settle on Biorock. A Biorock substrate should be available on site by March as oyster larvae will settle in April (Amelia Hesketh, personal communication). Initial experiments could test the growth of Pacific oysters since they likely can be more reliably cultivated at the site. If Pacific oyster populations establish, Olympia oysters could later be seeded since they preferentially settle on oyster shells (Amelia Hesleth, personal communication).

MUSSELS

Focal species: Bay Mussel

Background

Bay mussels (*Mytilus trossulus*) have been found growing on riprap in the intertidal near Iona Island and are a highly prevalent mussel species in the Strait of Georgia. Bay mussels are genetically similar to blue mussels (*Mytilus edulis*), commonly occur as hybrid species, and are often considered the same species (White et al. 2014). They colonize on various hard substrates in the rocky intertidal and subtidal such as rock, wood pilings and other human-made structures (White et al. 2014). Mussels attach to surfaces using their threads, and they can form expansive beds, providing a valuable food source for various sea birds. They are considered ecosystem engineers as they provide a complex three-dimensional structure that attracts diverse marine species (Koivisto et al. 2010). Mytilus species also improve water quality by uptaking nitrogen, phosphorus and carbon (Smaal et al. 2019).

Design Research

Bay mussels are not typically restored in this region because they are highly prevalent, but they can be transplanted by placing them on rocky substrate and covering them with a mesh cage so they don't leave the site (Amelia Hesketh, personal communication 2022). As mussels will readily attach to hard structures in the marine environment, it is expected they would spontaneously settle on Biorock (Eric Vanderzee, pers. comm. 2022). In British Columbia blue mussel farms, mussel are grown out in subtidal waters on suspended longlines or rafts near the surface (BC Shellfish Growers Association, n.d.). Surface roughness and crevices are important habitat features for mussels especially as refuges from physical disturbances (Cordell et al. 2017). A rugose surface texture will increase friction and lessen the chance of mussel threads dislodging (Amelia Hesketh, personal communication). For example, in Elliott Bay, Seattle, habitat panels designed with rough textures and high surface complexity were attached to a seawall, resulting in an increased abundance of bay mussels (Cordell et al. 2017). Mussels also require an open structure to get adequate flow and flushing of nutrients and waste (Miller 2020).

Design Considerations

Biorock could be designed to provide a complex heterogeneous substrate by warping mesh sheets to create crevices (figure 9). The Biorock design could also include stacked cages to create ledges and overhangs to provide a complex surface (figure 9). Elevating mussels from the bottom could also help to protect them from predation. While there are no studies showing that mussels grow on Biorock at faster rates, future experiments could test if they benefit from using calcium carbonate in Biorock material to aid in shell formation.

FISH

Focal species: rockfish, greenling, salmon, herring

Background

Fish species commonly occuring at Iona Island in the intertidal area include all five Pacific salmon species, three-spine stickleback, shiner surfperch, Pacific herring, Pacific sand lance and surf smelt (Dave Scott, personal communication). Eulachon and white sturgeon have also been found at Iona Island but are less common than they were historically. There are historical records of both Pacific herring and eulachon spawning near Iona Island (Metro Vancouver 2020).

Juvenile salmon use brackish habitat near Iona Island as they migrate from the Fraser River out to the Salish Sea as an area to transition from freshwater to saltwater (Metro Vancouver 2020). Juvenile salmon use eelgrass and saltmarshes as nursery habitat (Chalifour et al. 2019). In the Salish Sea, juvenile salmon also appear to use bull kelp forests as habitat for foraging and shelter (Schroeder 2019).

While there are no subtidal species inventories or surveys at Iona Island, Roberts Bank was used as a nearby reference site since there are extensive records on the biophysical setting and species monitoring records. It is assumed in this report that similar species could occur in the subtidal area adjacent to Iona Island.

Design Research and Precedents

At Roberts Bank terminal, there is a subtidal rocky reef ecosystem which includes kelp, hard substrate and multiple reef fish species such as quillback rockfish, copper rockfish, kelp greenling and lingcod (Archipelago 2014). Ten subtidal artificial reefs have been created for habitat compensation projects at Roberts Bank, in which all of these reef fishes occur. The artificial reefs consist of broken concrete pipe (Naito 2001) and quarried rock riprap (Archipelago reef fish survey 2014).

In British Columbia, multiple subtidal artificial reefs such as sunken vessels have been deployed and have been studied for their use as groundfish habitat (Bulger et al. 2019). Groundfish such as rockfish, kelp greenling and lingcod commonly colonize artificial rocky reefs at 5-10m depth in BC (Naito 2001). Artificial reefs that have structures such as body-sized crevices, holes and internal spaces can provide refuge habitat for reef fishes (Beaty et al. 2017). Juvenile rockfishes tend to occupy habitat with kelp and in rocky subtidal reefs with multiple small, body-sized holes and crevices and a non-uniform surface layer. Natural subtidal rocky reefs often consist of piles of boulders and cobbles (Beaty et al. 2017). Juvenile rockfish prefer shallow water of less than 15m, and use complex habitat with low vertical relief (Beaty et al. 2017). Reefs with high structural complexity create opportunities for refuge, and kelp beds also offer habitat for prey of rockfish. If cavities are too large, larger predators can prey on juvenile fish inside the reefs. Having multiple exits to internal chambers is preferred to allow more escape routes as well as access for light and water flow (Beaty et al. 2017). Generally, fishes do not favour sharp edges. Higher relief reefs in waters deeper than 100m tend to be occupied by adult rockfishes (Beaty et al. 2017).

In Raritan Bay, New York, a living breakwater design proposal by Scape Studio provides habitat for reef fishes (Baker et al. 2018). The breakwater incorporates habitat features such as “reef streets”, or narrow spaces between rocky ridges that create sheltered habitat for fish foraging and refuge from predators. These features increase availability of edge habitat with intertidal and subtidal rocky substrates and maximize structural complexity and species diversity (Baker et al. 2018). The design is specifically for juvenile reef finfish such as sea bass, scup, butterfish (Orff 2016). Void spaces between differently sized boulders and in cast ECOncrete breakwater units are sized to fit body sizes of these juvenile fishes for refuge (Scape Landscape Architecture, n.d.).

A review on ecologically-engineered seawalls also found that attributes such as high edge-area ratios and high density of holes can promote a higher abundance and diversity of fish species (Morris et al. 2018). In Elliott Bay (Seattle, WA), an ecologically-engineered seawall designed to augment juvenile Pacific salmon habitat showed an increase in salmon feeding rates post-installation (Sawyer et al. 2020). The design enhanced structural habitat complexity by creating shallow, nearshore intertidal textured wall panels with grooves, ledges and cobbled surfaces (Sawyer et al. 2020). This was designed to increase abundance and diversity of invertebrate prey for salmon (Sawyer et al. 2020), and resulted in high abundance of mussels and rockweed on the panels (Cordell et al. 2017). The design also involved reducing the amount of overhead shade since salmon are visual predators and require light for catching prey (Cordell et al. 2017).

Design Considerations

Hole diameters in the Biorock mesh scaffold for juvenile rockfish and salmon could range from 1cm to 10cm (see Appendix 2 for body sizes of focal fish species). While no studies have been found on salmon using rocks as refuge in subtidal habitat, it is possible that they may use holes in a Biorock structure as refuge from predators such as seals. Also, applying design principles from the Elliott Bay seawall such as panels with complex microstructures to host invertebrate prey could be considered in the design to support foraging habitat for juvenile salmon.

SEAGRASS

Focal species: common eelgrass

Background

Common eelgrass (*Zostera marina*), a native subtidal seagrass species, has been found at sites nearby Iona Island within the Fraser River Estuary region including at Roberts Bank (Hemmera 2014, Catherine Berris Associates 2010) and Boundary Bay (Chalifour et al. 2019). Common eelgrass has several benefits including habitat provisioning for forage fish (Pacific sand lance, surf smelt), juvenile salmon, dungeness crab, and as a spawning site for herring. Eelgrass serves as an important nursery habitat for juvenile salmon in the Fraser River Estuary and as a habitat for copepods upon which salmon feed (Sutherland et al. 2013). Eelgrass shoots form dense rhizomes that stabilize sediment. Other benefits include oxygen production and carbon sequestration through photosynthesis. One square meter of eelgrass produces 10 liters of oxygen per day (Beaty et al., 2017). Another eelgrass species, Japanese eelgrass (*Zostera japonica*) is present at Iona Island (Wootton and Sarrazin, 2011) however it is not recommended for transplanting as it grows in very exposed, shallow intertidal areas and would be at risk of being consumed by herbivores (Fiona Beaty, personal communication). Since common eelgrass is not found at Iona Island, it is recommended to start with a small-scale pilot transplant to test its success at the site (Fiona Beaty, personal communication).

Transplanting Opportunities

Local restoration efforts throughout the Strait of Georgia have shown successful native eelgrass transplantation initiatives including in Howe Sound (Wright et al. 2020). Transplantation can be achieved by harvesting shoots from donor beds and planting them in May to June (Beaty et al., 2017). Planting can be done by anchoring individual shoots with a steel washer to hold down the shoot until it can grow new roots.

Design considerations

Extreme wave energy can uproot plants, reducing eelgrass density and challenging eelgrass growth and survival (Wright et al. 2020). Planting shoots in high-density patches makes them more resilient to erosion or detachment generated by wave action (Beaty et al., 2017). Eelgrass could also be planted on the leeward side of the Biorock structure. The Biorock structure could be designed to shelter and protect transplants from erosion or detachment generated by current or wave action. Future experiments could involve modulating mesh density for optimal sediment movement and current velocity to minimize erosion and create a quiescent environment.

KELP

Focal species: bull kelp, sugar kelp

Background

Bull kelp (*Nereocystis luetkeana*) is an annual brown algae species that is found in both the intertidal and subtidal and adheres to rocky substrates. It is a floating surface canopy-forming species and supports nursery habitat for species such as Pacific herring, salmon, and rockfish (Lang-Wong et al. 2022). Kelp forests can also attenuate strong waves to aid in coastal protection from erosion and flooding (Lang-Wong et al. 2022). Other benefits include absorption of nitrogen, oxygen production, carbon sequestration and buffering against ocean acidification. Bull kelp has been found growing on rock riprap at Roberts Bank terminal (Port Metro Vancouver 2015) and iNaturalist shows observations of bull kelp washed up on the shore at Iona Island. Similarly, sugar kelp (*Saccharina latissima*) also uptakes carbon and nitrogen (Kim et al. 2015) and has been found growing at Roberts Bank terminal (Port Metro Vancouver 2015). Sugar kelp is an understorey kelp that grows in the intertidal and subtidal and is commonly farmed on the BC coast.

Design Research and Transplanting Opportunities

Bull kelp restoration experiments have been conducted in Vancouver Island, Hornby Island, and the Sunshine Coast (Shaw et al. 2018, Tomlin et al. 2020, Heath et al. 2015). Artificial reefs can be designed to facilitate transplanting and seeding of kelp (Eger et al. 2022). For example, artificial reefs in Korea have been combined with kelp aquaculture techniques using floating seeded lines (Eger et al. 2022). A common technique for kelp cultivation in BC involves culturing spores on rope (longlines) and suspending them in the ocean so that kelp are protected from sea urchin grazing (Lee-Ann Ennis, personal communication). Kelp are first cultivated on twine and the twine is wrapped around rope. The seeded lines can be suspended in water by anchoring them to structures and can act as a source population for the area (Lee-Ann Ennis, personal communication). After spores have grown into young kelp sporophytes (plants), they can be transferred to hard substrate in late February to March by attaching the holdfast to rock using rubber bands or cable ties (Lee-Ann Ennis, personal communication). Future lab experiments could be done to test if the gametophytes will settle on Biorock (Lee-Ann Ennis, personal communication). Another transplantation method involves securing young kelp to mesh mats by fastening the holdfast using cable ties (Eger et al. 2022).

For artificial reefs, using hard substrates with texture and high surface rugosity rather than smooth surfaces can help improve the strength of kelp attachment. Transplanting kelp on the artificial reef at the time of installation can help ensure the desired kelp species colonizes the structure first. Kelp should be raised off the seafloor to protect them from urchin grazing and sedimentation (Eger et al. 2022).

Design Considerations

Considering the rugose surface texture of Biorock, it possibly may serve as a suitable substrate for kelp holdfast attachment. Growing spores on ropes could be achieved by using the Biorock structure to anchor the ropes and designing the structure such that the ropes are elevated above the seafloor away from urchins. Biorock mesh scaffolds could be used to imitate the mesh mats transplantation approach. Creating a vertical canopy of kelp that grows above a submerged Biorock structure would help to add more structural habitat diversity to the reef as well.

POTENTIAL TO CREATE ECOSYSTEMS

When considering how a Biorock structure could build ecosystems that support multiple species, looking to new developments in the aquaculture industry holds an interesting avenue for design research. Regenerative ocean farming, also known as 3D ocean farming, vertical ocean farming or restorative aquaculture, is a polyculture aquaculture system that grows a combination of seaweeds and shellfish while sequestering carbon and facilitating the formation of reef ecosystems (Greenwave n.d). By using a vertical 3D multi-species system, all depths of the water column are utilized to create diverse habitat and efficiently use space. A regenerative ocean farming company called GreenWave (Connecticut, USA) has spearheaded the implementation of this model by growing mussels, oysters and sugar kelp on suspended longlines and using cages for other shellfish (Greenwave n.d.). A review on the habitat value of restorative aquaculture found that ocean farming structures such as ropes and cages can provide valuable substrate for biofouling invertebrates, which can in turn provide novel structured, complex refuge habitat and foraging opportunities for other invertebrates and fish (Theuerkauf et al. 2022).

Cages with open mesh filled with bivalves can also provide 3D interstitial spaces for refuge for juvenile fish and invertebrates that mimic natural bivalve beds, while excluding fish predators (Theuerkauf et al. 2022). In particular, they found that off-bottom mussel and oyster culture using suspended rack and bag systems were associated with the highest abundance and species richness compared to on-bottom or longline gear used for shellfish (Theuerkauf et al. 2022).

Some of the recommended commercial species for restorative aquaculture in Canada include sugar kelp, blue mussels and Pacific oysters (DFO 2013). Bivalves can filter contaminants from water and kelp can uptake dissolved nitrogen from the water as well as sequester carbon dioxide (DFO 2013). Kelp detritus and shell debris that fall to the seafloor can also provide food for benthic invertebrates, and dense kelp canopies can provide breeding habitat and shelter for fish (Theuerkauf et al. 2022).

A study on integrated multitrophic aquaculture showed that co-culturing blue mussels and sugar kelp resulted in increased sugar kelp biomass compared to growing them as a single culture (Hargrave et al. 2022). It is suspected that mussels improved water clarity and light availability via water filtration, which may have indirectly benefited growth of the kelp (Hargrave et al. 2022). Mussel excretion also provides a source of nitrogen that may be taken up by kelp at times of nitrogen depletion (Hargrave et al. 2022). A company in the Netherlands called Reshore is developing and testing a concept in which regenerative vertical aquaculture is combined with floating pontoons and artificial reef anchors to function as a living breakwater for coastal erosion protection (ReShore n.d.).

While the waters near Iona Island are currently closed to bivalve shellfish harvest due to contamination (DFO 2022), outplanting kelp, mussels and oysters and borrowing techniques and structural designs from the regenerative aquaculture industry could help inform a Biorock design that provides habitat and coastal erosion protection. If successful, these foundational habitat-forming species could potentially create ecosystems such as kelp forests, mussel beds and oysters reefs which are important food sources for higher trophic-level species. These species could also potentially contribute to enhancing water quality, sequestering carbon and attenuating waves. In the longer term, if the shellfish harvest closure ended, then opportunities for ocean farming for harvesting and sustenance could be explored.

DESIGN RECOMMENDATIONS

In artificial marine habitat design, a common principle is to mimic habitat attributes found in natural ecosystems in terms of macro and micro form and structure of substrates to accommodate the species assemblages that are typically found in those habitats (Beaty et al. 2017). In the case of Biorock, structures could be designed to mimic rocky subtidal or rocky intertidal conditions. Surface heterogeneity and complexity of form are other key design principles used in the design of marine structures for recruiting diverse species that can be applied at multiple scales (Hindle 2018). For example, heterogeneous substrate composition could include a variety of crevice sizes with high rugosity and porosity (Beaty et al. 2017, Hindle 2018). The topography and texture of a hard marine structure can create microhabitats and microclimates that influence the number of available niches and species diversity (Hindle 2018). Design principles for a living breakwater designed by Scape Studio recommend avoiding critical habitats, using non-uniform distribution of structural complexity and to create areas with high edge-area (or perimeter-area) ratios as strategies for maximizing biodiversity (Scape Landscape Architecture, n.d). They also recommended including pocket areas of micro-scale complexity and locating them on the wave-ward side of the breakwater such that they don't fill with sediment (Scape Landscape Architecture, n.d). Designs that provide variations in moisture, salinity, light, texture, and temperature can also promote biodiversity (Hindle 2018). For example, a study on rocky intertidal habitats in Burrard Inlet showed that rockweed growing on large rugged boulders created shaded, moist habitats sheltered from predators which provided thermal refuges for several marine invertebrate species (Walton et al. 2019).

For Biorock, habitat heterogeneity and complexity can be created using a variety of ledges and overhangs at varying heights (Figure 9). The metal mesh scaffolding could also be warped or crushed to increase topographic irregularity and emulate crevices or craggy surfaces (figure 9). Tunnels or cages with a dense mesh weave could also be used to increase porosity, using a variety of hole sizes to accommodate different body sizes of mobile species such as fish that may use the interior of the scaffolding as a cave-like refuge (figure 7). Intertidal structures could also incorporate terraces or shallow slopes to provide a large intertidal surface area. Using a combination of many approaches may also help to increase the diversity and the success of species establishment on Biorock (Chad Scott, personal communication). For example, for oysters, drawing from established successful techniques such as supplying oyster shells together with Biorock could help boost larval settlement (Stefan Miller, personal communication).

The illustrations that follow suggest a variety of types of structures, exploring both subtidal and intertidal design ideas drawn from the research on the focal species in this study, as well as more generalized design principles that promote biodiversity (figures 6,7,8,9). A hybrid design approach was taken that integrates ideas from living breakwaters, artificial reefs, regenerative aquaculture and ecological restoration techniques. This wide range of possible types of structures and design flexibility is an advantage of Biorock over conventional breakwater materials such as riprap.

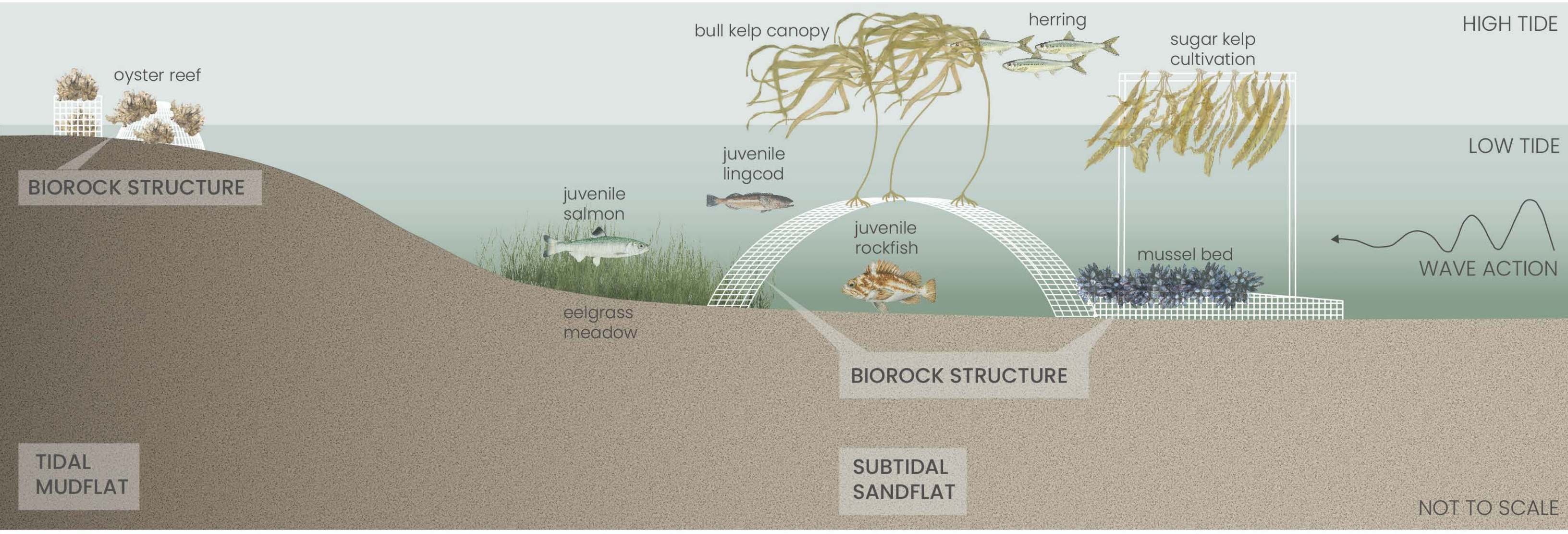

Figure 6. Side view of proposed living breakwater constructed from Biorock, providing wave attenuation and habitat in the shore zone.

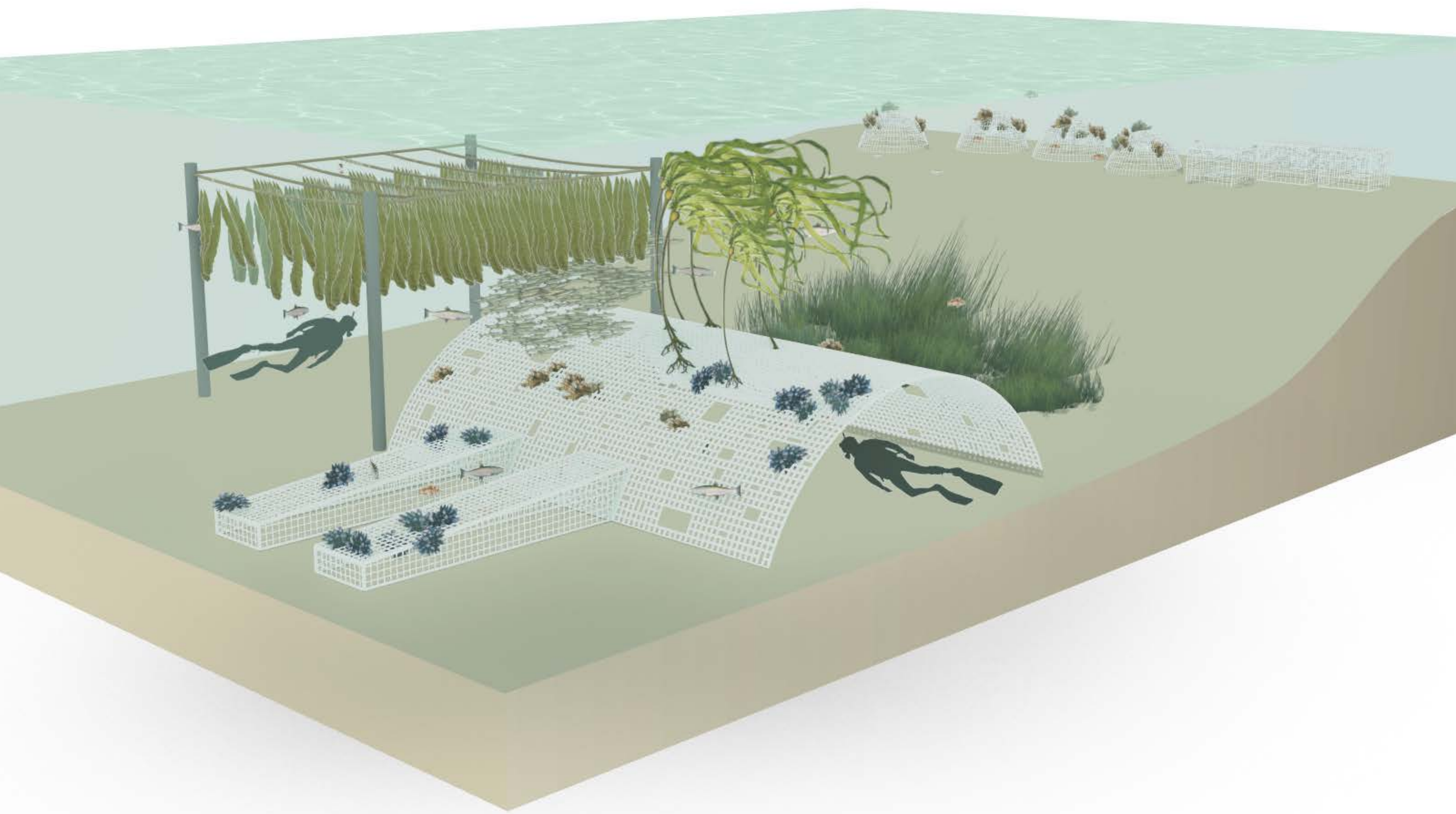

Figure 7. Perspectival view of proposed living breakwater constructed from Biorock, providing wave attenuation and habitat in the shore zone.

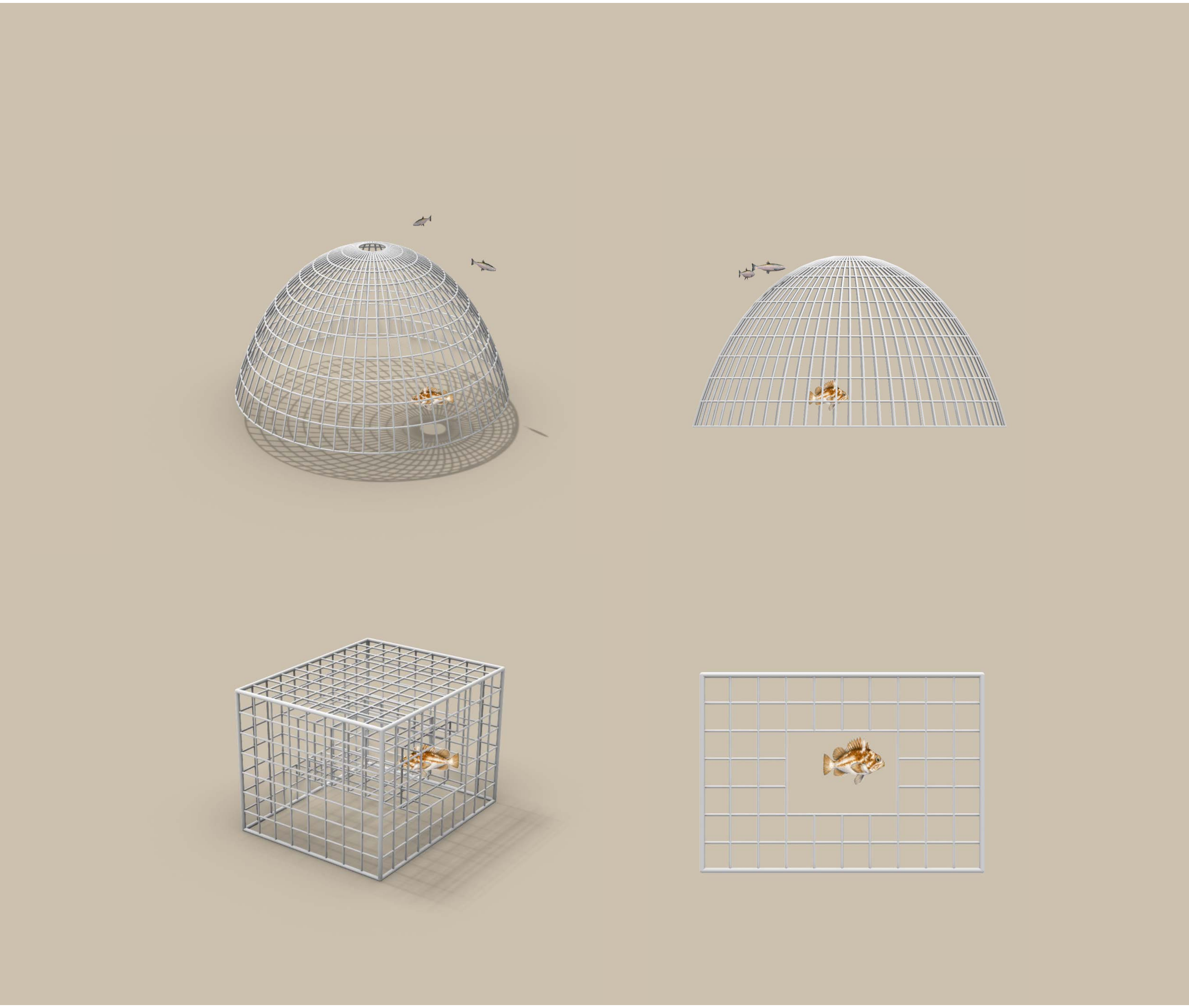

Figure 8. Domed cave and box cave Biorock structures.

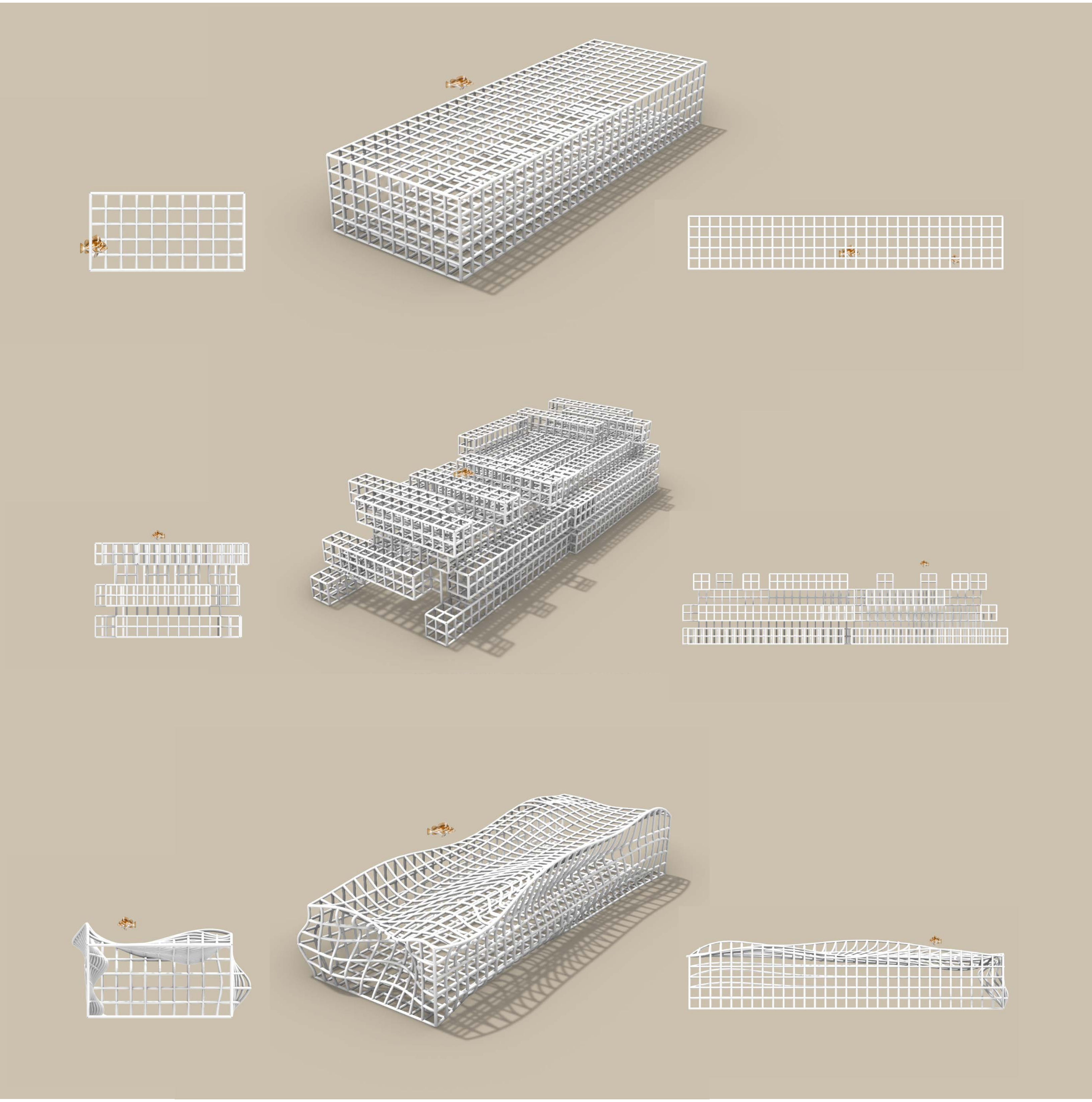

Figure 9. Biorock structures designed with varying levels of structural complexity.

SUMMARY

This report aimed to explore the potential opportunities for habitat and ecosystem creation for a living breakwater made using Biorock for shoreline erosion protection and biodiversity enhancement. It also aimed to offer recommendations for design considerations for a living breakwater to support the specific habitat needs of local species. Core design principles for promoting biodiversity in hard marine structures include augmenting structural heterogeneity and complexity, surface rugosity, porosity and edge-area ratios, providing diverse microclimate conditions, and mimicking natural forms.

There are multiple ways Biorock can be used as habitat, whether it be as a refuge, as substrate to attach to, or as a source of calcium carbonate for shell formation. Biorock appears to be a suitable material for creating diverse habitat types since it can be made into any customized shape and offers a large range of design possibilities that could increase the number of ecological niches. This means that different techniques for habitat creation can be used ranging from regenerative aquaculture, artificial reef design, ecological engineering and ecological restoration. Piloting the transplantation of bull kelp, sugar kelp, Pacific oysters and bay mussels onto Biorock as well as the transplantation of eelgrass adjacent to Biorock structures could offer valuable feeding and rearing habitat for several local species of juvenile fish.

NEXT STEPS

The design ideas suggested in this study are exploratory and speculative, and point to directions for further design research for the design of a living breakwater at Iona Island made from Biorock. Future steps in the breakwater project should also include engagement with Musqueam First Nation on decisions about species, restoration techniques and technologies, and opportunities for cultural continuity and future harvesting of marine food sources.

Future considerations for the Biorock design should take into account future changes in environmental conditions at the site. The current and future breaching of the jetties and causeway at Iona Island will increase freshwater inputs to the inter-jetty area of Sturgeon Bank, resulting in more brackish conditions. This salinity change may affect the species community composition and the Biorock formation process. Additionally, the resulting changes in water quality in the interjetty area after the future upgrade of the wastewater treatment plant to tertiary treatment may alter habitat suitability for some species. Climate change impacts on water temperature and pH could also potentially impact species found on site as well as the Biorock formation process. Future monitoring of environmental conditions such as sediment transport patterns, pH, salinity, nutrient levels, temperature, water current velocity, turbidity, light availability and dissolved oxygen levels could all inform species habitat suitability as well.

Understanding the influence of the Biorock structure on the surrounding environment will also help to inform its design. Specifically, the Biorock structure could influence microclimate conditions such as shade, temperature, wave velocities and sediment accretion patterns which may influence its habitat suitability for different species.

Since the scope of this study was limited to researching seagrass, kelp, fish and shellfish, future research could look at other algae species found at the Iona jetties such as sea lettuce (*Ulva spp.*), sea hair (*Ulva intestinalis*) and rockweed (*Fucus distichus*) which grow on rock substrates. Surveys for red coralline algae (*Mastocarpus spp.*) in the area that use calcium carbonate and grow on rock could also be investigated.

Monitoring of the Biorock structure after installation and after mineral accretion and species establishment could also be done to determine if the focal species can generate self-sustaining populations in the longer term, and to determine how much maintenance is needed to help the populations survive in the early stages of establishment (e.g. removal of predators or invasive competitors from the structure). Ongoing species surveys of the site should also take place as Biorock experiments are implemented.

Further research could involve contacting industry experts who work with custom-designed and patented artificial reef products such as ECOncrete and Reefballs to further understand how their designs are informed by species-specific habitat requirements.

SUGGESTED FUTURE RESEARCH QUESTIONS

How does Biorock compare to other natural hard marine substrates found in the Strait of Georgia such as gravel, cobbles, boulders, bedrock or limestone in terms of its physical form and structure? Can Biorock be designed to mimic attributes of these structures to provide habitat?

Can the Biorock formation process be manipulated to adjust the amount of surface rugosity?

What is an optimal mesh density that allows for build-up of large-diameter mineral accretions, such that there is still space for holes in the mesh after accretion that correspond with the body sizes of the focal fish species?

How do Biorock designs of varying structural complexity and heterogeneity influence biodiversity and abundance of species using the structure? (e.g. size, density and diversity of holes, caves and ledges, degree of warping in mesh)

What are the growth rates and survival rates of species growing on Biorock, and how do they compare between different structural designs?

Do calcifying species such as blue mussels and Pacific oysters have enhanced growth rates on Biorock compared to other materials such as boulders or shells?

At what stage in the Biorock formation process should species be transplanted onto Biorock?

Can planktonic life stages of kelp, oysters and mussels successfully settle on Biorock? Which life stage of these organisms has a preference for growth on Biorock at this site?

How successful are biofilms (accumulations of microorganisms) in establishing on the surface of Biorock, and can they facilitate colonization of other species?

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APPENDIX 1

INTERVIEW PARTICIPANTS

Name	Position	Organization
Fiona Beaty	Regional Coordinator	SeaChange Marine Conservation Society
Lee-Ann Ennis	Marine Biologist	Vital Kelp
Amelia Hesketh	PhD Candidate, Marine Biology	Department of Zoology, University of British Columbia
Chris Knight	Senior Designer	Michael Green Architecture
Stefan Miller	Fish and Fish Habitat Protection Biologist	Fisheries and Oceans Canada
Chad Scott	Marine Biologist, Mineral Accretion Technology	New Heaven Reef Conservation Program
Dave Scott	Biologist, Wild Salmon Program	Raincoast Conservation Foundation
Eric Vanderzee	Former Associate of Wolf Hilbertz, in Research & Development of Mineral Accretion Technology	-

APPENDIX 2

SPECIES DATA TABLES

scientific name(s)	common name(s)	species category	size	preferred habitat conditions/requirements	zone and depth	ecosystem type	species interactions	status	origin	found at Iona? (n.d. = no data)	design considerations	references
Marine Vegetation												
Zostera marina	common eelgrass	seagrass	2.5m-long stems (up to 3m long)	submerged or partially floating, forms meadows in muddy or sandy substrate, prefers protected shorelines with low to moderate wave exposure, subtidal flats, estuaries and tidal pools on exposed shores. located in areas of uniform relief and can be found rooted in a range of sediment types. Their rhizomes bury from 3 to 20 cm below the sediment surface, with deeper burial generally associated with loose or unconsolidated deposits. physical conditions: flat seabed, quiescent brackish water, salinity: 10-30psu, pH 7.3-9.0, wave-induced bottom velocities less than 1.8ms-^1.	Usually grows in subtidal and intertidal (+1.8 to -6.6 metres CD)	seagrass meadow	herring eggs attach to shoots, provides nursery habitat for juvenile salmon, herring, sole, perch, smelt, starry flounder, tubesnout, bay pipefish, three-spine stickleback, juvenile Dungeness crab, other invertebrates	BC: Yellow list (secure)	BC native	n.d. found at Roberts Bank Terminal and Boundary Bay	plant on leeward side of the biorock structure to protect from wave action. plant in the subtidal in a flat area on sandy mud substrate. Plant at a site that allows adequate light penetration for growth, which is dependent on water quality and depth. Biorock could be used to anchor transplanted shoots to help plants establish.	https://www.centralcoastbiodiversity.org/eelgrass-bull-zostera-marina.html https://www.fionabeaty.ca/_files/ugd/134da2_d85237792b9c4080891371c8482bb75d.pdf
Nereocystis luetkeana	bull kelp	kelp	up to 20m long stipe (stem), up to 40cm across holdfast (roots)	annual macroalgae, attaches to rocky substrate, common in high currents and moderate wave action, forms dense canopies at the surface. Preferred salinity: 20-24 psu. It prefers areas with significant water flow, but grows in sheltered to fully exposed waters.	intertidal and subtidal, up to 20m deep. rare in the extreme low intertidal	kelp forest	detritus provides feed for blue mussels and other filter feeders, habitat for fish (rockfish, greenlings, salmon, herring, tubesnout), urchins, sea otters	not listed	BC native	yes, iNaturalist. also found at Roberts Bank on man-made rocky subtidal reefs	consider current, and consider light availability, based on depth, water quality and shade. Elevate from bottom to protect from sedimentation and grazing by urchins. Needs substrate with high rugosity. Provide mesh mat with dense weave for holdfast to attach to.	https://www.centralcoastbiodiversity.org/bull-kelp-bull-nereocystis-luetkeana.html https://linnet.geog.ubc.ca/Atlas/Atlas.aspx?sciname=Nereocystis%20luetkeana https://www.ceaa-acee.gc.ca/050/documents/p80054/101365E.pdf
Saccharina latissima	sugar kelp	kelp	up to 50cm long stipe (Stem), blade up to 3.5m long	perennial macroalgae, occurs along protected and semi-protected shorelines, haptera attaches to rock, shells and other debris	low intertidal and upper subtidal, to 30m deep	kelp forest	consumed by sea urchins and other herbivorous invertebrates such as dusky turban snail	not listed	BC native	found at Roberts Bank on man-made rocky subtidal reefs	consider current, and consider light availability, based on depth, water quality and shade. Elevate from bottom to protect from sedimentation and grazing by urchins. Needs substrate with high rugosity. Provide mesh mat with dense weave for holdfast to attach to.	https://linnet.geog.ubc.ca/Atlas/Atlas.aspx?sciname=Saccharina%20latissima https://www.centralcoastbiodiversity.org/sugar-kelp-bull-saccharina-latissima.html https://www.ceaa-acee.gc.ca/050/documents/p80054/101363E.pdf

scientific name(s)	common name(s)	species category	size	preferred habitat conditions/requirements	zone and depth	ecosystem type	species interactions	status	origin	found at Iona? (n.d. = no data)	design considerations	references
Shellfish												
Crassostria gigas	Pacific oyster, Japanese oyster	shellfish, bivalve	adult diameter: 80-400mm common diameter: 150mm	temperatures of 20-25 C and salinities of 35 ppt are optimal for spawning. They prefer to attach to a hard or rocky surfaces (large rocks or bedrock) in shallow or sheltered waters but have been known to attach to muddy or sandy areas when the preferred habitat is scarce. At times they use vertical surfaces. They can also be found on the shells of other shellfish. Larvae often settle on the shells of adults, and great masses of oysters can grow together to form oyster reefs. feeding: filter feeder. very fast growing, high tolerance to a range of temperature and salinity fluctuations.	Benthic; brackish; depth range 0 - 15 m, in estuaries, subtidal and mid to high intertidal		predators include sea stars, snails, oyster drills and birds	not listed	endemic, introduced to BC from Japan	yes, iNaturalist	Needs hard rock substrate with high rugosity, irregularity and crevices. Uses convex surfaces. Needs an open structure to get adequate flow and flushing. For culturing, use off-bottom culture approach by growing out spat in elevated mesh boxes to prevent smothering from silt and to protect from benthic predators. Provide adult shells as an additional substrate for larvae settlement. For culturing, use remote-setting technique, providing Biorock as a substrate.	https://linnet.geog.ubc.ca/efauna/Atlas/Atlas.aspx?sciname=Crassostrea%20gigas https://www.sealifebase.ca/summary/Crassostrea-gigas.html https://www.pac.dfo-mpo.gc.ca/fm-gp/mplans/oyster-huitre-ifmp-pgip-sm-eng.html Shells and shellfish of the pacific northwest
Ostrea conchaphila	Olympia oyster	shellfish, bivalve	adult diameter: 90mm	filter feeder, larvae settle on underside of hard surfaces, reproduces at 12.5C, typical density of 0.0 to 36.7 oysters/0.25 m2. Found in estuaries, saltwater lagoons, bays, tidal flats, attached to pilings or free-floating structures. It has been found in mud-gravel tidal flats, in splash pools and in tidal channels. May settle on very small hard substrate pieces or the shells of Pacific oysters. Has low tolerance to fluctuations in temperature and salinity.	Benthic, brackish, in estuaries, lower interidal and subtidal zones to 50m depth		predators include crabs, gastropods, sea stars, and birds. Shell acts as a substrate for barnacle colonization	BC blue list (special concern)	BC native	n.d. few populations found in Strait of Georgia (Amelia Hesketh)	Needs hard rock substrate with high rugosity, irregularity and crevices. Uses convex surfaces. Needs an open structure to get adequate flow and flushing. For culturing, use off-bottom culture approach by growing out spat in elevated mesh boxes to prevent smothering from silt and to protect from benthic predators. Provide adult shells as an additional substrate for larvae settlement. For culturing, use remote-setting technique, providing Biorock as a substrate.	https://linnet.geog.ubc.ca/efauna/Atlas/Atlas.aspx?sciname=Ostrea%20lurida&ilifeform=186 Shells and shellfish of the pacific northwest https://www.registrelep-sararegistry.gc.ca/virtual_sara/files/plans/mp_olympia_oyster_0509_e.pdf https://www.sararegistry.gc.ca/virtual_sara/files/cosewic/sr_olympia_oyster_0911_eng.pdf
Mytilus trossulus	Bay mussel, foolish mussel	shellfish, bivalve	adult length 70-110mm	found in intertidal in calm sheltered areas, often form mats completely covering the underlying substrate, makes byssal threads to attach to rocks, docks, piling, and other hard surfaces	intertidal and subtidal up to 5m depth	rocky intertidal	important prey species for shorebirds	not listed	BC native	yes, iNaturalist	provide complex, heterogeneous rocky substrate with lots of crevices. provide rugose texture to increase friction and lessen chance of threads dislodging. needs an open structure to get adequate flow and flushing. Transplant mussels toward the top of the structure to protect them from seastar predation. For spat culturing, use off-bottom culture techniques such as long-lines with mussel socks or floating rafts.	https://www.centralcoastbiodiversity.org/pacific-blue-mussel-bull-mytilus-trossulus.html Shells and shellfish of the Pacific Northwest

scientific name (s)	common name(s)	species category	size	preferred habitat conditions/requirements	zone and depth	ecosystem type	species interactions	status	origin	found at Iona? (n.d. = no data)	design considerations	references
Fish												
Oncorhynchus tshawytscha	chinook salmon	pelagic, migratory	adult total length: 79cm adult body depth: 16cm juvenile total length: 5-18cm juvenile body depth: 1-4cm	Juveniles: Uses eelgrass, saltmarsh, kelp and woody debris as shelter or refuge from predators. Feeds on fishes such as Pacific herring and Pacific sand lance, crustaceans, and other invertebrates. Need light access for hunting as they are visual predators.	0-375m	tidal saltmarsh, coastal, freshwater, marine, brackish		BC: yellow list (secure), COSEWIC: threatened	BC native	yes, data from Dave Scott	needs light access for feeding, complex hard substrate for their invertebrate prey with grooves, ledges or irregular surfaces, kelp and eelgrass for feeding and shelter from prey	Estuary habitat associations for juvenile Pacific salmon and pelagic fish: Implications for coastal planning processes https://onlinelibrary.wiley.com/doi/full/10.1002/aqc.3142 Chinook salmon exhibit long-term rearing and early marine growth in the Fraser River, British Columbia, a large urban estuary Habitat use by juvenile salmon, other migratory fish, and resident fish species underscores the importance of estuarine habitat mosaics Quantifying lost and inaccessible habitat for Pacific salmon in Canada's Lower Fraser River Conservation in heavily urbanized biodiverse regions requires urgent management action and attention to governance https://linnet.geog.ubc.ca/efauna/Atlas/Atlas.aspx?sciname=Oncorhynchus%20tshawytscha&noTransfer=0 https://marinesurvivalproject.com/research_activity/list/habitat-restoration-protection/ https://salmonwatersheds.maps.arcgis.com/apps/Cascade/index.html?appid=d64ff8a3545e48c78473188166c98368 https://www.lummi-nsn.gov/userfiles/1_Appendix_C_Finfish_v4.0.pdf
Clupea pallasii	Pacific herring	pelagic forage fish	adult 25cm total length adult 5cm body depth	larvae and juveniles live near shore. adults live at further depth. spawns inshore in estuaries late winter to April, lays eggs on kelp, eelgrass and rock. pelagic schooling fish.	surface to 250m deep	coastal, freshwater, marine, brackish	feeds on crustaceans (mainly copepods) and small fishes. eaten by various mammals, birds and fish.	not listed	BC native	yes, data from Dave Scott	uses eelgrass and kelp for spawning roe	Fishes of the Salish Sea volume II https://www.fishbase.se/Summary/SpeciesSummary.php?ID=1520&AT=pacific+herring
Sebastes caurinus	copper rockfish	groundfish	adult total length: 17-58cm adult body depth: 5-19cm juvenile length: 9-36cm juvenile body depth: 3-10cm	Juveniles are found in shallow protected bays and inlets, they settle in shallow nearshore structures (eelgrass, kelp, piled boulders and bedrock), prefer shallow weedy bays with benthic or drifting macrophytes and huddle around wharves.	10-183m	subtidal rocky reef		not listed	BC native	n.d. but found at Roberts Bank artificial reefs	Provide complex structures that facilitate kelp growth in shallow nearshore, and include various sized holes for hiding. uses eelgrass for shelter	https://linnet.geog.ubc.ca/efauna/Atlas/Atlas.aspx?sciname=Sebastes%20caurinus&ilifeform=22 https://www.fishbase.se/Summary/SpeciesSummary.php?ID=3957&AT=copper+rockfish https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=34265&inline https://www.fionabeaty.ca/_files/ugd/134da2_d85237792b9c4080891371c8482bb75d.pdf
Sebastes maliger	quillback rockfish	groundfish	adult length: 22-61cm adult body depth: 7-20cm (range used: smallest length at maturity to maximum length)	Juveniles seek shelter in complex nearshore environments with heavy algal coverage, such as eelgrass and kelp, cobble clusters or caverns, and cloud sponges	0 - 274 m	subtidal rocky reef		threatened (COSEWIC)	BC native	n.d. but found at Roberts Bank artificial reefs	Provide complex rock structures with plenty of crevices and caves in subtidal environments. Uses eelgrass and kelp for shelter	https://www.fishbase.se/summary/SpeciesSummary.php?ID=3978&AT=quillback+rockfish https://www.fionabeaty.ca/_files/ugd/134da2_d85237792b9c4080891371c8482bb75d.pdf

scientific name (s)	common name(s)	species category	size	preferred habitat conditions/requirements	zone and depth	ecosystem type	species interactions	status	origin	found at Iona? (n.d. = no data)	design considerations	references
Hexagrammos decagrammus	kelp greenling	groundfish	adult length:61cm adult body depth: 15cm juvenile length: 5-18cm juvenile body depth: 1-4.5cm	Adults inhabit inshore kelp and eelgrass beds, rocky reefs and sandy bottoms. They rapidly colonize habitats and are commonly found in intertidal and subtidal regions in seaweeds and boulders among plant life on the bottom. They are solitary reef fish, spending the majority of their time within a few metres of the bottom. Juveniles settle to rocky intertidal or shallow subtidal waters, and are often found in tide pools. They are always found amongst plant life (eelgrass or kelp). They lay eggs at the bottom on encrusting rocky substrate.	Intertidal – 130 m common range: 0 – 100 m	subtidal rocky reef		not listed	BC native	yes, data from Dave Scott. Also found at Roberts Bank artificial reefs	uses kelp, eelgrass, and rocky reefs for shelter. lays eggs on rocks	https://www.lummi-nsn.gov/userfiles/1_Appendix_C_Finfish_v4.0.pdf https://oregonconservationstrategy.org/strategy-species/kelp-greenling-2/ https://www.fionabeaty.ca/_files/ugd/134da2_d85237792b9c4080891371c8482bb75d.pdf
Ophiodon elongatus	lingcod	groundfish	adult length: 50-152cm adult body depth: 10-30cm juvenile length: 6.7 cm juvenile body depth: 1cm	Young juveniles settle onto open sand, then move to complex but low profile habitats, such as eelgrass, small rocks and sea pens from April to July. As they age they move to kelp beds and offshore rocky reefs	1.5 – 475 m	subtidal rocky reef		not listed	BC native	n.d., but found at Roberts Bank artificial reefs	Ensure rocky reefs are situated in a site with appropriate current for egg masses. Very large boulders provide focus for territorial males and intensify adjacent current flows through crevices, which is ideal for egg incubation. Use kelp and eelgrass for shelter	https://www.lummi-nsn.gov/userfiles/1_Appendix_C_Finfish_v4.0.pdf https://www.fionabeaty.ca/_files/ugd/134da2_d85237792b9c4080891371c8482bb75d.pdf