The effects of coastal artificial reefs on biodiversity, aquatic food security and ecosystem services

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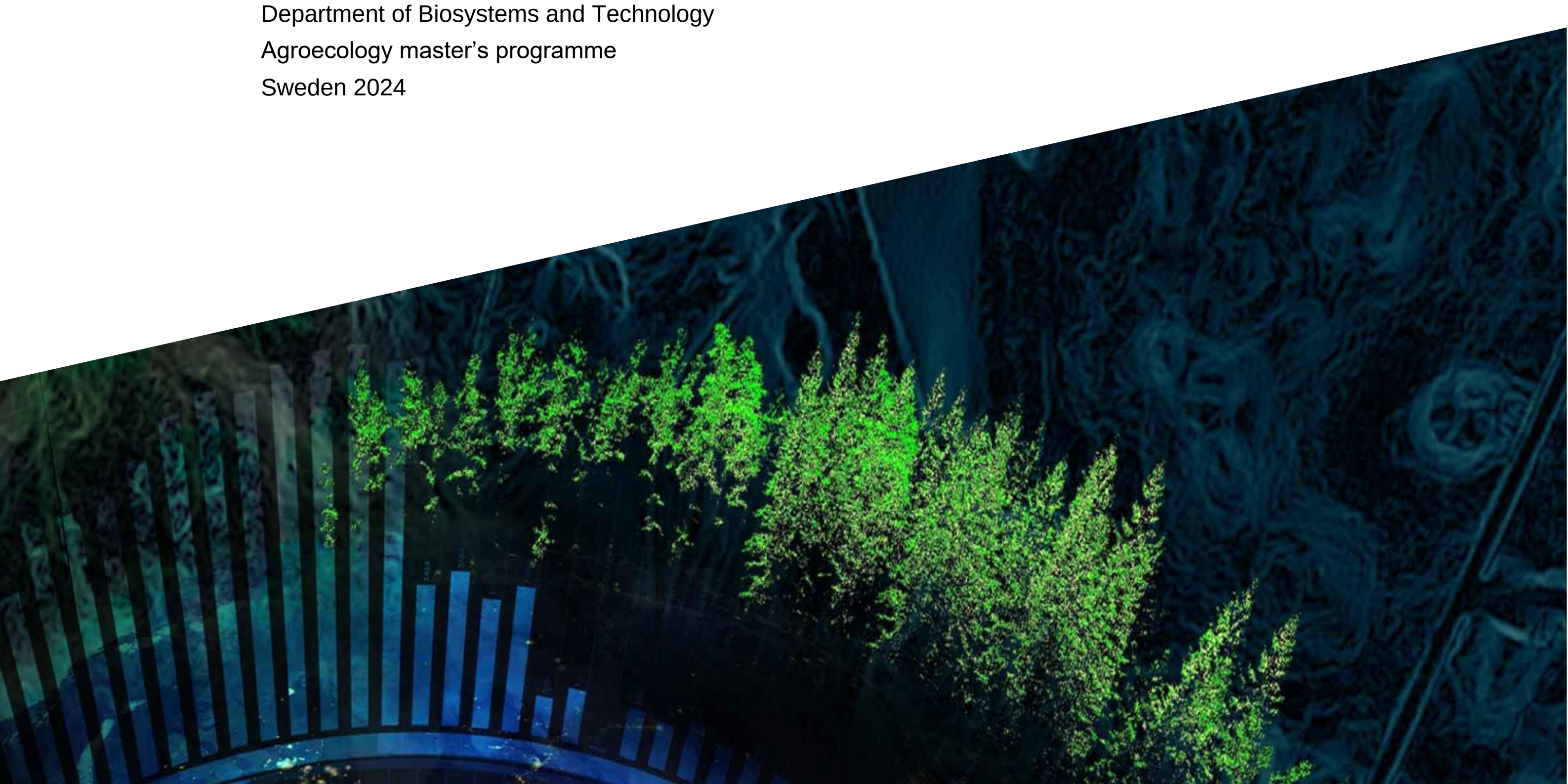

The effects of coastal artificial reefs on biodiversity, aquatic food security and ecosystem services

Effekter av kustnära artificiella rev på biodiversitet, akvatisk matsäkerhet och ekosystemtjänster

Verity Swift

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Foreword

The challenge of ensuring aquatic food security is a prime example of a wicked problem in that it involves the environmental health of one of the planet's largest ecosystems, concerns many industries and stakeholders, affects the whole of society and has no clear solution. This kind of broad problem fits well into an agroecological approach which takes a wide view of the entire ecosystem and strives to achieve social and environmental sustainability alongside economic. This independent project focused on the contributions artificial reefs can make towards supporting aquatic food security and how this security connects to biodiversity and ecosystem services.

Artificial reefs are an interesting topic as they are at the juxtaposition between the manmade and natural worlds. Conservation efforts are crucial in these current times to combat the damage to the environment and our food systems caused by anthropogenic activities. Usually, focus is primarily on terrestrial systems and land based agriculture but it is not possible to establish a truly sustainable food system without factoring in the health and contribution to nutrition provided by the aquatic ecosystems which cover the bulk of this planet.

During this independent project, my knowledge of marine species increased exponentially and it was engaging to try and tackle the different challenges that arose throughout the project's duration. This project required adaptability to changing weather conditions, ingenuity of equipment use and would not have been possible without the help and support of both supervisors, particularly during the fieldwork week. However, the results of this project only provide a snapshot in time of the artificial reefs. As such, it would be interesting to follow them across more years to track what benefits they may bring to both the local citizens of Helsingborg and the wider marine ecosystem.

It is my hope that this project can help demonstrate the link between small scale conservation efforts, global food security and other ecosystem services. I also hope to encourage consideration of aquatic food systems alongside the terrestrial as this is crucial for preserving environmental health and ensuring a nutritionally secure future for society.

Abstract

Aquatic food security relies on balancing the continual need for aquatic food provisioning and ecosystem services alongside the preservation of biodiversity and ecosystem health. This independent project aimed to establish whether the addition of coastal artificial reefs to an urban harbour area in Helsingborg had the potential to improve biodiversity, food provisioning and ecosystem services. Three sites were analysed: a stone reef, a living seawall and a floating mussel colony platform. All three sites were filmed in early April 2024 using a waterproof GoPro camera and samples of both macroalgae and blue mussels were collected for further analysis. Additionally, a survey was made available for one month; this aimed to ascertain how local residents and workers felt about the installation of these artificial reef structures. The artificial reefs were shown to support biodiversity via the provision of habitat for mobile species and attachment points for sessile fauna and flora. Both the stone reef and living seawall had greater species richness and a denser coverage of vegetation than was recorded during a similar inventory in April 2023 (Looström *et al.* 2023). Mussel size was affected by sampling depth, site and age but less so by type of hard substrate. The survey results showed that the citizens of Helsingborg appreciate the presence of the artificial reefs and placed the highest value on the potential benefits to food security over both ecosystem services and biodiversity. Overall, the data supports the hypotheses that artificial reefs can help to improve biodiversity, aquatic food security and ecosystem services, even within urban environments.

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Abbreviations

FAO	The Food and Agriculture Organisation of the United Nations
GDPR	General Data Protection Regulation
HELCOM	Helsinki Commission (also known as The Baltic Marine Environment Protection Commission)
OSPAR	Oslo and Paris Convention for the Protection of the Marine Environment of the North-East Atlantic
Q4	Question four
QR code	Quick-response code
SDGs	Sustainable Development Goals
SLU	Swedish University of Agricultural Sciences

1. Introduction

Aquatic foods

Aquatic foods, also known as blue foods, have been an important nutritional component of the human diet for thousands of years and are an ingrained part of many cultures across the world (Cresson *et al.* 2014; Jennings *et al.* 2016; Golden *et al.* 2021a; Naylor *et al.* 2021). Currently, 17% of the protein consumed globally comes from aquatic sources with harvest predicted to reach 204 million tons annually by 2030 (FAO 2018; WorldFish *et al.* 2020). These foods may be wild-caught or farmed and from marine, inland or coastal sources (WorldFish *et al.* 2020; Golden *et al.* 2021a; Naylor *et al.* 2021). Although often collectively referred to as 'fish' or 'seafood', the range of aquatic foods is diverse and includes plants, animals such as fish, cephalopods, crustaceans and molluscs; algae, microorganisms and both plant- and cell-based foods of aquatic origin (WorldFish *et al.* 2020; Golden *et al.* 2021a). With over 3700 different taxa of aquatic food identified, this food category has the potential to provide a myriad of nutrients to the human population (Gephart *et al.* 2021; Golden *et al.* 2021a; Golden *et al.* 2021b). When compared in terms of nutrient richness, the top seven categories of foods derived from animal sources are all of aquatic origin; these include the commonly eaten categories of salmonids, pelagic fish and bivalves, all ahead of the first terrestrial animal (cattle) in eighth position (Golden *et al.* 2021a). Additionally, it has been shown that eating more foods from aquatic sources has the potential to reduce the micronutrient deficiencies which affect around 30% of the global population (FAO 2018; Mannar *et al.* 2020; WorldFish *et al.* 2020; Golden *et al.* 2021a; Naylor *et al.* 2021; Thilsted 2021; Zhao *et al.* 2024). Along with the provision of essential fatty acids, the addition of aquatic foods into a meal has been shown to increase the bioavailability of plant-based nutrients (Thilsted 2021). This demonstrates just how vital a dietary component aquatic foods are and the impact they can have as a nutrition source globally.

With the total ocean economy, including fisheries, tourism and shipping, worth in excess of 24 trillion USD, the need for long-term planning and cooperation between these different aspects of blue industry is vital for the continued success of water based businesses; otherwise environmental impacts and resource depletion may render these industries untenable (WorldFish *et al.* 2020). An estimated 1.5 billion people derive their income from working in the aquatic foods industry (WorldFish *et al.* 2020). However, this is not always within large commercial enterprises; 50% of the total catch globally comes from small-scale fisheries on which 800 million people, predominantly in the Global South, rely for their livelihoods (WorldFish *et al.* 2020). Aquatic products remain one of the top commodities traded globally with newer innovations such as the plant- and cell- based sectors predicted to reach a market value of 70 million USD by 2030 (WorldFish *et al.* 2020; Naylor *et al.* 2021; Zhao *et al.* 2024). The sheer scale of the continually expanding aquatic food industry gives it widespread influence over societies, economies, public health and nutrition, and the climate and environment worldwide (WorldFish *et al.* 2020; Naylor *et al.* 2021).

However, aquatic foods are under threat; due to inadequate management of habitats and resources, many marine and freshwater fish are increasingly at risk of extinction on global, regional or even local scales (Arthington *et al.* 2016). Aquatic foods remain frequently overlooked by policymakers who generally target terrestrial foods when attempting to improve human nutrition and reduce the impacts of food production (WorldFish *et al.* 2020; Golden *et al.* 2021a; Naylor *et al.* 2021). Aquatic food security may be defined as having sufficient supply to meet the nutritional needs of the population, now and in the future, originating from a resilient system with minimal risks posed to the health and welfare of the animals, environment and people involved (Jennings *et al.* 2016). Secure production should also take the sustainability of multiple aspects into consideration; for example, working conditions should be socially acceptable, businesses financially viable and the ecosystem able to provide the necessary quantities of a diverse range of produce without compromising other ecosystem services (Jennings *et al.* 2016; WorldFish *et al.* 2020; Golden *et al.* 2021a). However, there is wide variation in the management of these social, environmental and economic aspects between the wild-capture and aquaculture sectors, and the challenge of sustaining the supply of aquatic food in the face of an ever increasing global population is one currently without a clear solution (Jennings *et al.* 2016; Springmann *et al.* 2018; Golden *et al.* 2021a; Kuempel *et al.* 2021).

Pressures on coastal ecosystems

The main challenges threatening aquatic systems include climate change, over-exploitation by the fishing industry, invasive and non-indigenous species, pollution and habitat loss or degradation (Pauly *et al.* 1998; Cresson *et al.* 2014; Arthington *et al.* 2016; Loch *et al.* 2020; Zhao *et al.* 2024). Furthermore, habitat loss, invasive species and climate change are all direct threats to biodiversity in their own right (Kuussaari *et al.* 2009). At the start of this decade, only 66% of global fish stocks were deemed biologically sustainable, a sharp decrease from 90% in the 1990s (WorldFish *et al.* 2020). The overfishing of larger species is providing a selection pressure for more smaller individuals which increases competition and reduces the biomass available for food provisioning (Pauly *et al.* 1998). The overfishing of some fish stocks is considered irreversible where populations have become locally extinct resulting in only remnants of once widespread species (Le Pape *et al.* 2017; Angelini 2019). Whilst larger species are declining predominantly as a result of overfishing, species of all sizes are also at risk from the absence of suitable habitats for feeding and breeding or due to the lack of migration corridors to enable fish species to reach the necessary sites (Arthington *et al.* 2016).

Non-indigenous species, such as the round goby (*Neogobius melanostomus*), can also put further pressure on marine organisms through predation and competition, disease or parasite transfer and hybridisation (Ruiz *et al.* 1999; Arthington *et al.* 2016). Furthermore, a huge variety of pollutants act as a similar stressor for marine species; these may be physical (plastics), thermal (heated industrial waste), acidifying (carbon dioxide) or chemical (pharmaceuticals and other toxicants) and can negatively affect the water quality for native marine species (Arthington *et al.* 2016; National Geographic Society 2024).

However, the main problem on which this report will focus is habitat loss which is a major issue affecting aquatic biodiversity and hence many ecosystem services, including the potential for food provisioning (Loch *et al.* 2020). Whilst fish constitute over half the vertebrate biomass in aquatic systems, other species important for food provisioning, such as shellfish and macroalgae, are also declining due to the negative effect of human activities on habitat availability in coastal regions (Arthington *et al.* 2016; Wilms *et al.* 2021). Alongside coastal degradation, there is an associated decline of crucial ecosystem services such as carbon sequestration, oxygen production and income generation (WorldFish *et al.* 2020). For example, seagrass meadows, which can sequester carbon with greater speed and efficiency than terrestrial forests, are in decline globally (Arthington *et al.* 2016; WorldFish *et al.* 2020).

It is estimated that 75% of the global population will live within 100miles of the coast by 2025 (WorldFish *et al.* 2020). Due to this high proportion of human inhabitants along coastlines, natural aquatic habitats are frequently converted into harbours or other residential or commercial structures (Rönnbäck *et al.* 2007; Arthington *et al.* 2016; Loch *et al.* 2020). This is a serious problem as shallow coastal bays act as nursery areas for many marine species (Kilfoyle *et al.* 2013; Eklöf *et al.* 2020). After such an anthropogenic environmental disturbance, the naturally occurring ecosystem may be completely lost; however, if only partially lost, the abundance and proportion of species remaining will reach a new equilibrium within the altered habitat, often with reduced biodiversity (Kuussaari *et al.* 2009; Arthington *et al.* 2016).

An important challenge when attempting to achieve sustainable management of marine resources is to balance the preservation of biodiversity alongside the continual provision of the goods and services, derived from healthy marine ecosystems, on which humans rely (Arthington *et al.* 2016). The European Commission prioritises food security and sustainable resource use as part of their Bioeconomy Strategy and acknowledges the need to learn more about the ecosystems and biodiversity found in coastal areas (European Commission 2020). Furthermore, the European Green Deal advocates for the development of a sustainable blue economy through the reduction of pollution, mitigation of climate change and the preservation of both biodiversity and aquatic food security (European Commission 2021a). The blue bioeconomy in particular is reliant on the continued availability of aquatic resources for use in the food, pharmaceutical and chemical industries to give some examples (European Commission 2022). As such, preserving the health of the marine environment is of paramount importance.

The Baltic Sea

The Baltic Sea, the largest brackish waterbody in the world, is epicontinental, consisting of multiple subbasins with an average depth of 55m and spanning 393,000km^2 (Elmgren *et al.* 2015; Kaskela & Kotilainen 2017; Liénart *et al.* 2021). It is largely tideless meaning its limited water exchange with the North Sea predominantly occurs in the Danish Straits, including the Kattegat and Öresund (Miller 1974; Kaskela & Kotilainen 2017). Water exchange is facilitated by changes in wind and air pressure, and is important for long-term changes in temperature, oxygenation and salinity (Medvedev *et al.* 2013; Kaskela & Kotilainen 2017; Snoeijs-Leijonmalm & Andrén 2017).

The coastal habitats of the Baltic Sea, in particular, have been severely degraded by pollution, eutrophication and over-exploitation of resources (Miller 1974; Korpinen *et al.* 2012; Franz *et al.* 2019; Liénart *et al.* 2021; Wilms *et al.* 2021). The rapid decline of seagrass (*Zostera sp.*), which grows worldwide in shallow, brackish waters, is negatively affecting the abundance of many Baltic marine organisms that rely on seagrass during at least one life cycle stage (Arthington *et al.* 2016). The abundance of blue mussels (*Mytilus edulis*) has also been declining in western Sweden (Christie *et al.* 2020). Persistent overfishing of predators from the upper trophic levels has led, via cascade effects, to a population increase amongst mesopredators, such as the goldsinny wrasse (*Ctenolabrus rupestris*) and the green shore crab (*Carcinus maenas*), both of which predate upon blue mussels in coastal stone reefs (Christie *et al.* 2020). Another mesopredator, the stickleback (*Gasterosteus aculeatus*), is causing problems in coastal regions of the western Baltic by triggering regime shifts from predator- to prey-dominated ecosystems; this results in eutrophication-like effects such as algal blooms, leading to habitat degradation and further threatening aquatic food security (Eklöf *et al.* 2020).

The seabed of the Baltic is predominantly homogenous mud or sandy mud but this smooth topography is interspersed with large boulders from former glacial erosion (Miller 1974; Kaskela & Kotilainen 2017; Wilms *et al.* 2021). In the Öresund Strait, these rocks are predominantly sandstone, a sedimentary rock formed from compacted sand, which lie on a flat sandy mud surface (Kaskela & Kotilainen 2017). These sandstone boulders form local stone reef systems on which macroalgae and other sessile fauna, such as mussels, can anchor (Wilms *et al.* 2021). Additionally, the spaces between the boulders offer habitat and shelter for other marine species including those at lower trophic levels and more vulnerable life stages such as juveniles (Cresson *et al.* 2014; Wilms *et al.* 2021).

In the southwestern Baltic Sea, these boulders have been extracted from the seabed for over a century in order to build harbour jetties, sea defences and other coastal developments (Fabi *et al.* 2011; Støttrup *et al.* 2014; Wilms *et al.* 2021). These activities degraded areas which were formerly stone reefs and of critical importance for many species, including commercially valuable ones such as gadoids (Wilms *et al.* 2021).

Artificial reefs

Ecological restoration is one means by which to improve biodiversity whilst preserving food security and maintaining human health and wellbeing (Gann *et al.* 2019). In a 2020 literature review, Loch *et al.* demonstrated that global restoration efforts in coastal regions have predominantly focused on wetlands (55%) but a significant percentage (19%) of restoration measures have involved artificial reefs (Loch *et al.* 2020). Artificial reefs are an example of blue-green infrastructure, which may be used as part of integrated management plans for coastal zones (Fabi *et al.* 2011). Green infrastructure can be used to promote multifunctionality and utilises bio-inclusive designs to protect and enhance both nature and natural processes in order to deliver benefits in the form of ecosystem services to society (European Environment

Agency 2021); the 'blue' element simply refers to the establishment of green infrastructure in water. Whilst this differs from traditional restoration ecology, which aims to return a site to its natural state from before a disturbance, both approaches seek to restore ecosystem services and biodiversity that were lost as the habitat degraded (Cresson *et al.* 2014; Loch *et al.* 2020).

Attracting fish through the use of artificial structures is a practice that dates back around 3000 years to tuna (*Thunnus* thynnus) fishing in the Mediterranean Sea (Riggio *et al.* 2000; Fabi *et al.* 2011). Rocks that were used to anchor fishing nets were left on the seabed at the end of each season and began to accumulate forming rocky habitats; the species colonising these new areas were then harvested by fishers outside of the tuna season (Riggio *et al.* 2000; Fabi *et al.* 2011). Whilst this concept spread to Asia and the USA during the mid-1600s and the early 1800s respectively, the notion of installing artificial reefs had limited uptake in Europe until the 1950s (Fabi *et al.* 2011). Subsequently, the use of artificial reefs has been steadily increasing in Europe since the 1970s with those installed in the Mediterranean primarily aiming to enhance fish stocks whilst those in northern Europe were targeted more towards research, restoration of natural habitats and recreation (Fabi *et al.* 2011). However, as of 2011, there were still very few artificial reefs in the Baltic Sea region but those present were installed as an aid to reducing, through biofiltration, the eutrophication and pollution resulting from food production and other industries (Fabi *et al.* 2011).

Artificial reefs may be defined as deliberately submerged structures which mimic characteristics of natural reef systems (Fabi *et al.* 2011; Cresson *et al.* 2014). Boulders, or boulder-like substrates, are frequently being utilised to augment seawalls or to restore stone reef systems (Loch *et al.* 2020; Wilms *et al.* 2021). In the Baltic Sea region, these reefs are regulated under the Helsinki Convention which protects the marine environment in the Baltic and prohibits the 'dumping' of unsuitable or pollutant materials during the formation of an artificial reef (HELCOM 2014). These structures initially recruit benthic species but can come to support entire trophic networks over time as food resources generated by the reef begin to help sustain predatory fish in the upper trophic levels (Cresson *et al.* 2014; Loch *et al.* 2020). Artificial reef structures have been shown to have lower species richness but may support a higher total biomass when compared to natural reef systems (Simon *et al.* 2013; Loch *et al.* 2020). Artificial reefs may be established for a variety of reasons including protection against trawling, to support small scale fisheries, for ecosystem restoration, for research or to promote tourism and other leisure activities (Fabi *et al.* 2011; Cresson *et al.* 2014).

The restoration of lost stone reefs, and therefore the volume of hard substrate in the Baltic Sea basin, has been shown to have positive impacts at large scale but significantly more so at small scale sites (Wilms *et al.* 2021). The spatial arrangement of the stone reef was shown to have the greatest effect on species recruitment post-restoration, particularly amongst small-bodied mesopredators (Wilms *et al.* 2021). Restoring stone reefs has been shown to strongly increase, for example, the abundance of gadoids, such as Atlantic cod (*Gadus morhua*), which have been over-exploited, and could therefore support top-down controls by predatory fish even in degraded aquatic systems like the Baltic Sea (Wilms *et al.* 2021).

Helsingborg

Helsingborg, a city on the southwest coast of Sweden, is known for its large harbour in the Öresund Strait. The City of Helsingborg, in response to the degradation of natural marine habitats and in alignment with Sustainable Development Goal (SDG) 14 'Life below water', developed the stone reef and living seawall projects in the Oceanhamnen area of Helsingborg harbour (Bertilsson Vuksan 2022; United Nations 2024a). The vision of the city's Environmental Strategists prioritises cleaner waters, more biodiversity within the harbour and a closer connection between the local populace and the Baltic Sea (Bertilsson Vuksan 2022; Centre 2023). The installation of the stone reef established a 'green area' within the harbour basin and the outer harbour wall was adapted into a living seawall, initially with the installation of 30 reef panels which has since expanded to 62 (Bertilsson Vuksan 2022). A floating platform was also installed to facilitate mussel cultivation with the aim of establishing if blue mussels could be successfully cultivated within an urban harbour setting (Helsingborg 2023).

The purpose of this independent project was to study how implementing blue-green infrastructure, in this case coastal artificial reefs, might affect biodiversity, aquatic food security and ecosystem services. The research focused on the artificial reef projects in Helsingborg harbour and aimed to establish which species were using the artificial reefs, including edible species, and to determine the views of local people regarding these projects via a survey. Furthermore, this project aimed to assess the natural science data obtained alongside the societal perspectives gleaned from the survey in order to gain a more holistic understanding of the effects of coastal restoration through artificial reefs in Helsingborg.

1.1 Objective

The objective of this independent project was to establish whether the addition of coastal artificial reefs in Helsingborg harbour had improved biodiversity, food provisioning and ecosystem services.

1.2 Hypotheses

Hypothesis 1: Artificial reefs have the potential to improve biodiversity in comparison to areas of marine disturbance without conservation efforts.

Hypothesis 2: Artificial reefs have the potential to increase food security relating to aquatic foods.

Hypothesis 3: Artificial reefs have the potential to increase ecosystem services for the local community.

1.3 Research questions

1. What changes can be seen in year two post-installation in comparison to the year one survey in terms of species present and density of reef coverage?

2. What differences can be seen in the blue mussel population between the different reef types and the adjoining non-enhanced areas?

3. How do people who live in and work in the area view the installation of the artificial reefs?

2. Method

2.1 Study area

The study took place in the Oceanhamnen area of Helsingborg. Helsingborg is an important shipping port for Sweden and is located in the Öresund Strait which extends between the Kattegat and the Baltic Proper. Formerly a shipyard, Oceanhamnen is under development by the City of Helsingborg into residential housing and offices alongside sustainable marine developments. External funding was secured by the City of Helsingborg via a 'Särskild fiskeavgift' or fisheries fee; this is a compensation fund set up to mitigate the negative impact on fisheries due to coastal development projects. This fund is used to enhance and support coastal habitats and a grant was given to the City of Helsingborg to facilitate the artificial reef installation.

Water channels were opened in 2020 to improve water quality and circulation in the area. Boulders were installed to form a stone reef and panels were installed on the vertical outer harbour wall to create a living seawall. Both the stone reef and living seawall were installed in April 2022 and the living seawall was further expanded in July 2023. An inventory of the stone reef and living seawall was carried out in April 2023 (Looström *et al.* 2023). Additionally, a floating platform was installed in the shallow harbour in June 2023 to allow for the cultivation of blue mussels.

The installation of the artificial reef structures occurred within the North Sea marine region as defined by the EU Marine Strategy Framework Directive and within the Baltic Sea region as defined by the Helsinki Convention (HELCOM 2014; European Commission 2021b). Installation fell under Action B26 of the Baltic Sea Action Plan and choice of construction materials was regulated under the OSPAR Convention as well as by the Helsinki Convention (HELCOM 2014; HELCOM 2021; OSPAR 2024).

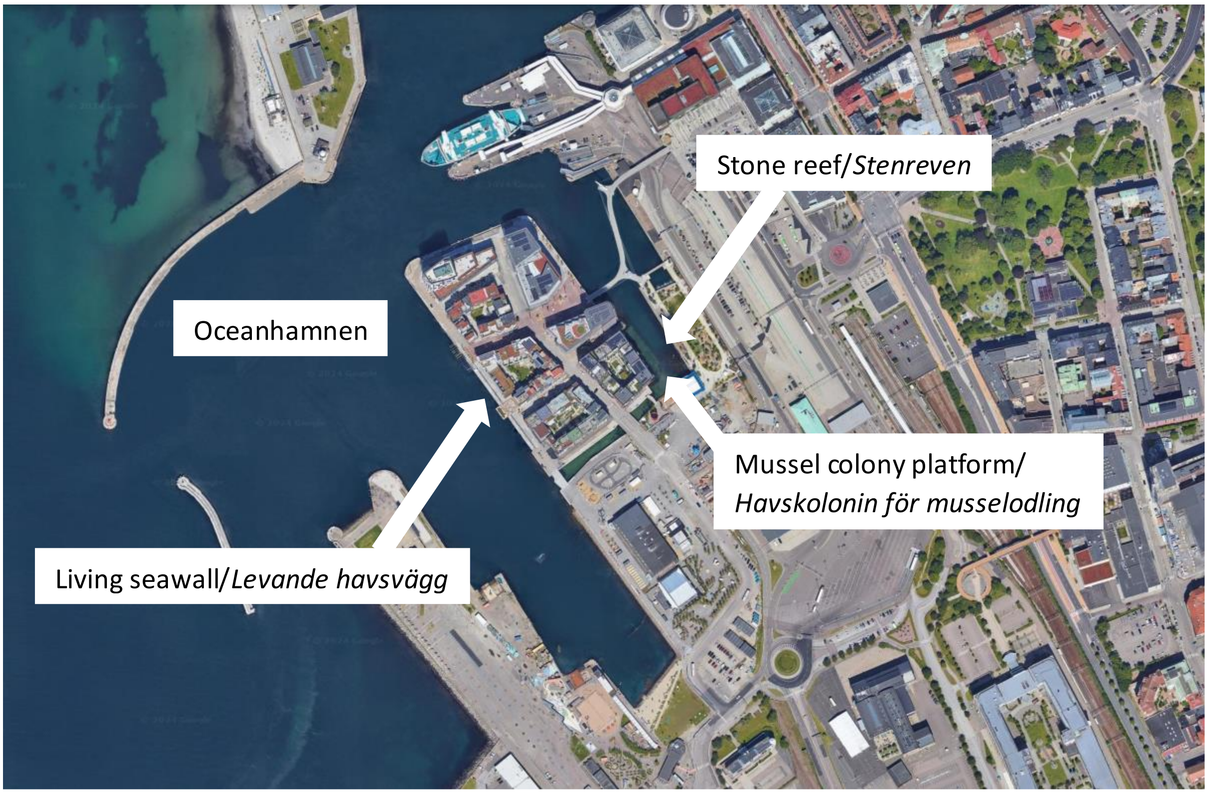

Figure 1. Image taken from Google Earth (2022) annotated to show the location of the stone reef, living seawall and mussel colony platform in Oceanhamnen.

The location of the stone reef, living seawall and floating platform within Oceanhamnen can be seen above in Figure 1.

Figure 2. The stone reef in Oceanhamnen. Photo credit (Bertilsson Vuksan 2022).

The stone reef is located in a shallow, sheltered harbour which was formerly a dry dock. As can be seen in Figure 2, the boulders which make up the stone reef are of various sizes and cover an area approximately 35m by 20m. The depth of the stone reef extends from above the surface to around three metres deep.

Figure 3. The above water section of the living seawall. Photo credit (Bertilsson Vuksan 2022).

The living seawall is 15m in length, extends from above the waterline to 5m depth and consists of differently shaped panel structures composed of concrete, ceramic and steel. The living seawall does not extend the full depth of the harbour wall which is as deep as 7-9m. These panels are mounted on the main harbourfront where boats formerly docked. As can be seen in Figure 3 above, the shape of these installations varies between round panels, kelp-shaped and S-shaped. The crevices in the panels are designed to provide microhabitats with additional shade and protection (Strain *et al.* 2017).

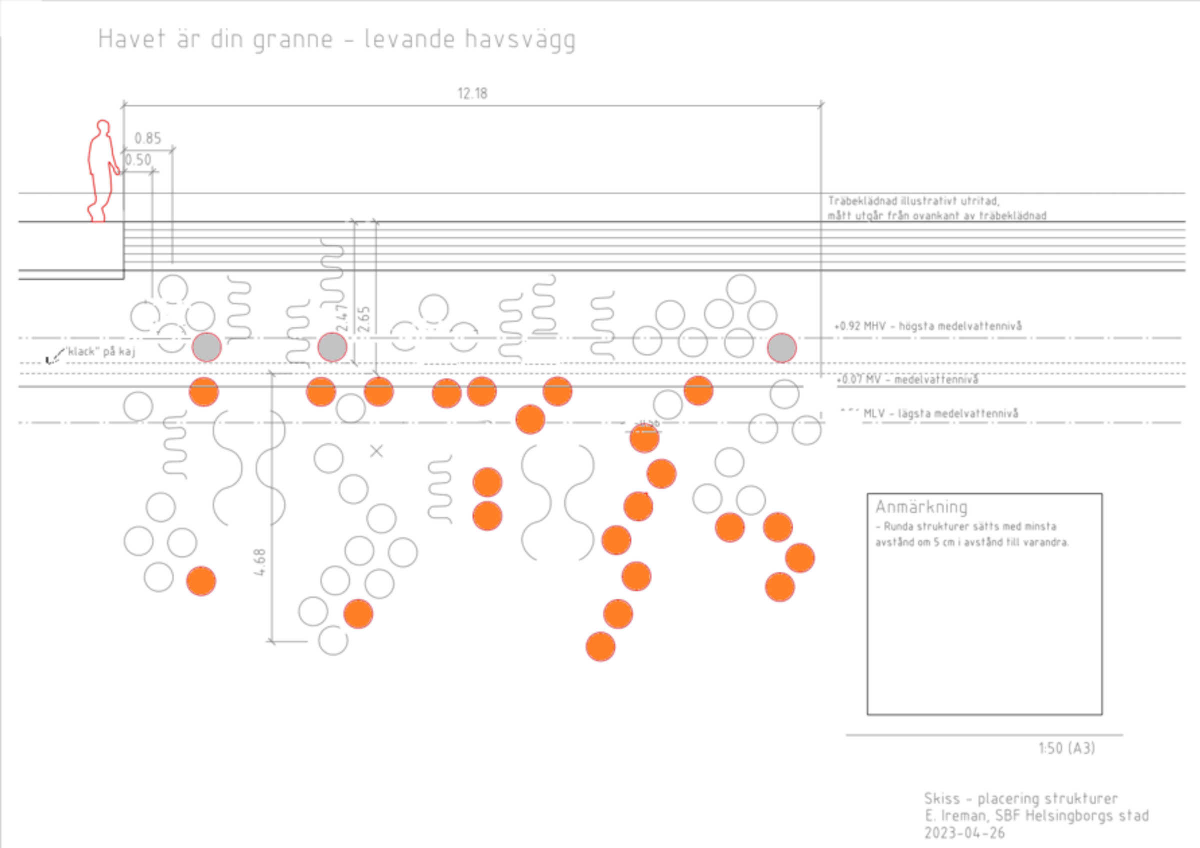

Figure 4. Layout of the living seawall. Clear circles and wavy lines represent the original installation of the reef structures onto the seawall in 2022. Coloured circles represent the expansion of the seawall in 2023. Image credit S. Bertilsson Vuksan (City of Helsingborg).

Figure 4 shows the current layout of the artificial reef structures along the 15m stretch of the living seawall. The newer reef structures installed in 2023 were set a further 10cm out from the seawall in order to create a more dynamic underwater environment.

Figure 5. Mussel nets hanging from the floating platform in Oceanhamnen. Photo credit Ingvar Eliasson (Centre 2023).

The mussel colony is located beneath a floating wooden platform which is anchored in close proximity to the stone reef (Figure 5). Mussels were collected from around the Öresund and attached to the 50 cultivation nets which hang from the platform (Centre 2023; Helsingborg 2023). This blue mussel colony is currently managed by around 65 interested local citizens who keep the mussels clear of algae to facilitate better growth (Helsingborg 2023). The citizens are split into five working groups which rotate care of the mussel colony on a five-week schedule (Centre 2023). The mussels should be ready for harvest in 2025 (Centre 2023). All three of these marine projects aim to raise awareness about ocean health amongst the local community in Helsingborg (Helsingborg 2023).

Helsingborg is in the Öresund Strait and so the artificial reefs are affected by both salt water from the North Sea via the Kattegat and brackish water from the Baltic Sea. Salinity in the Öresund varies between 8 and 20ppt (Rönnbäck *et al.* 2007). There was no freshwater output from the city into Oceanhamnen at the time of sampling. As all three artificial reef sites are in close proximity within the same water body, conditions such as salinity, temperature, water current and weather were consistent across all three sites.

2.2 Fieldwork

In order to investigate if artificial reefs can improve biodiversity, fieldwork was carried out in the first week of April in order to facilitate direct comparison to the inventory data collected during a similar assessment of the stone reef and living seawall by Looström *et al.* in early April 2023 on behalf of the City of Helsingborg. Differences in species composition and the density of reef coverage were assessed.

During fieldwork, the artificial reefs were evaluated using a waterproof GoPro camera. The original plan was to obtain all the camera footage and samples via snorkelling. However, during the fieldwork window, the water temperature was around 7°C, the air temperature around 3.5°C and it both snowed and rained. As such, the decision was taken to minimise time spent in the water and all the transect footage and some samples were obtained from a small raft. On the raft, the camera was both handheld for shallow transects and mounted on a pole of 4.3m in length for deeper transects and drop videos. The camera was handheld during snorkelling and a mixture of snorkelling and free diving was used to collect samples that could not be reached from the boat. In the case of the living seawall, conditions meant that it was unsafe to dive beneath the surface due to the size of the swell, proximity to the concrete seawall overhang and protruding structures, high mobility of the safety boat and poor visibility below the surface due to high turbidity in the water. As such, all samples obtained from the living seawall and living seawall control were gleaned either from within the boat or within arm's reach of the snorkeller.

To undertake the inventory of the stone reef, three transect lines were followed perpendicularly from the wharf, one centrally and one either side of the central line between the centre and outer edge of the reef; these transects extended as far as the visible periphery of the stone reef and had at least two repeats. An additional two transects were assessed parallel to the wharf, the first across the centre of the reef and the second just beyond the furthest reef edge from the wharf. The central cross-section had two repeats and the periphery only one as this tract assessed the seabed beyond the reef as a control. Additionally, the camera was mounted onto a long pole and used to film ten drop videos to gain longer, more static footage from across the stone reef. In order to do this, the pole on which the camera was mounted was lowered 1m at a time and held for 30seconds at each depth until either the seabed was reached or 4m depth. The drop videos were taken at intervals along the transect lines, four along the central transect line parallel to the wharf and two on each of the three perpendicular transect lines (one on each side of the parallel transect). These videos were taken at irregular intervals due to drift caused by currents from ferries docking nearby. The video data from the transects and the drop videos was assessed in parallel to increase the accuracy of the inventory. The weather remained consistent throughout filming.

The inventory of the living seawall included, as described above, horizontal transects of 15m length at 0m, 1m, 2m and 3m depth from the surface. It was not possible to obtain a transect at 4m depth due to the difficulty of keeping the camera pole vertical from a moving raft at this depth. A horizontal transect was also undertaken above the waterline as the waterline was around half a metre lower than usual, exposing an area that would normally be submerged. These transects were all extended along the next 15m of non-augmented seawall thereby serving as a control site for comparison. The mounted camera was also used to take drop videos down to a depth of 4m. As above, all footage was analysed and the results were compared against the data from the 2023 survey to assess what species were present at each site and how dense the coverage of the artificial reefs was (Looström *et al.* 2023).

Further drop videos were taken from the mussel colony platform down to a depth of 2m. One video was taken from each side of the platform and an additional video was taken of the adjacent dockside wall as a control.

Photo stills were taken from the videos to document the reef coverage, species present and other areas of interest. These stills were assessed and compared to a report based on the 2023 inventory of the reefs (Looström *et al.* 2023). Permission to use the raw data from the 2023 survey was granted by S. Bertilsson Vuksan from the City of Helsingborg. The results were also compared to corresponding areas of shallow harbour and seawall without artificial reefs in place. The aim of collecting this type of data was to facilitate before-after-control-impact performance monitoring (Kerr *et al.* 2019).

In addition, three static films of five minutes duration were made in the morning, afternoon and evening at the stone reef and living seawall. These films were made to look for fish species that may have hidden from a boat or snorkeller. There is a pre-existing static camera installed on the living seawall which was used to survey this area whilst the GoPro camera was lowered and held stationary at the stone reef site to acquire comparable footage.

Filming was chosen for data collection as it facilitated the simultaneous collection of information on a variety of species, with reduced observer bias, over a wide area whilst forming a permanent record for later analysis (Cappo *et al.* 2003). The stills later taken from these films were selected to try and give an overview of key points from footage.

To supplement the filming, samples of macroalgae were collected during the snorkelling for species identification. An entire *Fucus* macrophyte was also collected from the stone reef so that any associated animal or plant species could be assessed. A minimum of 30 blue mussels were also collected from the artificial reef sites to assess mussel size. Additionally, mussels were collected from the dockside wall next to the stone reef and from the seawall adjacent to the living seawall to serve as control samples.

2.3 Laboratory work

The laboratory work aimed to establish if artificial reefs can improve food security and also to aid the inventory work for the assessment of biodiversity. Macroalgal species were identified visually and via microscopy with additional aid from a compendium (Rueness 1998). Other species were identified using prior knowledge, with assistance from an Environmental Strategist (S. Bertilsson Vuksan), and by using further small species guides (Stockholms Universitet 2005; Naturskyddsföreningen 2022b; Naturskyddsföreningen 2022a) and other hand-drawn identification charts belonging to the City of Helsingborg.

The length and width of each mussel collected was measured using a standard ruler and compared across sites and control areas. The mussels from the mussel colony platform were measured in situ whereas the mussel samples from the other sites were measured in the laboratory. All mussel samples were later compared to a pre-existing frozen sample of mussels (dockside control), retained by the City of Helsingborg from a previous study, to facilitate a comparison of mussel size at greater depth; these mussels were taken from a deeper section of the dockside wall surrounding the stone reef. All living samples were later returned to the water after processing.

In order to test for statistically significant differences in mussel size between the sites, multiple t-tests were carried out using Microsoft Excel to directly compare every mussel sample against the mussel sample of every other site. As each sample of mussels was measured only once resulting in unpaired data, an independent samples t-test was chosen with the null hypothesis assuming that both the datasets assessed in each t-test were the same (Dytham 2017). This type of t-test was deemed appropriate as the datasets were continuous and had approximately normal distribution and homogenous variances (Dytham 2017).

2.4 Survey

A survey was carried out to augment the biophysical data. The aim of the survey was to establish whether local people appreciate the artificial reefs, whether the presence of the reefs has increased their awareness of biodiversity, whether local fishing is occurring and to ascertain whether any ecosystem services have been enhanced by the presence of the artificial reefs. This survey was constructed using Netigate and consisted of General Data Protection Regulation (GDPR) information (Appendix 1), a short introduction and some general questions followed by the opportunity to score statements relating to biodiversity, food security and ecosystem services, and closed with an opportunity to provide feedback (Appendix 2).

The survey was issued to three target groups in both Swedish and English. These groups included [1]residents of a local apartment building within the project circumference (Ophelias Brygga), [2]people working in a local office building adjacent to the apartment building (GreenHaus Castellum, includes the office of the City of Helsingborg) and [3]the local citizens already participating in the project to cultivate blue mussels on the floating platform (Havskoloni). In total, the survey was sent out to an estimated 360 participants (~70 in the citizen group, ~185 in the apartment building assuming more than one adult in 50% of the 124 apartments and ~105 in the office building assuming 15 staff members on each of the 7 floors). A short survey description, along with the relevant QR codes for survey access, was later displayed by both the stone reef and living seawall to allow passersby to contribute.

The survey remained available for one month. After the first two weeks, a problem was identified in the survey construction: the anonymisation process for GDPR meant that it was not possible to see which target group had given which responses within this survey, henceforth referred to as the ‘first round survey’. To counteract this, four replicate (second round) surveys were made, one each for the initial three target groups and a fourth for passersby as fieldwork was being undertaken during week three of the survey and local residents were showing interest in the project. This meant that responses in the latter two weeks of the survey were automatically separated by target group. The decision was made to replicate the new surveys in Swedish only as no respondents had attempted to answer the English version of the survey.

After the survey closed, the responses were collated; Microsoft Excel was then used to perform qualitative analyses of the results. The scoring data was also categorised into five bins (‘Strongly positive’, ‘Positive’, ‘Neutral’, ‘Negative’ and ‘Strongly negative’) in later stages for ease of comparison.

3. Results

3.1 Changes to species composition and density of reef coverage between 2023 and 2024

3.1.1 Species composition

Both the stone reef and the living seawall were fully covered by vegetation and sessile fauna in the footage from the transects and drop videos. The species identified at these sites can be seen in the tables below.

Table 1. Marine macrophyte species inventoried during the 2024 fieldwork in comparison to the data from the 2023 report of the surveillance of the stone reef and living seawall (Looström et al. 2023). Species were recorded in the table as low, moderate or high abundance to match the 2023 report. Species marked with an asterisk are non-indigenous.

			2023		2024	
Scientific name		Common name	Stone reef	Living seawall	Stone reef	Living seawall
Ulva lactuca		Sea lettuce	*		*	
Cladophora sp.		Green filamentous algae	*	**	*	*
Fucus sp.			**		**	
	Fucus evanescens*	Rockweed	**		***	
	Fucus serratus	Toothed wrack			*	
	Fucus vesiculosus	Bladderwrack	**		**	
Pilayella/Ectocarpus		Brown filamentous algae	***	***	***	***
Palmaria palmata		Dulse	*		*	
Phyllophora/coccotyllus		Red algae	*	*	*	*
Polysiphonia sp.			***	***	***	**
	Polysiphonia elongata	Banded siphon weed	**	**	**	**
	Polysiphonia fucoides	Black siphon weed	**	**	**	**
Ceramium sp.		Rosetangle	**	**	**	**
	Ceramium tenuicorne	Red hornweed	**	**	**	**
Hildenbrandia rubra		Rusty rock	*		*	
Zostera marina		Eelgrass			*	

Sixteen macrophyte taxa were identified on the stone reef and eight on the living seawall (Table 1). This is comparable to the data acquired in the 2023 survey in which the diversity of macroalgae was also higher on the stone reef (Looström *et al.* 2023). Eelgrass and *Fucus serratus* were identified as new additions to the stone reef area in 2024. The eelgrass was found on the sandy sediment between the stone reef and the mussel colony platform. It is also notable that *Fucus* species are yet to colonise the living seawall.

Table 2. Marine animal species inventoried during the 2024 fieldwork in comparison to the data from the 2023 report of the surveillance of the stone reef and living seawall (Looström et al. 2023). Species were recorded in the table as low, moderate or high abundance to match the 2023 report. Species marked with an asterisk are non-indigenous.

			2023		2024	
Scientific name		Common name	Stone reef	Living seawall	Stone reef	Living seawall
Bryozoa sp.		Moss animal	**	**	**	
	Electra crustulenta	Sea mat			**	
	Membranipora membranacea	Kelp lace			**	
Hydrozoa sp.		Hydrozoa/Hydroid	**	**	**	
	Clava multicornis	Club-headed hydroid			**	
	Cordylophora caspia*	Freshwater hydroid	**	**	**	
Porifera sp.		Sponge	**	**	*	
Idotea	Isopoda baltica	Isopod			**	
	Isopoda granulosa	Granular isopod			***	**
	Isopoda viridis	Isopod				**
	Jeara albifrons	Isopod			*	*
Amphipoda	Gammarus sp.	Amphipod			***	**
	Amphipodae indet	Amphipod			*	
Balanidae		Barnacle	**	**	***	***
Carcinus maenas		Green shore crab				*
Gastropoda	Littorina littorea	Common periwinkle			**	
	Peringia ulvae	Mud snail			**	
Mytilus edulis		Blue mussel	**	***	*	**
Syngnathus typhle		Pipefish				*
Myoxocephalus scorpius		Sculpin		*		
Gadus morhua		Atlantic cod	*			
Small fish species (various)					*	
Anatidae	Anas platyrhynchos	Mallard duck			*	
	Cygnus olor	Swan			*	
Phalacrocorax sp.		Cormorant			*	
Chironomidae larvae	Chironomidae indet	Non-biting midge			*	*

Twenty-one animal taxa were identified at the stone reef and nine at the living seawall (Table 2). These results were largely comparable between the 2023 and 2024 samples. Fish were seen visually on the stone reef but it was not possible to catch them on film for identification. A pipefish and a green shore crab were detected on the living seawall. Smaller species of gastropods, isopods, amphipods and chironomids were identified in the physical samples taken from both locations in 2024 which was beyond the scope of the 2023 inventory. The avian species recorded were all seen actively feeding at the stone reef during the fieldwork.

Plastic was also found at all sites during the sampling process.

Macrophyte-associated community assessment

A macrophyte, later identified as *Fucus serratus*, was removed in its entirety from the stone reef to see what species were using it as habitat. *Bryozoa*, *Hydrozoa* and barnacles were found to be growing directly on this macrophyte. Some blue mussels were also caught up in the sample. Multiple specimens of *Gammarus*, *Perringia*, *Littorina* and *Jeara* were found amidst the fronds. This highlights how much of the community from the stone reef inventory could be found in association with just one macrophyte.

3.1.2 Artificial reef coverage

The following section provides a visual demonstration of the biodiversity found around the artificial reefs.

Stone reef

Figure 6. Images of the stone reef. The upper image is from the 2023 report by Looström et al. (2023) and is described as depicting "boulders with heavy growth" on the stone reef. The depth at which the 2023 report image was taken was not recorded but the caption described an area of heavy growth. The lower two images are from the 2024 inventory.

Figure 6 highlights the changes in vegetation between 2023 and 2024. Whilst the depth of the image from the 2023 report was not specified, the report noted that the stone reef was completely covered in filamentous species of red and brown macroalgae with only small amounts of green macroalgae present (Looström *et al.* 2023). However, in the 2024 images, it can be seen that whilst the deeper boulders (lower left image) retained a similar species coverage to the 2023 image (uppermost), green macroalgae, namely *Fucus*, had become dominant in the shallower areas of the stone reef (lower right image).

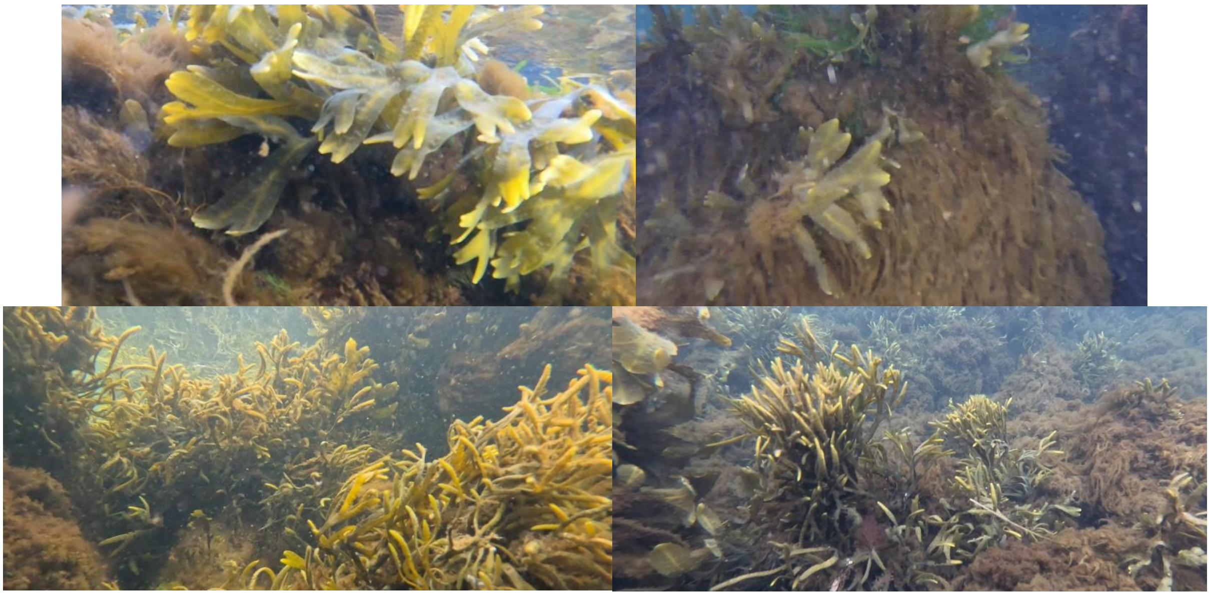

Figure 7. Fucus species on the stone reef. The upper two images are taken from the 2023 data, the lower two from 2024.

The 2024 survey of the stone reef revealed that the *Fucus* species were much larger in 2024 than was seen in 2023. This is the case in the images from both the shallower (lower left) and deeper (lower right) sections of the stone reef. As such, Figure 7 demonstrates that *Fucus* had become more established on the reef and was growing well. The 2023 report also described the stone reef as being dominated by filamentous red and brown macroalgae (Looström *et al.* 2023); this was not the case in 2024 as transects revealed that green macroalgae dominated the shallower reef areas.

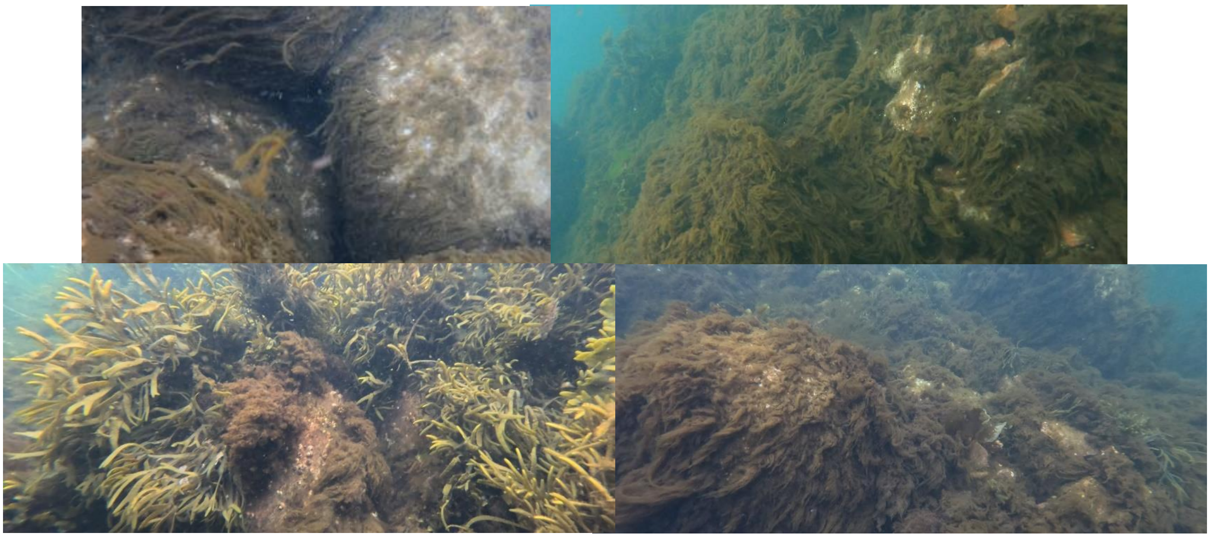

Figure 8. Exposed areas of stone reef. Upper photos from 2023 and lower from 2024.

The stone reef was well covered by vegetation. There were still a few areas where the boulders protruded in 2024 but these areas were much smaller than in 2023 (Figure 8). This indicates that more macroalgal species had attached to and were growing on the stone reef.

Figure 9. Shallower sections of the stone reef in 2023 (left) and 2024 (right).

Figure 9 illustrates how species composition altered between 2023 and 2024. *Ulva* and blue mussels were more prevalent in the shallower areas of the reef in 2023 (left). However, in 2024 the rapid growth of *Fucus* alongside other filamentous species had displaced the *Ulva* and blue mussels from the upper parts of the stone reef (right).

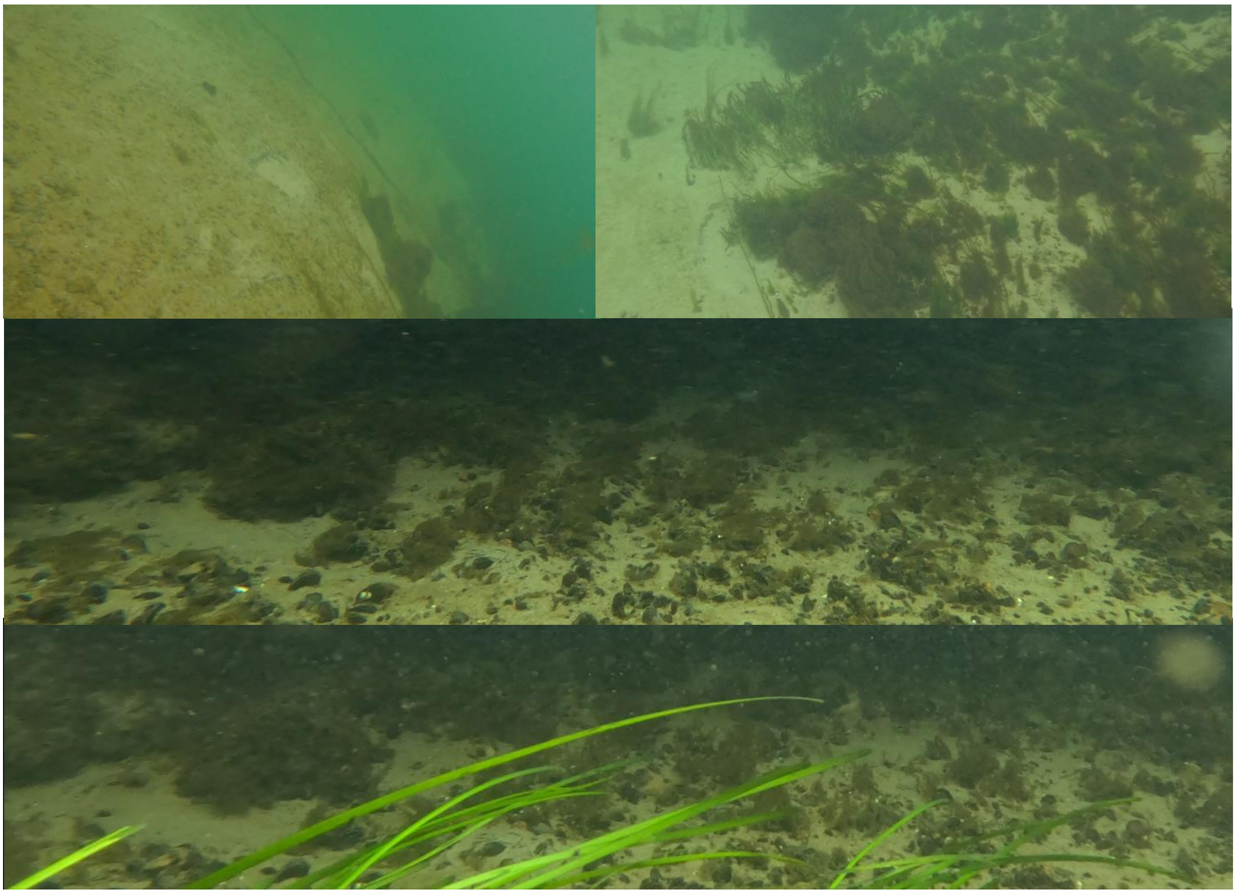

Figure 10. Harbour basin in the dock area surrounding the stone reef. The upper left image is from 2023 and the others from 2024.

The uppermost layer of the harbour basin around the stone reef consists of clay around 30cm deep which was displaced when quarry stones were installed around the dockside. In 2023, little vegetation could be seen on this substrate; however, in 2024, there was more coverage of the basin including a small area of seagrass, covering approximately 2m^2, located under the mussel colony platform (Figure 10). Additionally, substantially more macrophyte growth could be seen on the hard substrate of the stone reef than on the adjacent soft seabed which reinforces the importance of hard substrate for the attachment of sessile organisms.

Living seawall

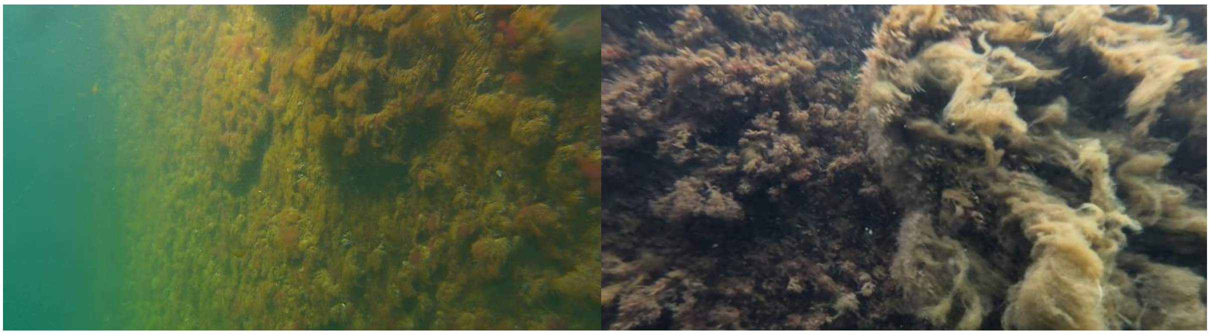

Figure 11. Panels from the living seawall in 2023 (left) and 2024 (right).

On the living seawall, coverage of the reef panels by macroalgae was more extensive in 2024 than in 2023 (Figure 11). It can also be seen in the 2023 image above (left) that the species composition of the macroalgae was very similar between the reef panels and the background harbour wall. However, greater variation can be seen in the 2024 image (right).

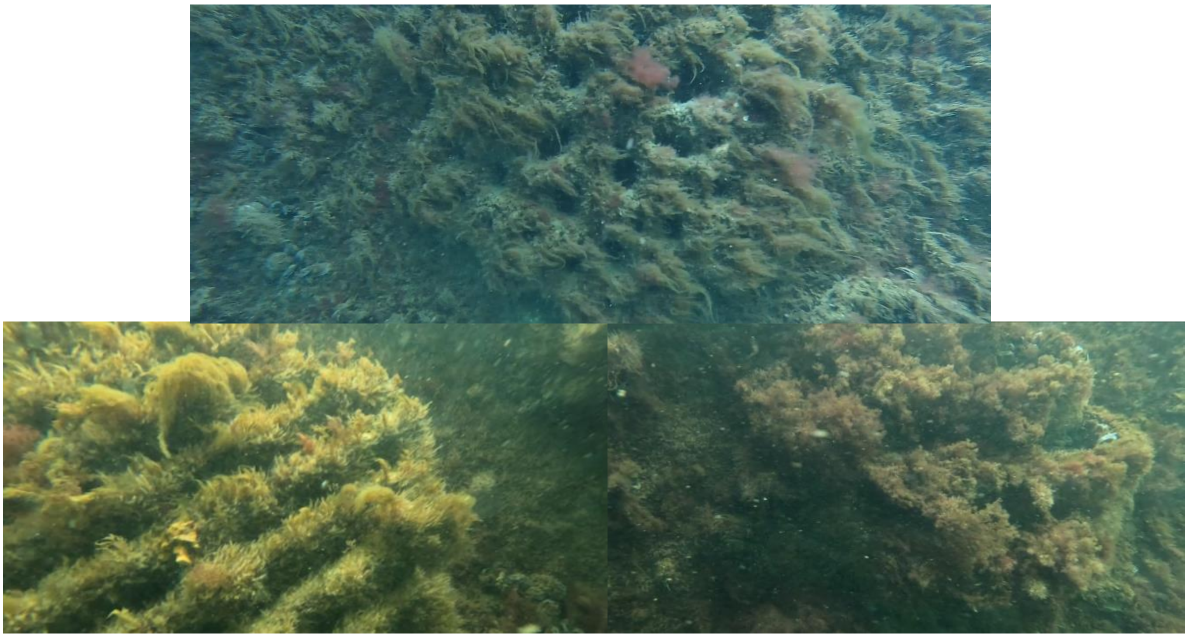

Figure 12. Panels from the living seawall. The upper image is from 2023 and the lower images from 2024.

Different panels from the living seawall are shown in Figure 12. More macroalgal coverage can be seen on the panels in the 2024 images.

Figure 13. S-shaped structures on the living seawall (same structures visible in all images). The upper right image was taken from the report by Looström et al. (2023) at 3m depth (Looström et al. 2023) and the upper left image from the 2023 raw data. The lower two images are from the 2024 fieldwork data and were also taken at 3m depth.

In Figure 13, all images show that the S-shaped reef panels were uniformly covered with macroalgae. However, the macroalgae was larger in the 2024 images. The 2024 image of the seawall at comparable depth to the 2023 data also shows that the seawall itself had dense natural coverage.

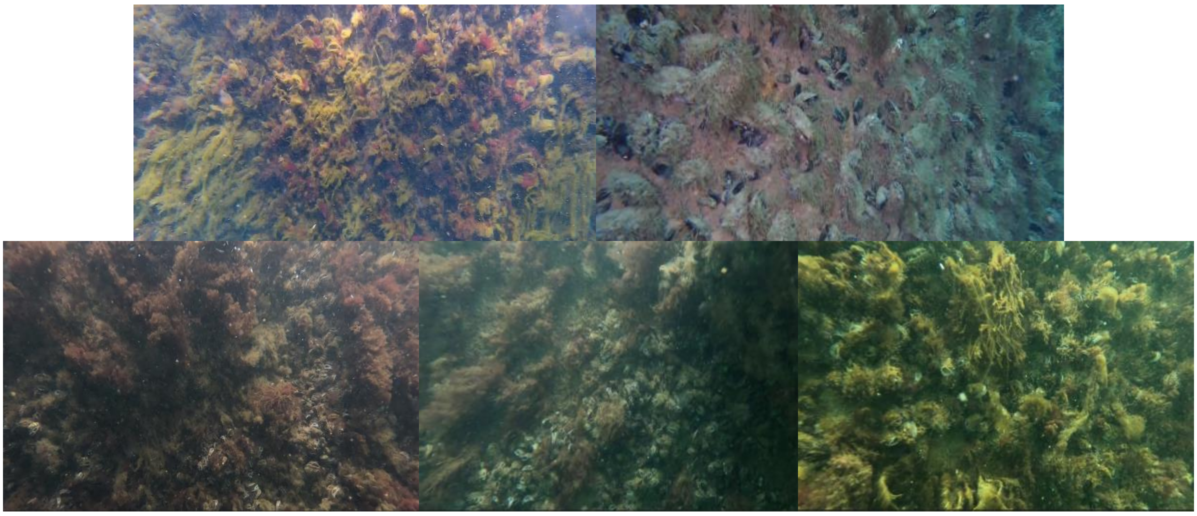

Figure 14. Background seawall between the panels of the living seawall. The upper two were taken in 2023 and the lower three in 2024.

The macroalgal coverage was greater and the mussel population denser in the 2024 images than in the 2023 images in Figure 14. The species composition of the background seawall remained consistent across the living seawall and adjacent living seawall control. The 2023 reports also noted that more mussels were found on the living seawall than on the stone reef which also held true for the 2024 inventory (Looström *et al.* 2023).

Mussel colony

The mussel colony had not been installed at the time of the 2023 survey so no comparative footage was available.

Figure 15. Mussel colony platform (2024).

The lower two images in Figure 15 give an indication of the strong current which can be found under the mussel colony platform. This was due to the displacement of water by ferries docking multiple times per hour. The ferry dock is in the background of the upper left picture. A small amount of colonisation by filamentous macroalgae can be also seen along the platform edges.

Static films

Small fish were seen by eye from the raft at the stone reef site but no fish were seen during the static camera filming sessions. No fish species were seen in the footage from the static camera at the living seawall either but a pipefish (*Syngnathus typhle*) was seen in one of the vertical drop videos at this site.

3.2 Differences in blue mussels between the artificial reefs

3.2.1 Mussel sampling

Figure 16. Mussel samples. Site obtained (left to right): stone reef, stone reef control, living seawall, living seawall control and frozen dockside control.

The range of mussel sizes and sample sizes across five of the sites can be seen in Figure 16. The mussel colony sample was measured in situ on the mussel colony platform and so was not taken into the laboratory for processing, hence the lack of image. However, the sizes of the one year old mussels from the colony were comparable to the smaller mussels in other images. This indicates that a range of ages was present in the other mussel samples.

Table 3. Sample size, average width:length ratio and estimated age and sampling depth of blue mussels collected from each site.

Site	Sample size	Average width:length ratio	Estimated age of population (yrs)	Depth of sampling (m)
Mussel colony	35	1.60	1	1-2
Stone reef	66	1.77	2	<1
Stone reef control	245	1.90	4	<1
Living seawall	47	1.95	2	<1
Living seawall control	120	2.02	>2	<1
Dockside control	23	2.08	>2	>2

The sampling depth in Table 3 was recorded as the depth below the waterline on the sampling day and measurement was consistent across all sites. However, it should be noted that the water level was around 0.5m lower than normal on the day on which sampling took place. Sampling depth was also limited by the conditions at some sites.

It is also clear from Table 3 that sample sizes varied. This was primarily due to the ease of sample collection which correlated to the abundance of mussels at each site. The mussel colony platform had the advantage of being easy to harvest. Additionally, the control sites of the dockside next to the stone reef and the harbour wall adjacent to the living seawall had far higher concentrations of blue mussels than the other sites.

The average width:length ratio also varied between the samples (Table 3). This indicates that site had an effect on the growth pattern of mussels, even between samples of the same age.

The maximum age of the mussels in the colony, on the stone reef and at the living seawall is known due to the date of installation. The stone reef control is also known as these samples were taken from a channel that was reopened to connect the former dry dock to the sea four years ago. The latter two controls can only be estimated as over two years old with any degree of accuracy but are likely to be the longest established of all the sampling sites.

Figure 17. Mussels on the stone reef (top) and on the dockside wall adjacent to the stone reef (bottom). The red circle in the upper image outlines a blue mussel.

Mussels on the stone reef itself were hard to detect beneath the dense macroalgal layer and were often isolated with only one to three specimens found together. Only one cluster was located during the snorkelling and this was in an area between multiple boulders where the current was reduced. However, in Figure 17, it can be clearly seen that the abundance of blue mussels was much higher on the concrete dockside wall but also that only limited amounts of other species were present in this area.

Figure 18. Mussels on a living seawall panel (top) and the background seawall between panels (bottom). Red circles outline mussels in the upper image, taken at 3m depth. The lower image was taken at around 1m depth.

Figure 18 compares mussels on the living seawall panels with the background seawall. On the living seawall, mussels were located within the indentations on the panel structures and were far fewer in number than on flatter sections of the seawall.

Figure 19. Living seawall (top) and living seawall control (bottom) above the waterline. The red rectangle outlines an example of a cleared area for reef panel installation. The difference between the water level during fieldwork and the usual waterline (approximately 0.5m) is indicated by the red arrow.

As can be seen in Figure 19, the seawall was scraped clean for the installation of the artificial reef panels and these areas have not yet been recolonised by blue mussels. Outside of the installation areas, the mussel belt continued without interruption along the length of the seawall. The water level was also around 0.5m lower than usual during the fieldwork meaning that the upper belt of blue mussels, which would normally be submerged, was visible above the waterline. This mussel belt was also documented as being present in the surf zone in the 2023 report (Looström *et al.* 2023).

3.2.2 Mussel dimensions

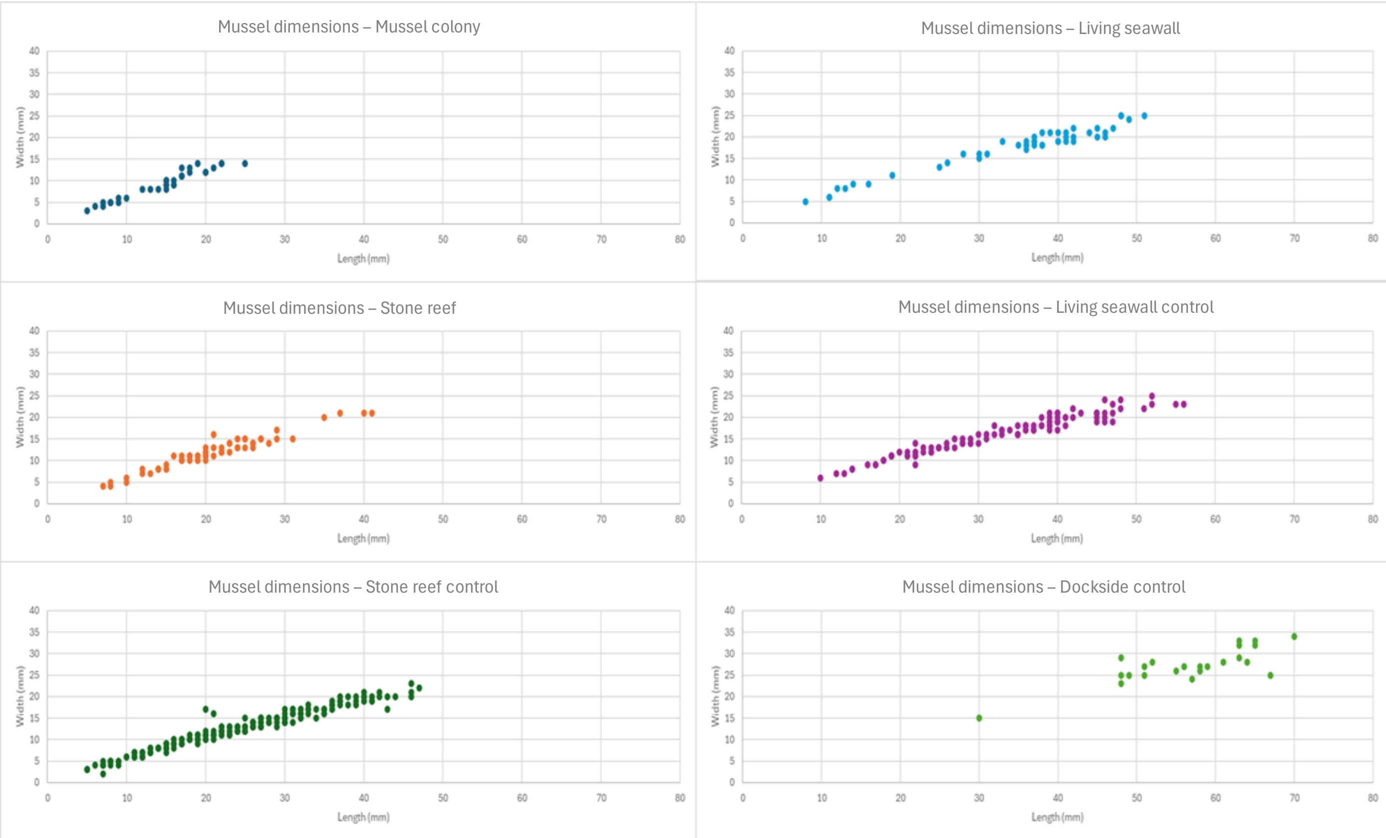

Figure 20. Width and length in millimetres of each mussel collected from the mussel colony, stone reef, stone reef control, living seawall, living seawall control and dockside control.

The size distribution of all the mussels collected, separated by sampling site, can be seen in Figure 20. The width:length relationship of the mussels followed a roughly linear pattern across all sites. Additionally, it can be seen in Table 3 that whilst mussel width:length ratio did vary across all sites, this ratio increased as mussel size increased which could account for the fairly linear graphs seen here. These samples will be further compared below.

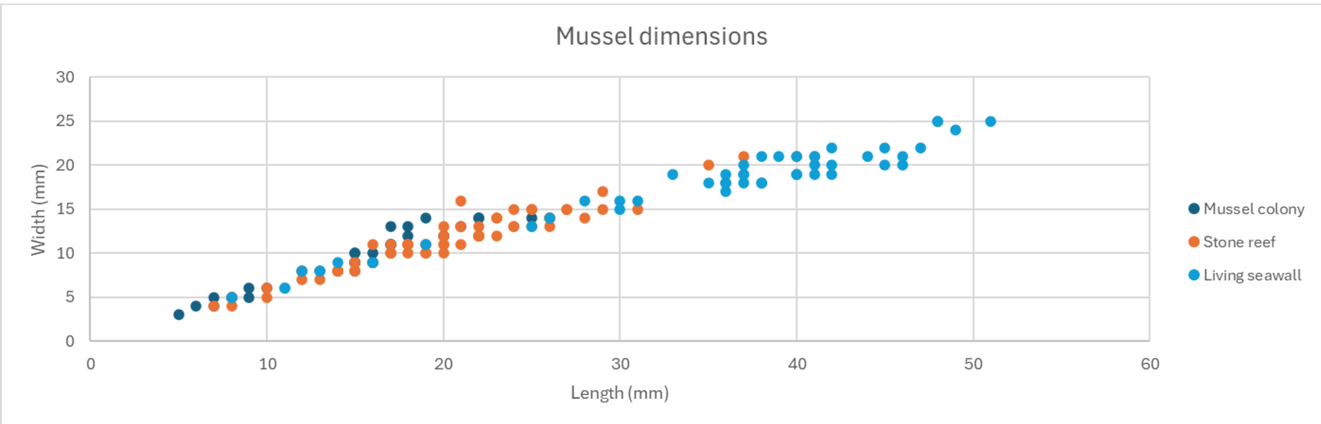

Figure 21. Width and length in millimetres for each mussel collected from the mussel colony, stone reef and living seawall.

The mussels from the colony sample had the smallest range but these were the youngest mussels at around one year of age which likely accounts for this difference in size (Figure 21). The mussel colony datapoints overlap with both the stone reef and living seawall datapoints indicating that there were likely one year old mussels in both of these samples as well. Mussels from the stone reef and living seawall were larger than those from the mussel colony, which likely reflects that two year old mussels were also sampled from these sites. The size of the smallest mussels on the stone reef and living seawall was comparable but the living seawall also had larger mussels than the stone reef; therefore, the living seawall sample had a wider range of mussel sizes despite this structure being the same age as the stone reef.

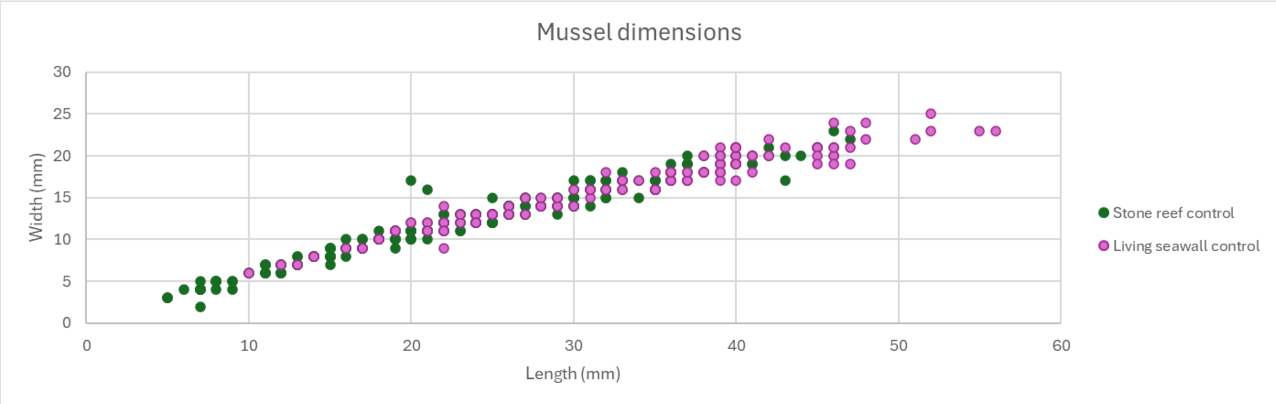

Figure 22. Width and length in millimetres for each mussel collected from the stone reef control and living seawall control sites.

The mussel samples from these control sites were both collected from nonaugmented concrete harbour walls (Figure 22). The upper range of the living seawall control sample extended beyond that of the stone reef control sample and, given that substrate was consistent, this indicated that site had an effect on mussel size.

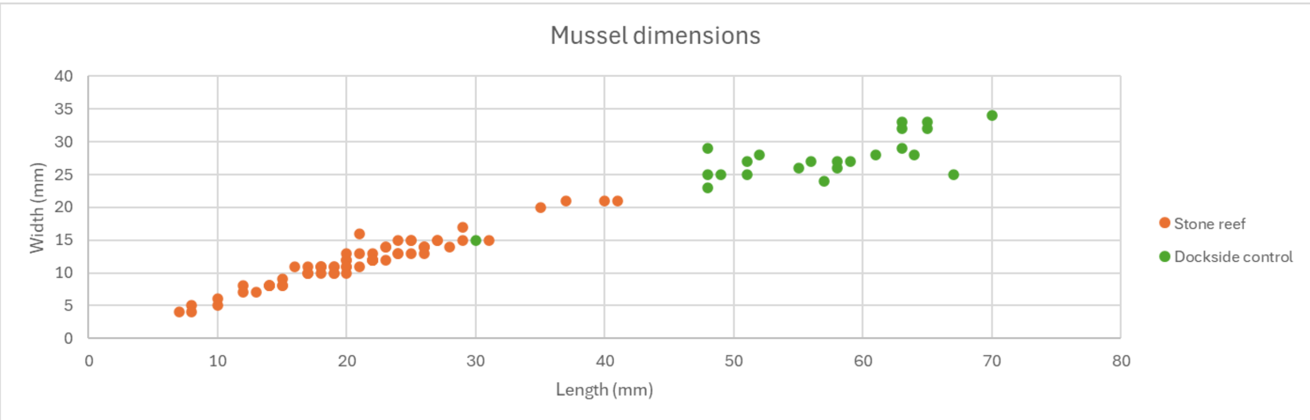

Figure 23. Width and length in millimetres of blue mussels collected from the shallower stone reef versus a deeper water section of the same harbour region (dockside control).

The graph in Figure 23 highlights that mussels taken from the deeper dockside site were much larger than those collected in the same area from the shallower stone reef. One outlier from the dockside sample can be seen within the stone reef datapoints implying that other ages and sizes of mussel were likely also present on the deeper dockside, further indicating that the small sample size of the dockside control was likely not fully representative.

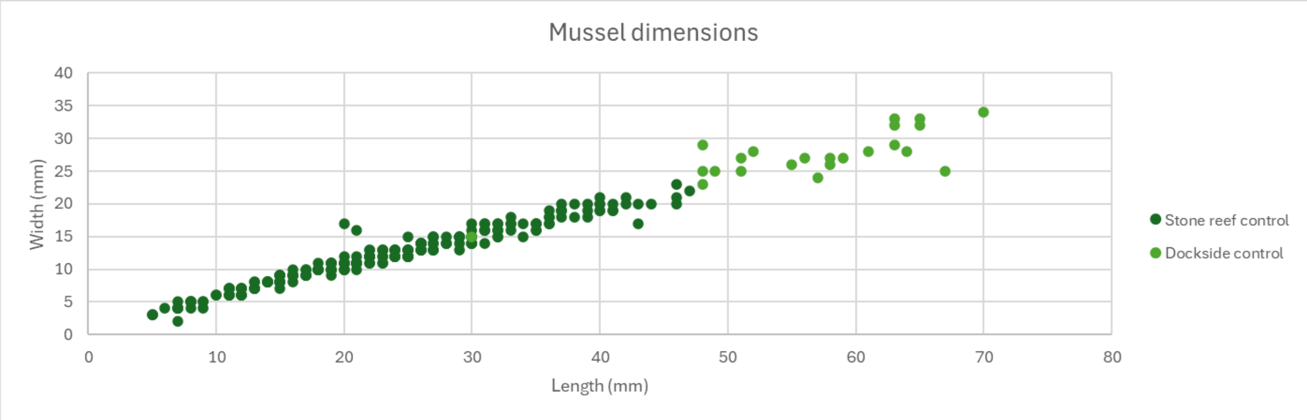

Figure 24. Width and length in millimetres of blue mussels collected from the stone reef control and the dockside control.

The mussels recorded in Figure 24 were all collected at different depths from the harbour wall adjacent to the stone reef. The smaller stone reef control mussels were gathered from a much shallower area than the dockside control, highlighting that mussel size was affected by depth.

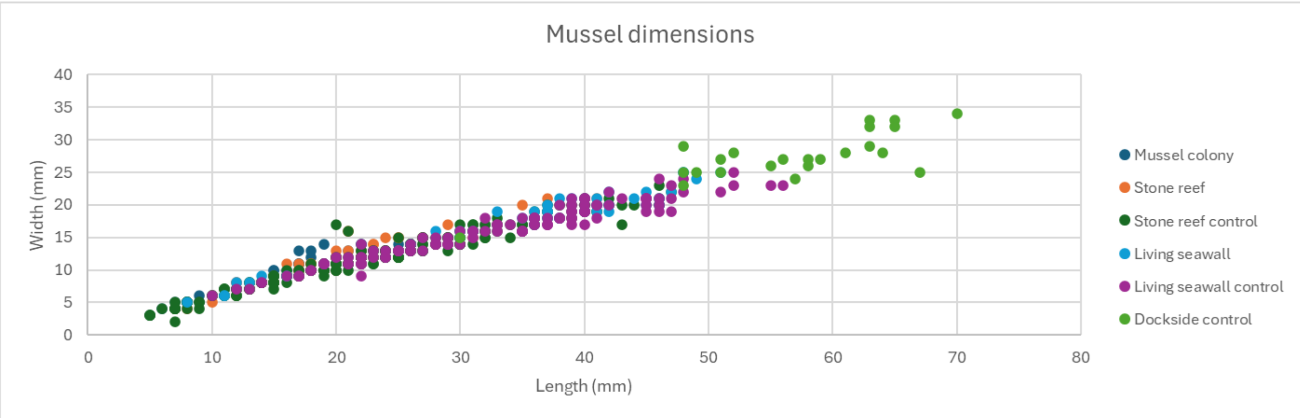

Figure 25. Width and length in millimetres of each mussel collected from the mussel colony, stone reef, stone reef control, living seawall, living seawall control and dockside control.

When all samples were overlaid on the same graph (Figure 25), there was considerable overlap between all of the different sites. The dockside mussels were the largest of all the datasets. The width:length relationship of the mussels starts fairly consistently across all sites but becomes non-linear and starts to curve as mussel size increases, indicating that growth rate may be faster for younger, smaller mussels.

Figure 26. Length distribution of the mussel samples from the mussel colony, stone reef, stone reef control, living seawall, living seawall control and dockside control. Estimated age and sampling depth can be seen in the upper right corner of each graph.

The length distribution of each mussel sample can be seen in Figure 26. Both the stone reef and stone reef control samples showed a normal distribution pattern. Sample size differed as can be seen in Table 4 below. The dockside control sample in particular may be insufficiently large to be fully representative but does give an indication of the much greater length of mussels, and therefore age, that can be found at greater depths.

The mussels in the colony sample were one year old and showed a peak at around 15mm. A peak at around the same length interval can similarly be seen in the living seawall, living seawall control and stone reef control graphs indicating that the size of the colony mussels was comparable to the size of one year old mussels at other sites.

In the living seawall sample, a second peak can be seen at 36-37mm which indicates the likely presence of both one and two year old mussels within the living seawall sample. These mussels were slightly smaller than those in the living seawall control which showed peaks at 22mm and 40mm respectively. It may just be that these mussels attached slightly earlier as areas of the living seawall had to be scraped during installation; this could account for the slightly better growth.

The stone reef sample showed a peak between 20-22mm but this sample size was much smaller than for the living seawall, harder to obtain and largely gathered from one area where a cluster of mussels was found sheltered from the currents. It is possible that mussel size varies deeper into the stone reef but the mussels were well camouflaged by the extensive macroalgae and so were hard to detect. The stone reef control peaked at 25mm, comparable to the stone reef but with a much broader range of sizes; this may further support that the stone reef sample was likely not fully representative of the mussel population present.

Furthermore, the comparable size range between the living seawall and its control and between the stone reef and its control indicates that the type of hard substrate was not a factor strongly influencing mussel size. The boulders and living seawall panels were not outperforming the harbour walls in terms of mussel size.

Table 4. Sample size, mean length, standard deviation, standard error and confidence intervals for the mussels collected from each sample site.

					Confidence interval (95%)	
Site	Sample size	Mean length (mm)	Standard deviation	Standard error	Lower	Upper
Mussel colony	35	14.49	5.13	0.87	12.79	16.19
Stone reef	66	20.79	7.02	0.86	19.09	22.48
Stone reef control	245	23.25	9.77	0.62	22.03	24.47
Living seawall	47	34.57	11.51	1.68	31.28	37.86
Living seawall control	120	32.98	10.34	0.94	31.13	34.82
Dockside control	23	56.57	8.82	1.84	52.96	60.17

Table 4 provides a statistical overview of the mussel sampling data. The stone reef control had the largest sample size and the dockside control the smallest. The dockside control sample had the largest mean length. However, of the five sites actually collected during this project, the living seawall had the longest mean length which is interesting as it outperformed its control site. The living seawall also had a large standard deviation indicating that there was a lot of variation in mussel size within this sample. The mean length of mussels from the stone reef was smaller than that of both the stone reef control and the dockside controls. As the stone reef did not outperform either of its control sites, this indicates that mussels were larger on the neighbouring harbour wall than within the stone reef.

Of the artificial reef sites, the living seawall mussels had a mean length of about 14mm and 20mm longer than the stone reef and mussel colony respectively, indicating that this site may be the best for mussel growth. The mussel colony sample seemed negatively affected in terms of size by having a population one year younger, although it would still be beneficial to replicate this study with larger sample sizes to confirm this finding.

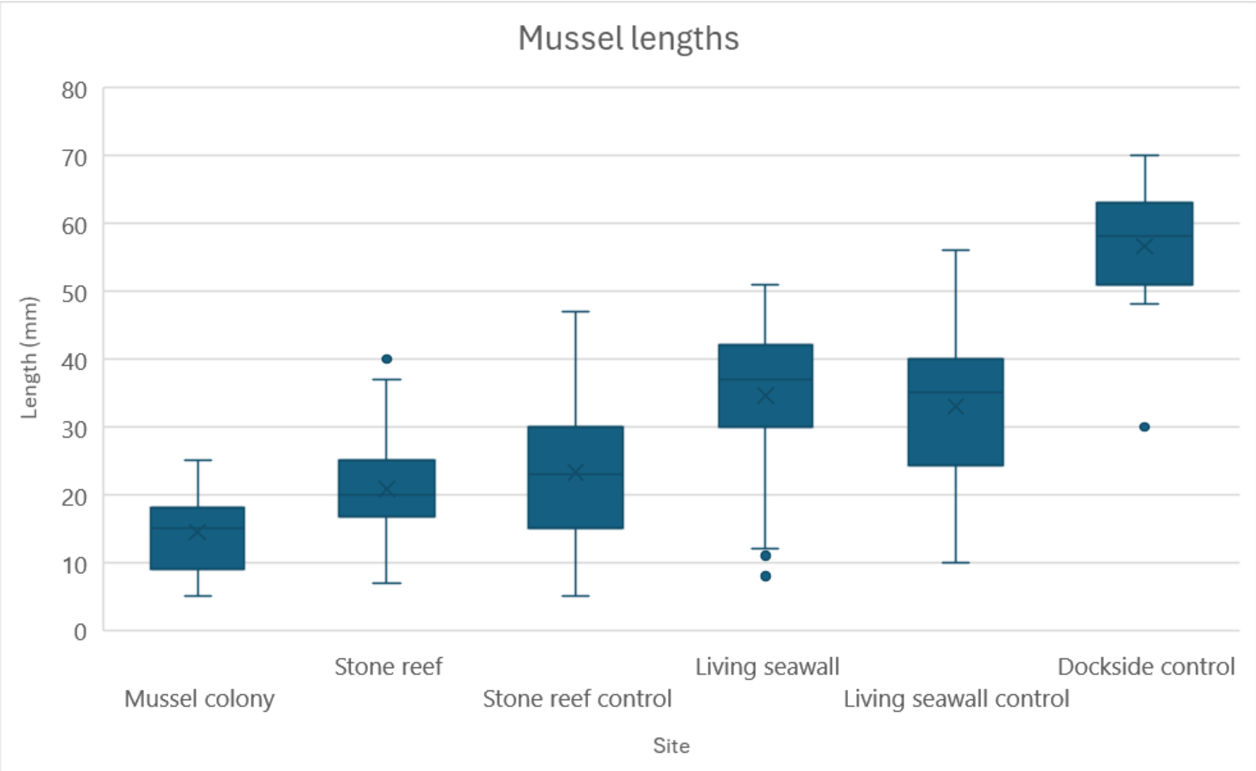

Figure 27. Box and whisker plot displaying the interquartile range of the lengths in millimetres of the mussels from each site. Outliers (datapoints outside the whiskers of the boxplot) are included as blue dots. The mean is marked by an 'x' and the median by a line.

Figure 27 confirms the findings from the graphs recorded above. The short tails on both the mussel colony and dockside control plots indicate low variation in sample size. The third quartile of the mussel colony is short, further indicating that many mussels of the same size were present within this quartile. The stone reef control has a fairly even distribution across all quartiles which matches the normal distribution seen in the graph in Figure 26 for this site. The stone reef has even distribution in the first and fourth quartiles but much less variation in mussel size in the second.

The living seawall has a longer first quartile indicating a higher variation in length amongst the smaller mussels within this sample. Whilst the median of the living seawall is higher than that of the living seawall control, the spread from first to fourth quartile is narrower than that seen in the living seawall control implying that differences seen here may be due to inadequate sample size from the living seawall. Similarly, the range of lengths for the stone reef mussels are all within the range from the first to fourth quartile of the stone reef control indicating that insufficient sample size may also be affecting the stone reef dataset.

The mussel colony quartiles are all relatively close implying a uniformity of size amongst the one year old mussel population. However, as the age of mussels increased across the other plots, the heterogeneity of size also increased indicating that the distribution of mussel size widens over time. The dockside control plot does show a narrower distribution but it is possible that this is attributable to the smaller sample size and so is less reliable.

The median value shows a non-linear increase with age across all the plots suggesting that growth rate may change with age; this correlates with the pattern seen in Figure 25. Longer tails, such as the first quartile of the living seawall, draw the mean value away from the median; in these instances, the median gives a more reliable indication of the data distribution.

Table 5. Results of the independent samples t-test ($p<0.05$) between the different sites.

t-test pairs	p value	t value	Degrees of freedom
Mussel colony vs Stone reef	<0.001	4.681	100
Mussel colony vs Stone reef control	<0.001	5.201	279
Mussel colony vs Living seawall	<0.001	9.601	81
Mussel colony vs Living seawall control	<0.001	10.193	154
Mussel colony vs Dockside control	<0.001	22.666	57
Stone reef vs Stone reef control	0.056	1.917	310
Stone reef vs Living seawall	<0.001	7.884	112
Stone reef vs Living seawall control	<0.001	8.544	185
Stone reef vs Dockside control	<0.001	19.538	88
Stone reef control vs Living seawall	<0.001	7.066	291
Stone reef control vs Living seawall control	<0.001	8.764	364
Stone reef control vs Dockside control	<0.001	15.752	267
Living seawall vs Living seawall control	0.385	0.871	166
Living seawall vs Dockside control	<0.001	8.045	69
Living seawall control vs Dockside control	<0.001	10.233	142

As can be seen in Table 5 above, there was no statistically significant differences in mussel length between the stone reef and stone reef control sites ($p = 0.056$), or between the living seawall and living seawall control sites ($p = 0.385$). This correlates with the data discussed previously (Figures 26 and 27). All other site comparisons show statistically significant differences in mussel length.

3.3 Views of local people on the artificial reefs in Oceanhamnen

3.3.1 Survey

A total of 50 respondents from across the target groups started the survey, out of which 45 completed it. This generated an estimated overall response rate of around 12.5%.

Table 6. Number of people in each target group who filled in the survey. Bracketed numbers indicate the number of survey responses within each group which were started but not completed.

Respondents	Havskoloni	Ophelias Brygga	Greenhaus Castellum	Passersby
First round survey	16 (3)	13	2	N/A
Second round surveys	5	4 (2)	11	1

Table 6 records the respondents for each survey group. Within the first round survey, two respondents selected that they were members of more than one target group but due to an issue with the anonymisation in the survey, it was not possible to differentiate which groups these respondents had selected. However, it did indicate that there was some overlap between people who lived, worked and were involved in the community projects within Oceanhamnen. No surveys were completed in English indicating that the respondents were likely either Swedish nationals or long-term migrants who had been in Sweden long enough to learn the language.

Partial responses have been included in the analyses of the survey data. Of the respondents, 94% were aware of the mussel colony, 72% knew about the stone reef but only 60% of respondents were aware of the living seawall. However, an error was made in the formulation of this question as it was assumed that the members of the target groups would have heard of at least one of the three options and the question was compulsory. There were two additional comments that the respondents had not heard of any of the three options but had picked an option at random in order to continue with the survey. It was not possible to know which option these respondents picked due to the anonymisation of the survey.

The majority of respondents had become aware of these projects through various social media channels; others saw articles in the news, saw the installation work, attended the H22 City Expo in Helsingborg or, for those within the Greenhaus Castellum, had heard about these projects from their work colleagues. Some respondents had also gathered information from the signage displayed around the sites by the City of Helsingborg.

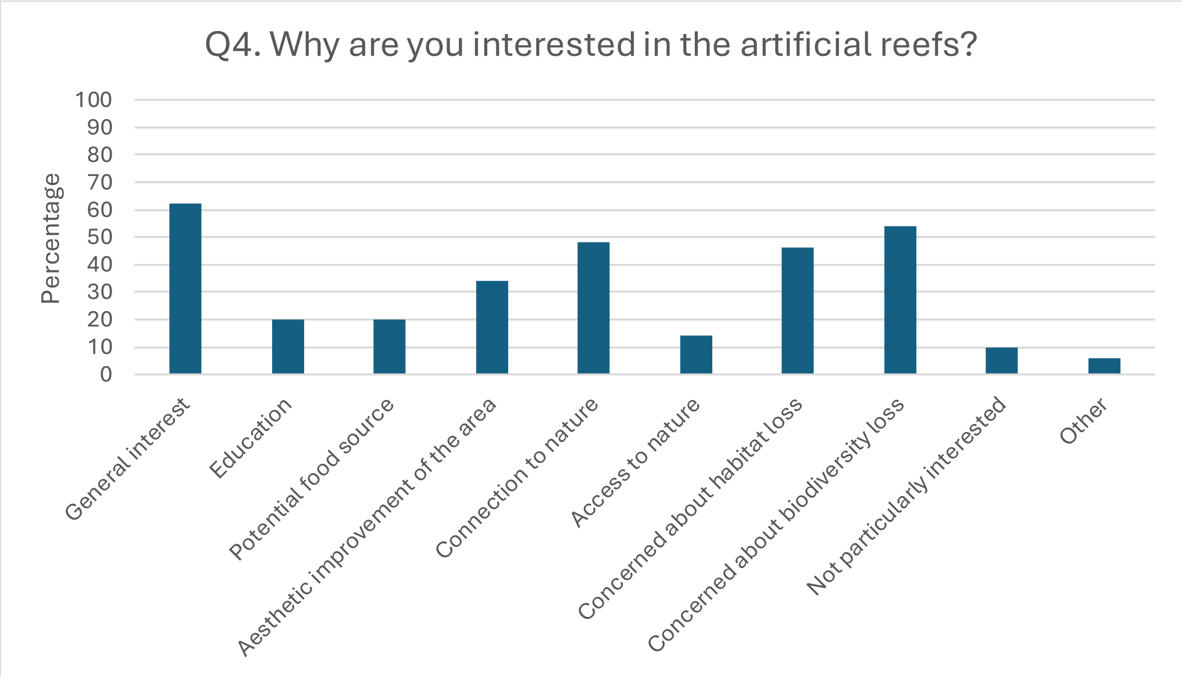

Figure 28. Percentage of the 50 respondents interested in each option provided in question four (Q4) of the survey. Comments in the 'Other' section were all positive and included interest in making new contacts, engaging children in "long-term sustainability" and increasing social connections within the local community.

Figure 28 shows that no option regarding the reason for interest in the artificial reefs appealed to 100% of respondents, although multiple responses were allowed. General interest was the highest common factor but 10% of respondents did report being disinterested in the artificial reefs. Interestingly, a connection to nature was rated as being more important than having access to it. Concern about biodiversity loss also outweighed that induced by habitat loss.

Biodiversity

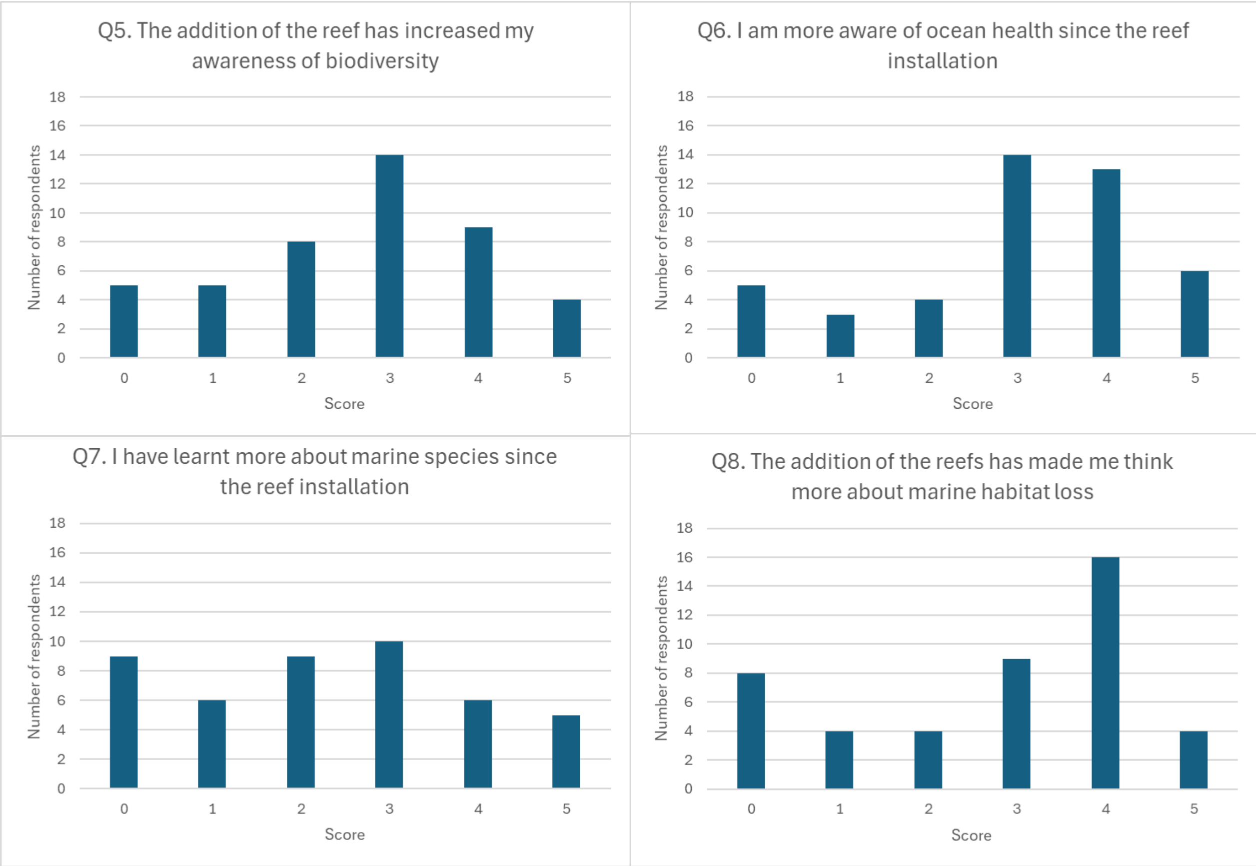

Figure 29. Scores from the biodiversity section of the survey (Q5-8). (0 = strongly disagree, 5 = strongly agree).

With scores from Q5 to Q8 (Figure 29) peaking between 3 and 4, this implies an overall positive view from the public relating to biodiversity following the addition of the artificial reefs. This correlates with the increased reef coverage and number of species seen in the 2024 inventory (Tables 1 and 2).

Food security

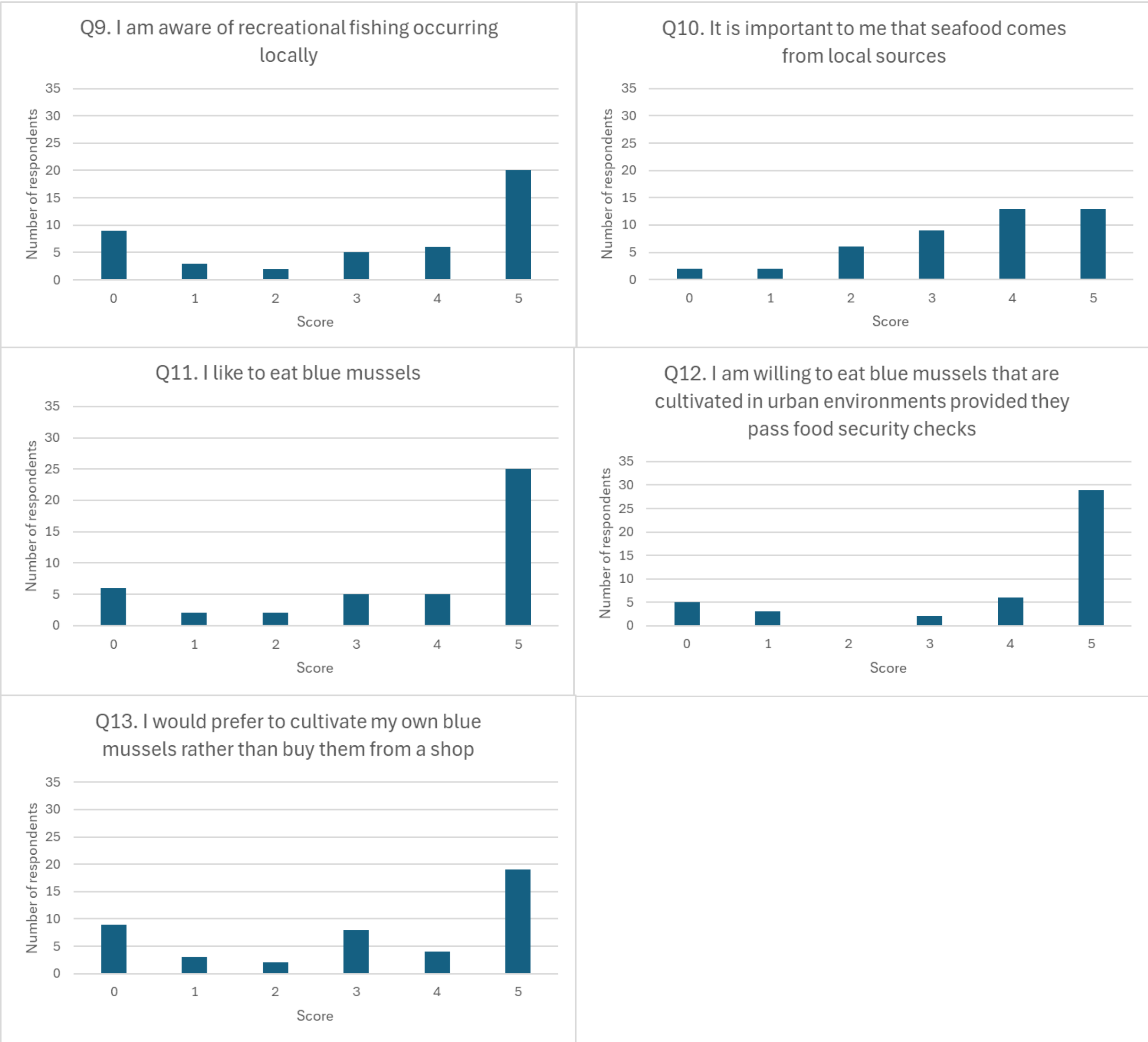

Figure 30. Scores from the food security section of the survey (Q9-13). (Q9 – 0 = never, 5 = on a daily basis; Q10-13 - 0 = strongly disagree, 5 = strongly agree).

In the food security section of the survey (Figure 30), local people showed strong preferences for cultivating safe local blue mussels for consumption, including in urban environments.

Ecosystem services

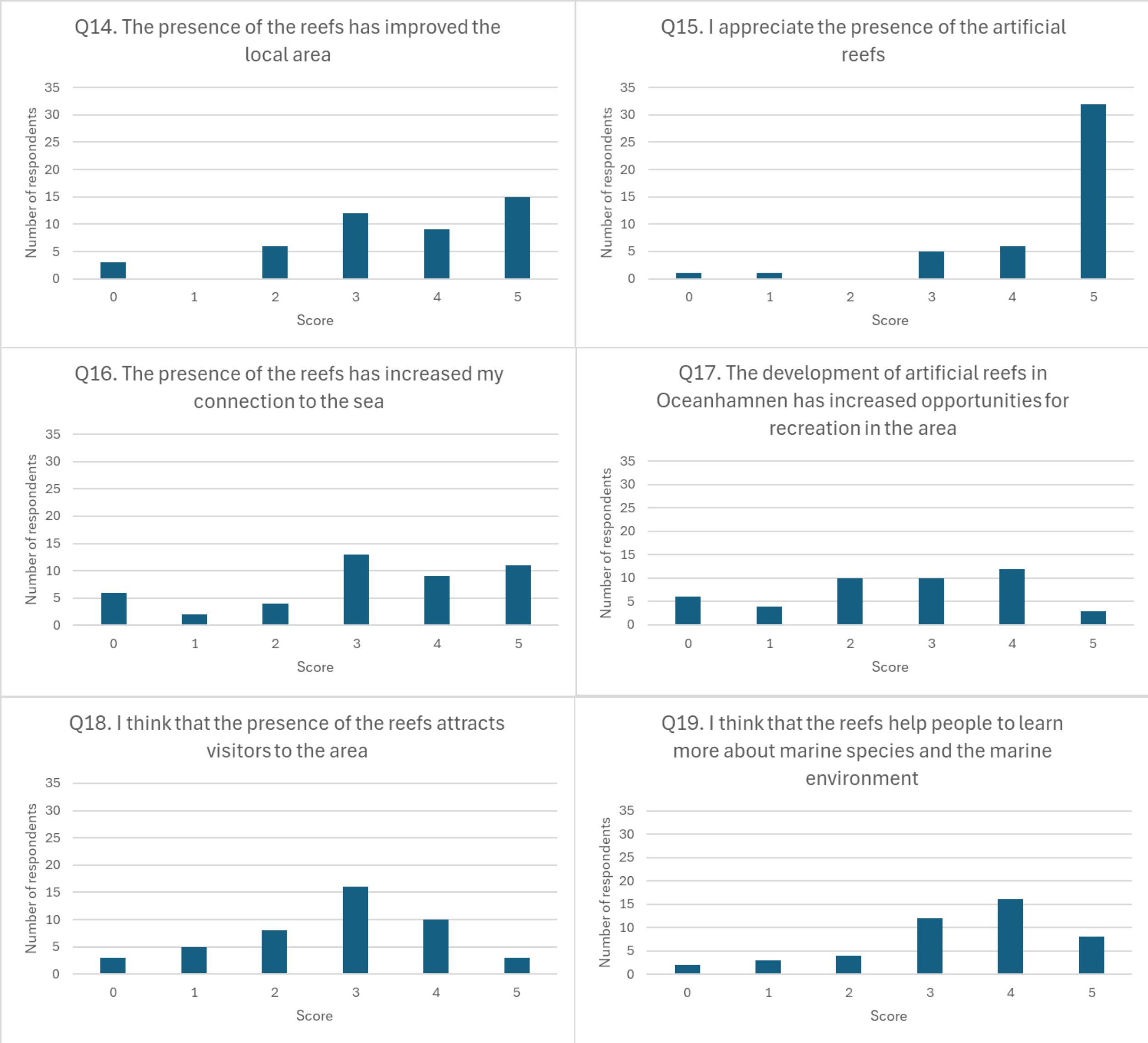

Figure 31. Scores from the ecosystem services section of the survey (Q14-19). (0 = strongly disagree, 5 = strongly agree).

The survey showed generally positive tendencies towards the ecosystem services aspects with local people appreciating the reefs which were viewed to have improved the area and increased both knowledge of and connection to the marine environment (Figure 31). The response was also positive, but not as strong, for beneficial influence on recreation and tourism opportunities after the installation of the artificial reefs.

General

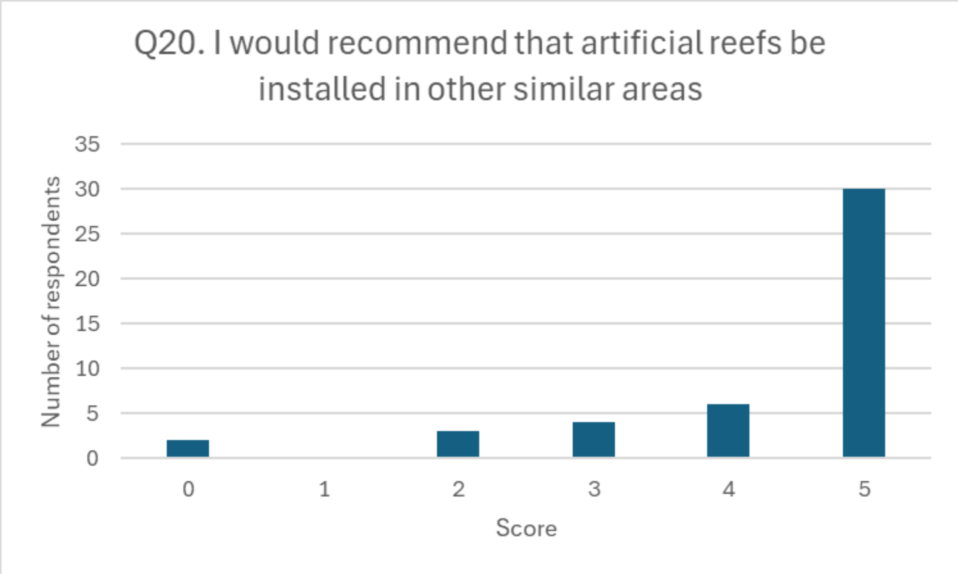

Figure 32. Scores from the general section of the survey (Q20). (0 = strongly disagree, 5 = strongly agree).

Figure 32 highlights the very positive overall response to the installation of the artificial reefs such that local citizens would support their expansion into new areas. This correlates well with the strong positive result, seen in Q15 above, which indicated that respondents appreciated the presence of the artificial reefs.

Survey feedback

The survey contained the option to provide further comments on both the overall topic and survey content. Feedback directly on the survey structure found it interesting, informative and clear to follow. However, there was some critique from a GreenHaus Castellum respondent who thought that the underwater camera should have been mentioned in the introduction and that links could have been included within the survey to provide further information for those respondents who wish to learn more about the marine environment and artificial reefs.

Regarding the artificial reefs, there was a comment from the Ophelias Brygga group that many residents in the apartment building were not aware of the plan to set up the mussel colony platform, or of the opportunity to join the citizen group to manage it, until after the project was already well established. Other comments mentioned the scarcity of information available about the artificial reefs in general. One respondent reported that they were not at all interested in the artificial reefs, despite having voluntarily completed a survey about them. The most negative comment came from a respondent who strongly expressed that they would never swim in or eat any aquatic food from a former shipyard so close to a container port and ferry dock as it was their view that it is not possible to sufficiently clean up previous contamination from lead and mercury.

However, it was felt by multiple other respondents that the mussel colony in particular was an important social project which had helped create new connections, a feeling of unity, and greater understanding both within the community and between the community and nature. This project was also felt to have created a commonality between the community and the municipality and to have increased cooperation between the two. A Havskoloni respondent commented that the mussel farm was working well, had good administrative support and was, on the whole, keeping participating citizens engaged. Another respondent appreciated that the artificial reef initiatives were trying to increase harmony with the natural environment but requested that more information be displayed around the site about what is really happening beneath the water's surface. Similarly, respondents from the GreenHaus Castellum would like more information about the reefs and underwater camera to be displayed on site but felt that the reefs have enormous educational value and make the area beautiful to walk around.

3.3.2 Analysis of survey results

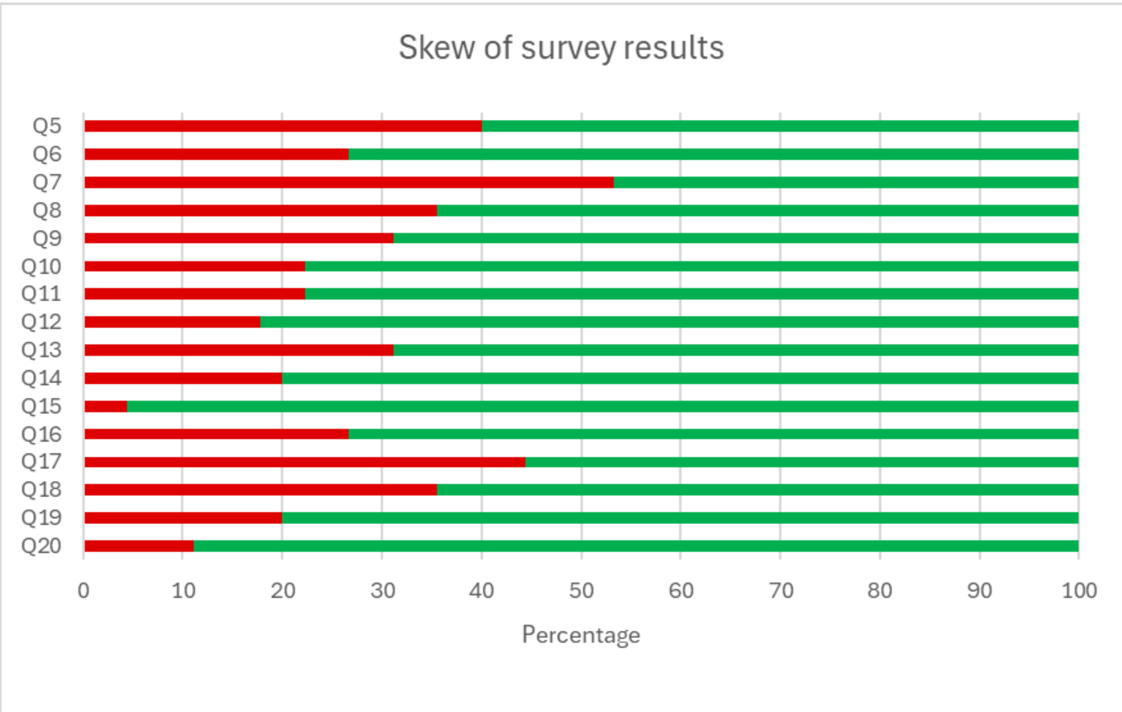

Figure 33. Percentage of responses that were skewed towards negative and positive in the survey (Q5-20). Scores 0, 1 and 2 were grouped as negative responses (red) and scores 3, 4 and 5 were grouped as positive responses (green).

The only survey question for which the percentage of negative responses outweighed the positive was Q7 indicating that the majority of respondents did not feel that they had learned more about the marine species since the installation of the artificial reefs (Figure 33). However, there were also comments from the GreenHaus Castellum group stating that they had not learned more about marine species as they had advanced knowledge of them already but could see that the knowledge of others may have been improved. It is possible that these views skewed this result.

When viewed collectively, the overall responses for all sections skew towards the positive, indicating that the installation of the artificial reefs had had a beneficial effect on biodiversity, food security and ecosystem services according to the public's perspective. 61% of the total responses for the biodiversity section were positive and 75% for both food security and ecosystem services. The strongest positive response was for Q20 in which 89% of respondents would recommend that more artificial reefs be installed in other similar areas.

The following two tables contain the same data but have been colour coded in different ways to aid interpretation.

Table 7. Biases of the survey respondents by group for Q5-20. Bracketed numbers indicate the sample size for each column. The average score for all respondents can be seen in the 'Total' column. Scores were coded as less than the average score for all respondents (orange) or higher than the average score for all respondents (green).

Section		Total (45)	Mixed group (26)	Havskoloni (5)	Ophelias Brygga (2)	Greenhaus Castellum (11)	Passersby (1)
Biodiversity	Q5	2.64	2.54	2.6	4	2.64	3
	Q6	3	3.12	2.8	3.5	2.73	3
	Q7	2.29	2.62	1.2	3.5	1.91	1
	Q8	2.73	3	1.8	4	2.45	1
Food security	Q9	3.24	3.04	4	2	3.45	5
	Q10	3.51	3.42	4	4.5	3.27	4
	Q11	3.69	3.58	5	3.5	3.27	5
	Q12	3.96	3.69	5	4	4	5
	Q13	3.16	3.27	4.2	3.5	2.18	5
Ecosystem services	Q14	3.53	3.46	2.2	5	4	5
	Q15	4.44	4.19	4.6	4.5	4.91	5
	Q16	3.11	3.19	1.2	4.5	3.45	4
	Q17	2.6	2.62	1.4	4.5	2.64	4
	Q18	2.76	2.85	1.8	4.5	2.64	3
	Q19	3.36	3.27	3.2	4.5	3.45	3
General	Q20	4.27	4.19	4.2	4.5	4.36	5

The biases seen in the survey responses are shown in Table 7. The mixed group from the first round survey scored lower than average for awareness of biodiversity and local fishing. Food safety and proximity of cultivation of aquatic foods also scored lower than average for importance but interestingly there was a stronger than average preference for self-cultivated rather than shop-bought mussels. Improvement to the area, education and generally liking the artificial reefs all scored lower than average in this mixed group. It could be that sub-groups polarised these results as it can be seen that the Havskoloni group, for example, were strongly positive about the food security aspects in relation to the artificial reefs. The mixed group also scored slightly less positive than average about installing artificial reefs in more areas. However, despite the small sample sizes, more nuances can be seen in the second round survey results which are discussed below.

It is interesting to note that while the Havskoloni citizen group showed a strong positive bias towards the food security components, consistently rating these higher than average, this group gave lower rankings for all biodiversity, general and ecosystem services components, with the exception of appreciating the presence of the artificial reefs. This group was also less likely than average to recommend that more artificial reefs be installed.

The GreenHaus Castellum group (office workers) seemed most aware of the ecosystem services components but this group scored lower than average for increased visitors and were less likely than average to want to cultivate and eat blue mussels. They also scored lower than average for increased knowledge of ocean health, marine species and habitat loss. As this group had the largest sample size of second round survey respondents, there is a higher likelihood of these results being representative of this target group.

The residential group from Ophelias Brygga were not aware of fishing occurring locally and were less likely to enjoy eating blue mussels but were otherwise more positive than average towards all other aspects relating to the reefs. This group showed a strongly positive bias towards aspects relating to ecosystem services.

The passerby group was also strongly positive about the food security aspect and most of the ecosystem services components but did not relate positive improvements in biodiversity to the artificial reefs and did not strongly correlate the reefs' presence with increased visitors to the area. The passerby did not feel they had learned more about marine species or marine habitat loss and was also less positive than average that the artificial reefs were helping the general public to learn more about the marine species and the marine environment. While these responses are consistent for this respondent group, the sample size of respondents in both the passerby and Ophelias Brygga groups were very small and so the biases of these groups may be disproportionately represented within the data.

Table 8. Survey responses by group for Q5-20 as in Table 7. The scores for each survey question have been re-categorised into the following five bins: 'Strongly negative' (red, 0-1), 'Negative' (orange 1.01-2), 'Neutral' (yellow, 2.01-3), 'Positive' (light green, 3.01-4) and 'Strongly positive' (dark green, 4.01-5). Bracketed numbers indicate the sample size for each column.

		Average Score					
Section		Total (45)	Mixed group (26)	Havskoloni (5)	Ophelias Brygga (2)	Greenhaus Castellum (11)	Passersby (1)
Biodiversity	Q5	2.64	2.54	2.6	4	2.64	3
	Q6	3	3.12	2.8	3.5	2.73	3
	Q7	2.29	2.62	1.2	3.5	1.91	1
	Q8	2.73	3	1.8	4	2.45	1
Food security	Q9	3.24	3.04	4	2	3.45	5
	Q10	3.51	3.42	4	4.5	3.27	4
	Q11	3.69	3.58	5	3.5	3.27	5
	Q12	3.96	3.69	5	4	4	5
	Q13	3.16	3.27	4.2	3.5	2.18	5
Ecosystem services	Q14	3.53	3.46	2.2	5	4	5
	Q15	4.44	4.19	4.6	4.5	4.91	5
	Q16	3.11	3.19	1.2	4.5	3.45	4
	Q17	2.6	2.62	1.4	4.5	2.64	4
	Q18	2.76	2.85	1.8	4.5	2.64	3
	Q19	3.36	3.27	3.2	4.5	3.45	3
General	Q20	4.27	4.19	4.2	4.5	4.36	5

Whilst Table 7 above compared the biases between the groups, Table 8 has been re-categorised to facilitate comparison of the scores in relation to each question.

It can be seen that the only 'Strongly negative' responses came from the passerby group who did not feel they had learnt more about marine species or reflected on habitat loss. The passerby group scored food security as a top priority and was 'Strongly positive' about the presence of the artificial reefs in Oceanhamnen.

The mixed group were predominantly 'Neutral' or 'Positive' in their responses. The lack of 'Negative' or 'Strongly negative' responses in the combined group is a promising sign as this group is the most representative of the local populace. Food security was the most consistent result with 'Positive' across all questions.

The respondents from the Havskoloni group showed the most 'Negative' responses across the survey and these results confirmed that the primary interest of this group was in food. This was a slightly surprising result as this group also expressed an overall 'Strongly Positive' response towards the presence of the artificial reefs (Q15).

The GreenHaus Castellum scored both the presence of the reefs and food security highly. However, the questions relating to biodiversity all scored 'Neutral' or worse, although this result may have been skewed by pre-existing knowledge.

The Ophelias Brygga group scored almost entirely 'Positive' or 'Strongly positive' with the exception of being the least aware of fishing occurring locally.

Table 9. Summary of the results from Table 8 by section. The 'Biodiversity' section represents Q5-8, the 'Food security' section Q9-13 and the 'Ecosystem services' section Q14-19. The scores for each survey section have been categorised into the following five bins: 'Strongly negative' (red, 0-1), 'Negative' (orange 1.01-2), 'Neutral' (yellow, 2.01-3), 'Positive' (light green, 3.01-4) and 'Strongly positive' (dark green, 4.01-5). The bracketed numbers indicate the sample size for each column.

	Average Score					
Section	Total (45)	Mixed group (26)	Havskoloni (5)	Ophelias Brygga (2)	Greenhaus Castellum (11)	Passersby (1)
Biodiversity	2.94	3.02	2.75	3.50	2.77	2.75
Food security	3.76	3.64	4.20	4.00	3.67	5.00
Ecosystem services	3.22	3.22	2.36	4.50	3.31	3.80

Table 9 shows that the overall responses range between 'Neutral' and 'Strongly positive' for each of the sections above. Food security had the most 'Strongly positive' responses, closely followed by ecosystem services. However, biodiversity was ranked as 'Neutral' by the majority of respondent groups indicating that this parameter is less important in people's perception than both food security and ecosystem services.

The scores in the 'Total' column follow the same trend as the scores seen when the data is broken up by group – food security was the most valued, closely followed by ecosystem services and then biodiversity. Overall, biodiversity ranked lowest for all groups except the Havskoloni. Ophelias Brygga was the only group to score ecosystem services as its top priority.

4. Discussion

4.1 Biodiversity

The stone reef and living seawall both had higher observed species richness and density of coverage in 2024 compared to 2023; these positive increases in species establishment over time indicate that the artificial reef structures are supporting biodiversity. However, it is likely that there were some discrepancies in scoring for low, moderate and high abundance (Tables 1 and 2) between the 2023 and 2024 inventories (Looström *et al.* 2023). *Pilayella*, for example, was scored at high abundance in the 2023 data; however, there was visibly more in the 2024 transect footage but no higher score was available. Blue mussels, on the other hand, were scored as high abundance on the living seawall in 2023 and only moderate in 2024 despite more blue mussels being visible on the living seawall panels in the 2024 footage than in the 2023 footage. The 2024 scoring predominantly focused on the panels themselves over the background seawall as the background wall did not differ from the control site. It was unclear whether the 2023 study incorporated the background wall in its estimate or if differences may be due to the larger study area in 2023 facilitated by the use of scuba diving equipment. However, these uncertainties in scoring comparisons between the years were a limitation of this project.

Macroalgae and bivalves are not domesticated species but nevertheless natural colonisation by a variety of different wild seaweeds and blue mussels was to be expected at all three of the Helsingborg project sites, with anchorage available at the stone reef and living seawall and on the floating platform’s cultivation lines (Thilsted 2021). One reason for the increased diversity of species found at the stone reef compared to the living seawall (Tables 1 and 2) may be that the stone reef provided a more complex three-dimensional environment which could facilitate more niches and therefore support more biodiversity.

In this project, more differences could be seen between the reef surfaces and the reference (control) surfaces than could be seen in the 2023 report (Looström *et al.* 2023). It was difficult to assess whether one artificial reef was more successful at promoting biodiversity than the other as both the stone reef and living seawall showed the most colonisation by the species that predominated the surrounding area before their installation – mussels in the case of the living seawall and *Fucus* in the case of the stone reef. Both also shared a coverage of filamentous macroalgae. The amount of macroalgal present indicates that the hard surfaces remained suitable for attachment. Mussels seemed to congregate between the rocks on the stone reef and in the crevices of the seawall panels implying that the more exposed outer surfaces may be less beneficial for attachment in areas with a stronger current or surf.

Whilst it can be taken as a positive that the coverage of both sites had increased, more may need to be done to increase the diversity of species at the living seawall. Poor connectivity between habitats can hamper recolonisation of new substrates from source populations (Franz *et al.* 2019). For example, the required dispersal distance from existing *Fucus* populations was likely too long to facilitate colonisation of the living seawall. The eggs of *Fucus vesiculosus* tend to fall straight down to the seabed making recolonisation of more distant areas a slow process, and so it may be necessary to transplant these species into place to combat the dominance of filamentous species (Serrão *et al.* 1999; Rönnbäck *et al.* 2007). As mussels produce pelagic larvae in large amounts which are then distributed by currents, re-colonisation by mussels is much faster than by *Fucus*; as such, mussels may cover available habitat so extensively that macroalgae will later struggle to gain a foothold (Kautsky 1982; Rönnbäck *et al.* 2007; Franz *et al.* 2019). This may negatively affect the living seawall as colonisation by mussels is likely to outpace what is possible by *Fucus* migration from adjacent areas.

In the Öresund Strait, *Fucus* extends to an average depth of around 1.5m which is consistent with what was seen on the stone reef (Torn *et al.* 2006). These macrophytes, which form the underwater forests of the Baltic Sea, are large, long-lived and no other species is able to fill their niche (Rönnbäck *et al.* 2007; Wikström & Kautsky 2007). *Fucus* provides habitat for a large invertebrate biomass which in turn acts as a food source for the higher trophic levels (Wikström & Kautsky 2007). As such, the loss of *Fucus* is accompanied by the loss of the species-rich community that utilises it as habitat along with declines in commercially important fish species, such as perch and pike, which use *Fucus* forests as spawning grounds (Kautsky *et al.* 1992; Rönnbäck *et al.* 2007; Wikström & Kautsky 2007). Few fish species were documented during the inventory but filming took place quite early in the season meaning it was likely still too cold for many fish species to have moved into the area for spawning or feeding (Taylor *et al.* 2017).

Decreases in the coverage and depth distribution of *Fucus vesiculosus* have led to habitat loss alongside increases in filamentous macroalgae (Torn *et al.* 2006; Franz *et al.* 2019). However, whilst filamentous macroalgae dominated all depths of the stone reef in 2023, *Fucus sp.* have started to gain a strong foothold in the upper sections of the reef; this is restoring vital lost habitat and providing niches that will actively support other marine species (Torn *et al.* 2006;

Wikström & Kautsky 2007; Franz *et al.* 2019). Coastal communities on hard boulders have been amongst the most species-rich and productive in the Baltic Sea since the last Ice Age and can typically host around 60 taxa of sessile marine flora and fauna (Kautsky & Kautsky 2000; Wahl *et al.* 2013; Franz *et al.* 2019).

A high predominance of filamentous macroalgae, such as on the deeper sections of the stone reef, may negatively affect the production of aquatic food by reducing circulating oxygen and therefore the biomass of the benthic fauna needed to support the higher trophic levels of the food chain (Norkko & Bonsdorff 1996; Troell *et al.* 2005; Rönnbäck *et al.* 2007). The feeding success of species such as cod can also be reduced in the absence of perennial vegetation (Isaksson *et al.* 1994; Rönnbäck *et al.* 2007). However, grazers such as isopods and gastropods can control the amount of filamentous macroalgae colonising hard substrates thereby clearing space for colonisation by perennial macroalgae (Råberg *et al.* 2005; Rönnbäck *et al.* 2007). It is to be hoped that the perennial vegetation continues to take over more of the stone reef with time but this will need to be monitored. Macroalgae have the potential to provide coverage down to about 15m depth in the transition areas of the Baltic Sea (Voipio 1981; Rönnbäck *et al.* 2007).

In contrast to the stone reef, manmade seawalls are usually homogeneous with only a single dimension and therefore lack the structural complexity found on the natural rocky shores they replace (Dafforn *et al.* 2016). The conversion of harbour walls into living seawalls is an example of ecological engineering, which has been shown to support ecosystem functioning and biodiversity (Dafforn *et al.* 2016; Strain *et al.* 2017). In Helsingborg, the addition of the living seawall reef panels has helped to increase colonisation beyond that of the base seawall (Figure 14). The increased coverage by macroalgae in 2024 compared to 2023 (Figure 11) was likely due to the additional surface area provided by the panels facilitating more growth (Looström *et al.* 2023). The original panels installed in 2022 are quite flat to the seawall whereas the addition of more panels in 2023 gave more depth to the living seawall and hence higher structural complexity. However, this support is to a lesser extent than stone reef as the vertical arrangement of the living seawall provides less surface area, fewer sheltered hiding places and fewer microhabitats (Strain *et al.* 2017). This was reflected in the results of the inventory in both 2023 and 2024 (Tables 1 and 2).

Worldwide, over 50% of natural foreshores have been replaced by manmade structures such as seawalls (Strain *et al.* 2017). This highlights the enormous potential impact that installing artificial reef panels on living seawalls could have around the world. However, it should be noted that the foreign materials used to create living seawalls and stone reefs may attract different ecological communities with varying species composition, including non-indigenous species (Kilfoyle *et al.* 2013; Dafforn *et al.* 2016; Loch *et al.* 2020). Whilst artificial reefs undoubtedly provide suitable habitat for colonisation, they will not fully replicate the characteristics of a natural environment, potentially leading to a different species assemblage and therefore different ecosystem services in comparison to natural habitats (Kilfoyle *et al.* 2013). As such, artificial reefs cannot be considered a complete replacement for lost habitat and should be carefully evaluated to see if the structure installed is actually providing sufficient and effective mitigation (Kilfoyle *et al.* 2013).

Additionally, the seafloor in the sheltered harbour area was previously sandy mud prior to the construction of the stone reef; this reef facilitated the migration of new species into the harbour area as they could attach to points along the newly installed hard substrate that was not previously available (Cresson *et al.* 2014; Wilms *et al.* 2021). As the loss of biodiversity is reducing marine resilience, including the capacity to maintain water quality and provide food, maintaining essential habitats such as coastal reefs is important for restoring biodiversity and therefore ecosystem services (Worm *et al.* 2006).

During the survey, local people responded that they felt others had learned more about marine species (Figure 31) since the installation of the artificial reefs but did not feel they had personally gained any new knowledge in this area (Figure 29). Whilst this could be due to the GreenHaus Castellum cohort who indicated they had pre-existing knowledge and so had not actively learnt more about marine species since the installation, this could be an area in which the City of Helsingborg could focus a public information campaign in future. Table 7 also indicates that increasing the availability and accessibility of information about biodiversity and marine species would be beneficial to local citizens.

4.2 Food security

Blue mussels have the potential to grow over 30mm long in their first year and reach a maximum length of 90mm after approximately five years (Kautsky 1982). This demonstrates that growth rate declines as mussels become larger, which matches the trend seen in Figure 25. Blue mussel growth was shown to be dependent on age, site and sampling depth, but not on type of hard substrate. The ferries docking close to the harbour cyclically altered the water depth during sampling. However, the stone reef control and the dockside control came from shallower and deeper areas of the same harbour wall and thereby confirmed that depth had a bearing on mussel size. The mussels from the dockside were likely older than those present on the stone reef (Table 3), which could potentially account for the larger size of the dockside mussels (Figure 23). Additionally, the mussels from the stone reef may have been more vulnerable to predation, for example from seabirds, than at the deeper dockside site, resulting in more frequent recolonisation and therefore smaller mussels in shallower areas. This indicates that age, site and depth are all interconnected variables which affect mussel size.

The comparison of mussel dimensions (Figure 21) implied that mussel growth was better on the living seawall than on the stone reef. However, it was much easier to find mussels on the living seawall due to less macroalgal coverage and so this may have affected the result. It is possible that the panel crevices on the living seawall also offered greater protection for the mussels than the baseline seawall (Figure 18) although it may be worth investigating whether mussels attached to the surfaces of panels are more vulnerable or whether the surfaces are difficult for the mussels to attach to. As the mean length of the mussels in the artificial reef sites was comparable to their control sites regardless of the augmentation of the boulders or living seawall panels (Table 5), this indicates that mussel growth was predominantly site dependent and not so dependent on the availability of more naturalised substrates.

Sampling design is important here in order to try and encompass the full range of mussel sizes available at each site and so future research could be done on larger sample sizes to see if the same size distribution patterns are replicated. Additionally, whilst mussel size was little affected by type of hard substrate after two years (Figure 26, Table 5), it would be interesting to re-assess this in future to see if the artificial reefs start to outperform the surrounding harbour walls in terms of mussel growth over time.

It could be postulated that the best way to grow mussels would be to allow them to uniformly colonise a concrete wall, such as a seawall or dockside, as the control sites showed by far the highest mussel abundance. However, as can be seen in the dockside comparison in Figure 17, this approach would not beneficial for other species such as macrophytes or fish. Whilst adding reef panels or boulders may not increase food security directly in relation to mussels, it does increase attachment points for macroalgae, act as nursery areas and shelter for other species and increase biomass thereby benefitting the wider trophic network and supporting other aquatic foods that are desired by humans (Cresson *et al.* 2014).

Whilst promoting food security in the long term aligns with the installation of artificial reefs, in areas where this is not possible to implement, cultivating on flat surfaces such as a seawall could help augment nutritional security. However, the areas where this would be most applicable are also likely to be areas with higher levels of pollution and, as blue mussels are filter species, this could render them unsafe for human consumption and so negate the benefits of cultivation for food provisioning. It has also been postulated that artificial reefs may contribute to self-purification of the marine environment by facilitating high settlement and later reproductive rate of sessile filter-feeding organisms (Chojnacki 2000; Fabi *et al.* 2011). This is an example of habitat restoration through biofiltration although it may raise a food safety concern over the ingestion of organisms such as blue mussels from a polluted waterbody (Fabi *et al.* 2011).

The transition areas of the Baltic Sea, such as the Kattegat and Öresund, have historically suffered heavy pollution as a sewage outlet from around 70 Danish and Swedish municipalities, as a hot water effluent outlet from Swedish nuclear power plants, as the 'flushing point' for the huge catchments draining into the wider Baltic Sea, from oil spills and from the myriad shipping transits passing through the Danish Straits (Miller 1974; Fabi *et al.* 2011). Persistent eutrophication and pollution have deteriorated the water quality (Fabi *et al.* 2011). Efforts have been made to reduce the volume and effects of pollution in the Straits but, as they remain an active shipping zone, questions may be raised about whether the water quality in these areas will render the mussels, which act as marine filters, unsafe for human consumption. However, in general, limiting pressures from human activity within the constraints necessitated by food provisioning should help efforts to restore resilience to coastal marine environments (Arthington *et al.* 2016).

A pollution cap was installed in Oceanhamnen and municipal wastewater from Helsingborg was diverted away from the area (Helsingborgs Stad 2019; Helsingborgs Stad 2021). Water quality tests carried out in 2023 showed that contaminants such as mercury, lead, dioxin, polychlorinated biphenyls and dichlorodiphenyltrichloroethane were all under the limits set by the World Health Organisation meaning that the consumption of mussels cultivated here should be safe for the public (Helsingborgs Stad 2023). The mussel colony has the potential to enhance the food environment of Helsingborg by increasing the availability of fresh, locally cultivated mussels (WorldFish *et al.* 2020). This could also alter consumer behaviour, nutrition and health (WorldFish *et al.* 2020). As consumers continue to show preference for convenience foods, being in close proximity to a source of good quality mussels has the potential to influence the diet of the citizens of Helsingborg (WorldFish *et al.* 2020).

However, given that multiple pieces of macroplastic were found during sampling, this implies the presence of microplastics as well. Plastic waste negatively affects marine ecosystems; microplastic in particular can become part of the food chain and may have direct effects on human health when ingested (Carberya *et al.* 2018; WorldFish *et al.* 2020; Yuan *et al.* 2022). Microplastics can also carry biofilms which may include pathogens and antimicrobial resistant microorganisms (Carberya *et al.* 2018; Wang *et al.* 2019). Microplastics are fairly ubiquitous in aquatic environments but, whilst the transfer of microplastics up the trophic levels can have negative effects on human health, analysing the extent of the effects of microplastics within artificial reefs remains beyond the scope of this project (Wang *et al.* 2019; Yuan *et al.* 2022).

Blue mussels within the Baltic Sea subsist at the edge of their salinity tolerance meaning that any changes in salinity are likely to have a pronounced effect on growth (Kautsky 1982; Almada-Villela 1984; Franz *et al.* 2019; Liénart *et al.* 2021). As the Öresund Strait is a transition area into the Baltic Sea Proper, the mussels at the Helsingborg sites are likely to be affected by water influxes from the North Sea which can temporarily raise salinity and therefore promote better mussel growth in these sites. As salinity is the main factor affecting mussel growth in the Baltic Sea, salinity therefore also determines maximum mussel size meaning that the wider environment will determine the total biomass produced by mussels (Kautsky 1982; Almada-Villela 1984). This could be a limiting factor for food security in some areas.

Mussels exhibit changes in their morphology in response to the surrounding environment, such as wave exposure (Lauzon-Guay *et al.* 2005). Growing mussels from a floating platform, an example of suspended aquaculture, has the advantages of easy harvesting and faster growth rates over mussels grown on solid substrates but this can be directly impacted by the density of mussels added to each cultivation net (Lauzon-Guay *et al.* 2005). Mussels grown in high density conditions typically exhibit a lower width:length ratio, an adaptation that allows growth for a longer time without becoming constrained by neighbouring mussels (Lauzon-Guay *et al.* 2005). The mussel colony has the lowest width:length ratio; it may be that this is age-dependent but could also possibly be related to growing close together on the cultivation nets. The mussels on the cultivation nets were quite small at the time of sampling but it would be interesting to see if continued growth starts to lead to increased fall-off of these mussels in response to increased competition for space and resources. Width:length ratios typically increase with mussel size (Lauzon-Guay *et al.* 2005); this is consistent with the findings seen in Table 3 above. Additionally, whilst mussel cultivation was not particularly enhanced by substrate type (Figure 22), mussels were growing well in the mussel colony and so it would be interesting to review the colony again in one year to see if the size becomes comparable to the two year old mussels found on the neighbouring stone reef.

Blue mussel farming in the Baltic Sea can help improve socio-economic sustainability through the provision of livelihoods (SDG1) (Kotta *et al.* 2020; United Nations 2024a). The survey demonstrated that aquatic foods are important to the community in Helsingborg (Figure 30) indicating there would be local demand for mussels if cultivation were to continue longer term. However, in Figure 28, the potential of the artificial reefs as a food source was not listed as a strong priority with only 20% of participants registering it as an interest. As Figure 30 indicates a strong preference for cultivating mussels locally rather than buying from distant suppliers, this implies that there may be a disconnect between the aquatic food end product and where it comes from. This suggests that more needs to be done to raise awareness that mussel cultivation is possible locally, even in urban harbours areas.

Currently the mussel colony is maintained via the work of community volunteers but, if scaled up in future, it may possibly provide livelihoods for some local inhabitants. The volunteer citizen group is also gaining new knowledge and skills, although their survey results indicated that they were predominantly taking part in anticipation of the expected harvest next year. The platform itself is located down a short flight of stairs but is otherwise fairly inclusive in terms of accessibility.

It is possible that social media could play a role in inducting these mussels into the local diet. The Instagram page 'Havoteket' documents the activities of the City of Helsingborg relating to their marine projects; these projects have also received other media attention, for example in local newspapers. Increased publicity and awareness of this project will likely generate interest amongst the locals to try this new food source. However, once the novelty of the project passes, it will require conscious consumer choices in order to maintain the demand for a continuous supply of locally produced mussels for the community in the long term.

4.3 Ecosystem services

Ecosystem services can be split into three categories, cultural, regulating and provisioning, all of which have economic value (Rönnbäck *et al.* 2007). Provisioning services provide raw materials, aquatic foods and medicines; coastal ecosystems support over 75% of commercially and recreationally important finfish species in Sweden by providing feeding, breeding and nursery grounds, most commonly in macroalgae-dominated habitats like the stone reef (Rönnbäck *et al.* 2007). Regulation includes biogeochemical cycling and other ecological processes which contribute to ecosystem resilience, mitigation of eutrophication, climate regulation and control of nuisance species, pests, pathogens and pollutants (Rönnbäck *et al.* 2007). Cultural services include an aesthetically attractive environment which can provide inspiration, enjoyment, education and research opportunities, as well as the possibility for activities that contribute to community health and wellbeing such as swimming, fishing and sailing (Rönnbäck *et al.* 2007). Poor water quality can negatively affect coastal property prices, recreation and tourism (Leggett & Bockstael 2000; Söderqvist *et al.* 2005; Rönnbäck *et al.* 2007). There is also an element of preserving these coastal ecosystems for future generations, recorded as a stronger motivation by Swedish citizens than for their own use – this also tallies with the tendencies seen in the survey in which the knowledge that the artificial reefs are present was scored more positively than any direct interactions (Söderqvist 1998; Rönnbäck *et al.* 2007).

In the ecosystem services section of the survey, the Havskoloni group seemed the least aware of any direct benefits from the artificial reefs other than the food provisioning (Table 7). As this group consists of motivated volunteers, it was perhaps a little surprising to see that the responses of this group related so strongly to food with much lesser regard for the environment in which this food is being grown. In contrast, the Ophelias Brygga group were least aware of fishing occurring locally. This was also somewhat strange as this group lives in the closest proximity to the reefs; however, some of these apartments are reportedly seasonal homes so that may explain this result. However, this group showed the highest appreciation of all the groups for the biodiversity and ecosystem services (Tables 8 and 9) that have been introduced to and provide a nicer environment in the Oceanhamnen area; this was interesting as it highlighted that indirect ecosystem services, such as clearer waters and opportunities for recreation, were most appreciated by those living in the immediate vicinity of the artificial reefs. The GreenHaus Castellum group were the most aware of ecosystem services which makes sense as these respondents were primarily from the office of the City of Helsingborg and so included educated professionals working on the artificial reef projects. Whilst this group scored lower than average for increased knowledge of ocean health, marine species and habitat loss, this would make sense for workers in this field who would already have prior knowledge of these issues.

Overall, the local citizens of Helsingborg placed the highest value on aquatic food security with an average score of 3.8 out of 5 (Table 9). Ecosystem services was ranked second with a score of 3.2, trailed by biodiversity with 2.9. This gap in scoring between food security and the other two elements suggests a knowledge gap amongst the local community as ecosystem services are directly dependent on biodiversity and food provisioning is an example of an ecosystem service (Rönnbäck *et al.* 2007). Figures 28 and 31 demonstrated that local people in Helsingborg deemed it important to feel connected to the sea but not as important to have access or to interact with the area directly. However, responses to Figure 31 also indicated that local citizens appreciate the presence of the artificial reefs. Knowing the reefs are there seems more important than incorporating them into daily activities. There is scope here to increase local people's understanding of the interconnectedness of biodiversity, food security and ecosystem services and their understanding of why an ecosystem approach is necessary to ensure the continuation of the food security they depend on. This correlates with Table 8 and suggests there is more to be done by the City of Helsingborg to raise the awareness of local citizens regarding the importance of ocean health and to demonstrate how essential support of the wider ecosystem is beyond what can be directly consumed.

Studies have shown that people are more likely to be motivated to support initiatives that secure ecosystem goods and services for the long term, which indirectly necessitates the preservation of biodiversity, than to support initiatives that directly preserve biodiversity (Pearce 2001; Rönnbäck *et al.* 2007). This was also reflected in the results of the survey which indicated that citizens of Helsingborg similarly value ecosystem services over biodiversity (Table 9). The loss of mussels or macroalgae can have major consequences for ecosystem services which makes it all the more vital that initiatives such as the artificial reefs continue to be put in place to support these populations and therefore their associated ecosystem services (Rönnbäck *et al.* 2007).

Broadly speaking, there are four dominant habitat types along the Swedish coast which are: [1]macroalgae on rocky substrate, [2]blue mussels on rocky substrate, [3]seagrass on sediment and [4]bare sediment (Rönnbäck *et al.* 2007). Each of these habitats supports different ecosystem services with a sandy seabed encouraging recreation, macroalgae and seagrass supporting fisheries and mussel beds helping to mitigate eutrophication (Rönnbäck *et al.* 2007). The

Oceanhamnen area pre-installation had an abundance of bare sediment but the addition of the artificial reefs has provided new rocky substrate for both macroalgae and mussels, along with support for local foodwebs and potentially improved water quality.

Ecological function must be maintained by the processes in ecological communities in order for marine ecosystems to be healthy (Franz *et al.* 2019). These processes are disproportionately influenced by foundation species, such as blue mussels, macrophytes and seagrasses, which occur in high abundance at low trophic levels (Rönnbäck *et al.* 2007; Hawkins *et al.* 2009; Franz *et al.* 2019). This highlights the importance of artificial reefs as they help support these populations which, in turn, directly contribute to coastal health.

Humans rely, both economically and socially, on the services provided by marine ecosystems, such as climate regulation and food provision (Dafforn *et al.* 2016). These ecosystem goods and services are themselves dependent on biodiversity (Hooper *et al.* 2005; Rönnbäck *et al.* 2007; Cardinale *et al.* 2012; Dafforn *et al.* 2016; FAO 2018). Aquatic ecosystems are naturally highly biodiverse, both structurally and functionally, and so have the potential to contribute to the recreational, social, cultural, economic and, crucially, nutritional betterment of society (FAO 2018). Furthermore, biodiversity also increases ecosystem resilience and so provides a buffer against potential economic losses (Worm *et al.* 2006; Rönnbäck *et al.* 2007; FAO 2018).

An prime example of biodiversity supporting ecosystem services is the blue mussel, a keystone species within the Baltic Sea, which can filter particulate matter from water, provide both habitat and food for other species and promote the cycling of nutrients and organic matter between pelagic and benthic ecosystems thereby reducing eutrophication (Kautsky & Evans 1987; Hawkins *et al.* 2009; Franz *et al.* 2019; Liénart *et al.* 2021; Åkermark *et al.* 2022). Eutrophication has altered the coastal waters around Sweden from systems with long-lived seagrasses and perennial macroalgae in clear water to turbid waters filled with large amounts of filamentous macroalgae (Kautsky & Kautsky 2000; Rönnbäck *et al.* 2007). Mussels, which can make up over 80% of the biomass on hard substrates, filter phytoplankton as a food source reducing algal blooms, and therefore water turbidity, which improves both water quality and transparency, and additionally has positive effects on the depth distribution of seagrass and macroalgae (Kautsky 1982; Kautsky & Kautsky 2000; Rönnbäck *et al.* 2007; Kotta *et al.* 2020; Åkermark *et al.* 2022). Additionally, mussels are a food source for commercially important fish such as cod (Franz *et al.* 2019). Blue mussels are a valuable asset with a strong influence on the economic and recreational opportunities in the Baltic Sea; this one species can contribute to cultural, regulating and provisioning ecosystem services (Rönnbäck *et al.* 2007; Kotta *et al.* 2020; Åkermark *et al.* 2022).

Blue mussels can also be used as a bioindicator for environmental status (Rönnbäck *et al.* 2007; Liénart *et al.* 2021). Declines in blue mussel populations have knock-on effects on the structure of coastal communities, ecosystem function and therefore ecosystem services (Franz *et al.* 2019). Populations of blue mussels have replaced declining *Fucus* species in many Baltic habitats which has promoted an increase in red filamentous macroalgae (Rönnbäck *et al.* 2007; Franz *et al.* 2019). Furthermore, the presence of large blue mussel populations has been correlated with negative impacts on the diversity of sessile fauna, as can be seen above in Figures 17 and 19. Dense and extensive mussel beds, such as those seen on the seawall, are associated with low levels of biodiversity as they outcompete other sessile species for space on hard substrates (Kautsky 1982; Franz *et al.* 2019). Conversely, it has been shown that declines in mussel populations facilitate recolonisation by perennial macrophytes, including *Fucus* (Torn *et al.* 2006; Rönnbäck *et al.* 2007; Franz *et al.* 2019). This indicates that, in terms of blue mussels, biodiversity is inversely associated with food security. Declines in perennial macroalgae leading to replacement by blue mussel beds leads to reduced fish production, reduced storm protection, reductions in aesthetics and recreation but an increase in the capacity of the area to mitigate eutrophication (Rönnbäck *et al.* 2007).

Blue mussel biomass and coverage have been recorded as decreasing across the Baltic Sea region since the early 1990s; this was attributed to increased predation pressure, higher winter temperatures and changes in salinity (Franz *et al.* 2019; Liénart *et al.* 2021; Åkermark *et al.* 2022). Decreasing abundance and biomass of blue mussels negatively affects local biodiversity and overall ecosystem function (Koivisto & Westerbom 2010; Franz *et al.* 2019; Liénart *et al.* 2021). Mean shell length also decreased by 6% between 1993 and 2015 across the northern Baltic Sea (Åkermark *et al.* 2022). However, it has also been suggested that eutrophication led to an increase in mussel shell length in the 1970s and ‘80s which would indicate that the trend of decreasing shell length in mussels since the 1990s may be attributable to a reduction in eutrophication which, whilst negatively affecting mussel size and filtration capacity, would have beneficial effects for the wider marine ecosystem in the Baltic Sea (Kautsky *et al.* 1992; Liénart *et al.* 2021; Åkermark *et al.* 2022).

As the biomass of blue mussels decreases, the food intake per unit foraging time also decreases for seabirds which can lead to reduced reproductive success (Waldeck & Larsson 2013;

Åkermark *et al.* 2022). This demonstrates that the health of coastal mussel populations can have a direct impact on the wider coastal foodweb and that a thriving mussel population can actively support biodiversity by acting as a food source for other species, both water- and airborne (Waldeck & Larsson 2013; Åkermark *et al.* 2022).

Mussel populations have also become dominated by smaller individuals which is negatively affecting their filtration capacity, a decrease of 16% between 1993 and 2015 in the Baltic Sea (Kautsky 1982; Åkermark *et al.* 2022). Mussels with a shorter shell length have lower filtration capacity; as shell length directly correlates to the filtration capacity of mussels across the entire population, optimising the growth of mussels will result in the provision of better ecosystem services (Liénart *et al.* 2021; Åkermark *et al.* 2022). The larger mussels from the dockside control (Figure 25) will have the best filtration capacity but as the mussels on the colony platform, stone reef and living seawall mature, their filtration capacity should continue to increase over time and so continue to improve water quality in the Oceanhamnen area. The installation of other stone reefs and living seawalls around the Baltic Sea region could also facilitate the attachment of more blue mussels and so increase the overall capacity for biofiltration in a known-polluted waterbody.

4.4 Comparison of artificial reef attributes

The stone reef is a direct replacement for lost natural habitat, the living seawall is an augmented manmade structure and the mussel colony an example of floating food production. As manmade harbours have limited natural value, the addition of these artificial structures is not an ethical issue because they are contributing positively towards a healthier marine environment in Oceanhamnen and towards multiple Sustainable Development Goals, including 'Life below water' (SDG14), 'Good health and wellbeing' (SDG3) and 'Sustainable cities and communities' (SDG11) (United Nations 2024a).

Each of these artificial reefs contributes in a different way to the coastal ecosystem in Helsingborg harbour. The stone reef predominantly supports biodiversity and ecosystem services but only indirectly supports food security through the provision of biomass to the upper trophic levels and the provision of nursery habitat, both of which support the species on which the fishing industry relies. Similarly to the stone reef, the living seawall supports biodiversity and ecosystem services although it could be argued that it does so to a lesser extent than the stone reef as its species composition remains more limited. However, the living seawall did have a higher abundance of blue mussels and so could be said to contribute more towards food security than the stone reef. The mussel colony primarily supports food security but has a further ecosystem services component through the biofiltration performed by the mussels. The mussel colony also has the most potential for maximising the biomass of mussels with minimum effort whilst generating social values within the local community that maintains the colony.

Whilst it can be seen that the three hypotheses of this study are correct, none of the three installations in Helsingborg can be said to support all of the assessed attributes. However, the combination of all three reef types in close proximity may facilitate the provision of these attributes, even within an urban harbour setting such as Oceanhamnen. It would depend on the priorities of the local community, as well as the coastal landscape type, as to which artificial reef type or types would be best candidate for installation within other coastal areas.

All control sites were dominated by large mussel beds on otherwise flat concrete surfaces and so could support food security and, to a limited extent, ecosystem services, but make little contribution towards biodiversity and so would not support the wider foodweb. As can be seen in Figures 17 and 19 above, these mussel beds were fairly shallow, extensive and potentially easy to harvest by just scrapping the concrete wall. Blue mussels can be harvested after three years and so, if food security was the priority, harvesting one third of the dockside walls annually could be the best way to secure a local food source. This may even outperform the mussel colony platform as the dockside walls have a much larger surface area. However, the dockside walls are species-poor and so this approach would do little to support biodiversity or ecosystem services.

Local citizens can experience immediate benefits from increased aquatic food security whereas the benefits of biodiversity and ecosystem services are not immediate and may occur more remotely. People may be motivated by access to fresh seafood and by a more pleasant coastal environment but more education is needed to sway public interest towards preserving the wider marine ecosystem over instant gratifications as these will be lost without putting more extensive marine protections into place. In other words, it would be beneficial to engage the public in supporting processes rather than outcomes. Even if food security remains the priority, broader public thinking and education are needed so people understand that artificial reefs can support the larger marine foodweb.

In order to motivate public interest in artificial reefs, a human-centric incentive would be needed that aligns social values with the desired natural goals. For this, a focus on ecosystem services could work for those in close proximity, or a focus on food security for those at greater distance; biodiversity has been shown to be less of a motivator, at least amongst the local citizens of Helsingborg (Table 9). The benefits of biodiversity may be less tangible but more education is needed so people understand that biodiversity underpins important aspects such as food provisioning and clean waters. It could be that a combined focus on ecosystem services and food security would generate the widest social buy-in to more coastal conservation projects of a similar nature to the ones in Helsingborg. Stakeholder engagement is vital to the success of such projects (Gann *et al.* 2019).

As the artificial reefs are not long established, carrying out monitoring surveys in future years would be beneficial to see how they develop and change over time. It may be that with further development, different outcomes, such as biodiversity, become more prominent and the values of the local community may also change.

4.5 Agroecological perspective

Humanity finds itself in the midst of the "Blue Revolution" in which economic, cultural and environmental pressures are driving the transition away from wild capture towards intensive aquaculture production of aquatic foods (FAO 2018; Kuempel *et al.* 2021). The expansion of blue growth globally now means consumption of fish has exceeded that of all terrestrial meats combined (FAO 2018). Whilst this movement is influenced by environmental awareness, technological advances and the globalisation of trade, both management and regulatory decisions still differ worldwide meaning the future of aquatic food production is not yet certain (FAO 2018; Kuempel *et al.* 2021). Globalisation is likely a strong driver behind the increased demand for aquatic products as once traditional and localised cuisines have now spread across the world (FAO 2018; Kuempel *et al.* 2021; Zhao *et al.* 2024). It should also be borne in mind that society as a whole now has far more awareness of environmental health than was known during the "Green Revolution" and so there is a greater drive this time to ensure that the "Blue Revolution" does not surpass ecological limits and put too much strain on aquatic systems (Springmann *et al.* 2018; Kuempel *et al.* 2021). Nevertheless, it is clear that if managed correctly with proper consideration for ecosystem limits, marine ecosystems have the potential to meet the protein demand of the ever-expanding human population, as well as providing additional benefits for both human and environmental health (Tilman & Clark 2014; Willett *et al.* 2019; Kuempel *et al.* 2021).

Aquaculture is estimated to be over 2.5 times more efficient in terms of labour than commercial fisheries (Kuempel *et al.* 2021). However, currently over 50% of the global aquatic products produced by aquaculture originate from just ten species, calling into question the legitimacy of this approach as a future strategy for sustainable production due to its lack of biodiversity (Ottinger *et al.* 2016; Kuempel *et al.* 2021). This would be negated to some extent by a corresponding transition away from commercial fisheries which would potentially leave millions more tonnes of wildlife within the world's oceans (Kuempel *et al.* 2021). Nevertheless, proactive policies and regulations with a scientific evidence base would be needed to mitigate the potential negative impacts of the expansion of aquaculture (Gentry *et al.* 2017; Kuempel *et al.* 2021). It is likely that the uptake of mariculture (farming within a marine environment) will continue to expand making Helsingborg's trial of urban mussel cultivation very interesting as a potential starting point and segway into further mariculture developments (Kuempel *et al.* 2021).

Human activities are likely to continue to jeopardise marine populations in coastal ecosystems, especially as the global population continues to increase, and so it is vital that a multitude of different conservation measures are put into place on a variety of scales (Arthington *et al.* 2016). The artificial reef projects in Helsingborg fit into the EU Mission to "Restore our Ocean and Waters", hitting all criteria of engaging citizens in research and innovation via blue investments with the aim of nature restoration in the Baltic Sea (European Commission 2023). Artificial reefs are often installed within marine protected areas in coastal regions to restore degraded habitats and support smaller scale fisheries (Cresson *et al.* 2014). These reefs are associated with increased biomass of fish resulting from the enhanced growth of recruited individuals due to the increased availability of resources, such as shelter and food, in the artificial habitat (Cresson *et al.* 2014). Over time, artificial reefs become established as breeding grounds and nursery areas for fish populations (Cresson *et al.* 2014).

The placement of artificial reefs should be based on scientifically sound criteria, be developed within the regulatory framework of the region and not cause further marine pollution or degradation as a result of installation (Fabi *et al.* 2011). Ideally, environmental impact assessments should be applied to reef installations and further multi-year monitoring of the artificial reefs, surrounding marine environment and living resources should continue on afterwards (Fabi *et al.* 2011). Management measures should aim to avoid possible conflicts and to maintain reef resources over time (Fabi *et al.* 2011). Feasibility studies for reef installation may include evaluation of the environmental features and substrate in the proposed area along with the local fish assemblage, pre-existing sensitive ecosystems which may be important for exploitable species and review of the socio-economic aspects of fisheries in the area (Fabi *et al.* 2011). It should also be considered whether the goal of restoration is to replicate the species composition of natural habitats or to restore functional trophic interactions even if different equivalent species take over the niches (Kilfoyle *et al.* 2013; Loch *et al.* 2020).

Site selection should demonstrate the need for an artificial reef, an absence of conflicts with current and future users due to installation, no negative environmental impacts predicted for installation, sufficient substrate and depth to provide stability, close to port and of sufficient depth to protect juveniles of species important to the fishing industry (Fabi *et al.* 2011). The structure of the proposed reef should also be planned with reference to the oceanography of the area (Fabi *et al.* 2011). It is debated whether attempts to correct the negative impact of human activities on biodiversity should focus on single large scale habitats or on multiple smaller scale habitats (Wilms *et al.* 2021). Whilst larger habitats can provide stable conditions for a greater abundance of species, smaller scale habitats tend to be more heterogenous and several of these smaller systems may cover a greater geographic range than one larger system (Wilms *et al.* 2021). However, dispersal may be more likely within marine systems and so one larger site could potentially re-populate neighbouring habitats across distances estimated at over 40kilometres (Wilms *et al.* 2021).

It has been shown that the depth and arrangement of submerged materials are important when trying to attract aquatic species, including fish, to an artificial reef (Fabi *et al.* 2011). The complexity of the habitat is linked to geodiversity and therefore directly affects biodiversity even within aquatic environments (Kaskela & Kotilainen 2017). Understanding how the geodiversity of the seabed links to species richness is key for establishing suitable marine protected areas or to determine the lowest impact areas for anthropogenic activities (Kaskela & Kotilainen 2017). It is vital to understand the abiotic factors that make up an environment as well as the biotic.

Some authors separate artificial reefs into two categories: production reefs and protection reefs (Fabi *et al.* 2011). Production reefs aim to increase exploitable biomass, including fish stocks, via the spatial redistribution of fish populations towards new habitat resources (Fabi *et al.*

2011). Protection reefs, on the other hand, seek to protect resources used by the fishing industry by preserving the natural habitats and ecosystems that support them whilst reducing conflicts between different users and protecting human infrastructure (Fabi *et al.* 2011). Production reefs often consist of larger units with holes in a variety of sizes and shapes to facilitate colonisation by marine organisms; protection reefs, in contrast, are heavy units which deter trawling and may include metal beams designed to entangle netting (Fabi *et al.* 2011). The stone reef in Helsingborg has attributes of protection and production as it supports both biomass and ecosystem services.

Marine reserves may increase species abundance, richness, biomass, fecundity and size as well as facilitating habitat recovery (Arthington *et al.* 2016). In this specific case example, the habitat around Helsingborg has been permanently altered by human activity and the installation of artificial structures will change the available niches within this environment. Similarly, it is important that marine reserves have the capacity to meet both biodiversity and socio-economic goals (Arthington *et al.* 2016). 34 phyla can be found within the world's oceans compared to a mere 15 on land (FAO 2018). This emphasises the importance of preserving biodiversity as it underpins existing and potential future inputs to both pharmaceutical and agricultural industries (Pearce 2001; Rönnbäck *et al.* 2007).

The loss of biological diversity is actively altering the functioning of ecosystems which in turn directly affects both the produce and the ecosystem services which they provide to society (Rönnbäck *et al.* 2007; Cardinale *et al.* 2012). Perturbations in a habitat as a result of anthropogenic activity may incur an extinction debt, in which it takes time for populations to become extinct following a major environmental disturbance (Kuussaari *et al.* 2009). However, there is some suggestion that an as yet unpaid extinction debt may be mitigated by targeted conservation efforts such as in the case of habitat restoration (Kuussaari *et al.* 2009). This could indicate that the correct placement and timing of artificial reef installation could help directly preserve biodiversity, and therefore ecosystem services, through the improvement of habitat availability and quality (Kuussaari *et al.* 2009).

Monitoring of attempted ecological restorations is crucial; measurable parameters should be tracked to establish progress towards the restoration goals (Gann *et al.* 2019). In the case of Helsingborg, these goals included cleaner water, improved biodiversity and closer connection of the local population to the sea (Bertilsson Vuksan 2022). However, a longer time period will be needed before the outcomes of the stone reef, living wall and floating platform projects can truly be determined. At a minimum, monitoring should be carried out before and immediately following habitat restoration to ensure resultant initial changes can be attributed to the restoration effort (Loch *et al.* 2020). It takes time to assess whether the higher trophic levels of native species have recovered and if ecosystem services have been restored (Loch *et al.* 2020). Further research is also needed to determine how reefs should be managed in order for their ecological processes to generate the desired biological and socio-economic outputs (Fabi *et al.* 2011). It would be interesting to assess what future implications this research area may have for aiding conservation efforts around manmade structures in marine areas.

With both the availability and diversity of wild aquatic foods declining worldwide, installing structures such as the stone reef and living seawall has the potential to help shore up the trophic levels and so support the larger aquatic foodweb through a 'bottom-up' approach (Dafforn *et al.* 2016). As habitats and nursery areas return, greater biomass will be generated at the lower trophic levels which can support the foodweb and thereby increase food security. If shown to be successful, one potential application for the vertical reef system could be to add it to the external walls of offshore windfarms to create more living seawalls and provide useable habitat within the photic zone but further offshore. However, regulations and costs currently prohibit the off-shore cultivation of mussels but nonetheless the ability to cultivate mussels locally in harbours, such as in Helsingborg, still renders this a good opportunity to increase urban food production (Gephart *et al.* 2021).

More than three billion people, predominantly in lower income countries, rely on aquatic foods as their primary protein source, with over one third of these described as wholly dependent on blue food (FAO 2018; WorldFish *et al.* 2020). In order to ensure a more sustainable future, aquatic food security cannot continue to be determined by production and quantity alone (Thilsted 2021). Instead, it is vital that society's thinking be expanded to encompass a broader ecosystem approach to solving this complex problem. Consumer demands are ever increasing for a diverse array of safe and nutritious aquatic food products but this is alongside an increased consumer awareness of, and concern over, the environmental costs of such production (FAO 2018; Thilsted 2021). A consumer movement such as this is likely to drive the much needed overhaul of the aquatic foods industry as innovative cultivation techniques and more sustainable practices are needed to establish food security for future generations. Investment and research, along with diversification, are crucial components in the drive to improve food security and aquatic sustainability (Thilsted 2021).

Demand for blue food is heavily influenced by how available and affordable it is for the local population (Naylor *et al.* 2021). Urbanisation in coastal zones may result in a locally increased demand for aquatic foods (Naylor *et al.* 2021). As such, if successful, initiatives such as the mussel cultivation being undertaken in Helsingborg harbour may go some way towards meeting this increased demand without environmental detriment. The decline of Baltic Sea fish populations has increased the reliance on imports and trade for Nordic countries, such as Sweden (Naylor *et al.* 2021). With the demand for aquatic foods set to increase globally, the environmental and nutritional effects of this will largely depend on the type and quantity of aquatic food consumed and to what extent this increased consumption directly substitutes for terrestrial animal protein (Naylor *et al.* 2021). If ultra-processed foods, for example, are replaced with higher dietary intake of aquatic foods, this could have positive effects on the prevalence of non-communicable diseases, such as obesity, within the human population (Naylor *et al.* 2021). However, it is important that this societal benefit does not come at a heavy cost to the environment or biodiversity in general. It is likely that aquaculture would have to be expanded more so than wild capture to meet this rising global demand (Naylor *et al.* 2021).

Farmed blue food remains one of the fastest growing sectors within the global food industry (Gephart *et al.* 2021). The global demand for responsibly sourced aquatic food has triggered a rise in certification, although this is to the exclusion of many small-scale producers (Naylor *et al.* 2021). Consumers prefer that blue foods be safe, tasty and fresh over sustainably obtained (Gephart *et al.* 2021). As such, education is a key component in starting to shift consumer mindset towards prioritising ecosystem health and long-term food security. Additionally, there is a risk that continuing climate change may place constraints on the availability of blue food (Naylor *et al.* 2021). This would cause rising prices, disproportionately impacting lower income consumers meaning that it is just as crucial to consider food equity and social justice in relation to the aquatic foods sector as it is in land-based agriculture (Naylor *et al.* 2021).

Fisheries exploit marine resources at higher rates than any non-human predator on the planet, sometimes harvesting in excess of 10% of the available adult biomass of prey species versus the <1% taken by other predators (Darimont *et al.* 2015). In fact, humans have been shown to take a higher proportion of fish than marine predators at all trophic levels establishing *Homo sapiens* firmly as a global "super predator" (Darimont *et al.* 2015). Human predatory behaviour has rapidly outpaced both rival predatory species and prey adaptations for defence or evasion; this human dominance is aided by cultural and sociopolitical systems, almost ubiquitous geographic expansion, rapid population growth and technology (Darimont *et al.* 2015).

Alongside this, as prey declines, exploitation continues to increase due to economic values rising as resources dwindle (Darimont *et al.* 2015). One corrective strategy to address this over-exploitation could be to mirror the behaviour of other predators, targeting less of the total population and selectively harvesting juveniles more so than the adult breeding population, rather than focusing so heavily on yields (Darimont *et al.* 2015).

It is vital that aquatic foods be included in strategies for sustainable food systems and nutritional security at both national and global levels (Naylor *et al.* 2021). Fish have a higher feed conversion efficiency than terrestrial animals meaning that they are much more efficient at changing energy inputs into body mass (WorldFish *et al.* 2020). Additionally, across all blue foods, farmed bivalves and macroalgae have been shown to have the least environmental impact in terms of emissions of greenhouse gases, phosphorus and nitrogen (Gephart *et al.* 2021). Macroalgae and mussels may be cultivated without any inputs of feed or fertiliser; they can also improve water quality and sequester carbon and so provide additional ecosystem services during cultivation (WorldFish *et al.* 2020). As bivalves and seaweeds are unfed, they form extractive systems which end up removing enough phosphorus that, despite the nitrogen emitted during production, it results in overall negative emissions (Kotta *et al.* 2020; Gephart *et al.* 2021). Farming bivalves also results in lower CO_2 emissions than capture of wild bivalves, likely due to the easier collection of cultivated stocks (Gephart *et al.* 2021).

Widespread sustainable marine management is vital, not just for wildlife conservation but also to help support the food industry and to promote a more holistic future. Loss of habitat leads to loss of biodiversity which leads to the loss of aquatic food security and ecosystem services and so directly impacts society (Cardinale *et al.* 2012). In the same way that the conversion of land for agriculture results in the loss of habitat, cultivating food in marine systems can comprise ecologically important areas that may serve as nursery habitats or carbon sinks (Gephart *et al.* 2021). Both trophic structure and ecosystem function should be considered when assessing ecosystem recovery (Loch *et al.* 2020). Aquatic restoration benefits from closer proximity to natural habitats and coastal restoration projects have been shown to particularly benefit birds and fish (Loch *et al.* 2020). Artificial reef systems can increase the available habitat for marine species and may help to negate the adverse effects of manmade structures in coastal regions.

The challenge of balancing the commercial and recreational interests with conservation persists as many stakeholders continue to vie for marine space (Arnason 2012; Kuempel *et al.* 2021).

The development of technology has increased the potential for collective global actions (Kuempel *et al.* 2021). However, steps towards sustainable aquatic food security may still be hampered by political, social, economic and legislative factors as well as by negative public perceptions of expanding aquacultural production (Kuempel *et al.* 2021). The prospect of adapting urban harbour areas has the potential to positively influence biodiversity, food security and ecosystem services and may therefore alleviate some of the demands for marine space by increasing the multifunctionality of existing coastal developments. These adaptations would also be easily accessible by local citizens who could then see the results of artificial reef installation and urban aquatic food cultivation firsthand, which could sway public support towards further conservation measures.

Aquatic food systems do not exist in isolation. Coastal systems connect freshwater and marine ecosystems although marine systems tend to be larger and without barriers for dispersal (Angelini 2019). The artificial reefs support the growth of macroalgae which, as a primary producer, can then support animal growth higher up the trophic levels (Angelini 2019). Species which are mobile and generalist help to colonise these new ecosystems and begin to support the foodwebs in these areas (Angelini 2019). On a broader scale, aquatic food systems exist within other systems such as agricultural ecosystems, social and economic systems, policy and culinary systems, transportation and health systems, etc. (WorldFish *et al.* 2020). Despite the seeming vastness of the world's oceans, industries such as tourism and undersea mining still compete for space with conservation efforts and fisheries, all driven by the blue economy (WorldFish *et al.* 2020). As such, the aquatic food industry forms crucial connections to many other environments and industries across the world.

Whilst agricultural research globally has traditionally focused on terrestrial livestock and crops, there is a need to expand this sector to further explore the true potential of aquatic foods (WorldFish *et al.* 2020). Projects like the artificial reefs align with the goals of the 2030 Agenda and support a multitude of Sustainable Development Goals, not just 'Life below water' but also no hunger, good health and education, clean water, innovation, sustainable cities, responsible consumption and 'Life on land' (SDGs 2, 3, 4, 6, 9, 11, 12, 14 and 15) (United Nations 2024b; United Nations 2024a). It has been estimated that, with proper management, the ocean could potentially meet the protein needs of over two thirds of the global population (six times the current output of aquatic food systems) (WorldFish *et al.* 2020). Aquatic foods must be considered alongside both livestock and land crops in order to develop sustainable nutritious diets within the limits of our planetary boundaries (Springmann *et al.* 2018; WorldFish *et al.*

2020). It is not possible to consider global food security without factoring in the contributions from the aquatic food sector (Springmann *et al.* 2018; WorldFish *et al.* 2020; Zhao *et al.* 2024). True food security must be considered from both land and water perspectives and this will need to be reflected by policymakers worldwide (WorldFish *et al.* 2020).

Projects like the artificial reefs tie into the wider picture of ocean governance which aims to manage the waterbodies of the world and their associated resources collectively to ensure their continued health and prosperity for present times and future generations (WorldFish *et al.* 2020; European Commission 2024). It is important to take an evidence-based approach to future decisions regarding marine health and sustainable aquatic food production; both innovation and thorough scientific research will be needed to meet the environmental, social and economic demands of this endeavour (WorldFish *et al.* 2020). Whilst aquatic food production typically incurs less environmental costs than terrestrial production, conservation and restoration efforts need to be balanced with transformation to more sustainable systems (WorldFish *et al.* 2020). It remains vital to connect food safety and nutrition with environmental health to ensure the development of sustainable aquatic food systems (WorldFish *et al.* 2020).

5. Conclusion

The artificial reefs in Helsingborg are supporting biodiversity by providing habitat for many species and attachment points for sessile flora and fauna. Mussel growth was affected by age, sampling depth and site, but not by the type of hard substrate. Helsingborg citizens valued food security most, closely followed by ecosystem services, but place a lower regard on biodiversity. Overall, this independent project found that coastal artificial reefs can help to improve biodiversity, aquatic food security and ecosystem services, even in urban marine environments.

References

Åkermark, C., Li´enart, C., D'Agata, C. & Karlson, A.M.L. (2022). Long-term decrease in Baltic Sea blue mussel shell length *Estuarine, Coastal and Shelf Science,* 276, 108029.

Almada-Villela, P.C. (1984). The effects of reduced salinity on the shell growth of small Mytilus edulis. *Journal of the Marine Biological Association of the United Kingdom,* 64(1), 171-182.

Angelini, R. (2019). Aquatic food webs will need to stand on giants' shoulders. *Acta Limnologica Brasiliensia,* 31.

Arnason, R. (2012). Property rights in fisheries: how much can individual transferable quotas accomplish? *Review of Environmental Economics and Policy,* 6, 217–236.

Arthington, A.H., Dulvy, N.K., Gladstone, W. & Winfield, I.J. (2016). Fish conservation in freshwater and marine realms: status, threats and management. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 26, 838-857.

Bertilsson Vuksan, S. (2022). The Ocean is Your Neighbour. City of Helsingborg Environmental Administration.

Cappo, M., Harvey, E., Malcolm, H. & Speare, P. (2003). Potential of video techniques to monitor diversity, abundance and size of fish in studies of marine protected areas. *Aquatic protected areas. What works best and how do we know?,* 1, 455-464.

Carberya, M., O'Connorb, W. & Thavamania, P. (2018). Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. *Environment International,* 115, 400-409.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B., Larigauderie, A., Srivastava, D.S. & Naeem, S. (2012). Biodiversity loss and its impact on humanity. *Nature,* 486, 59-67.

Centre, K. (2023). *Helsingborg sea colony grows mussels in Oceanhamnen*. https://www.gu.se/en/ocean/helsingborg-sea-colony-grows-mussels-in-oceanhamnen [02.03.2024]

Chojnacki, J.C. (2000). Environmental effects of artificial reefs in the southern Baltic (Pomerian Bay). In: *Artificial reefs in European Seas*. Kluwer Academic Publishers. 307-318.

Christie, H., Kraufvelin, P., Kraufvelin, L., Niemi, N. & Rinde, E. (2020). Disappearing Blue Mussels - Can Mesopredators Be Blamed? *Frontiers in Marine Science,* 7, 550.

Cresson, P., Ruitton, S. & Harmelin-Vivien, M. (2014). Artificial reefs do increase secondary biomass production: mechanisms evidenced by stable isotopes. *Marine Ecology Progress Series,* 509, 15-26.

Dafforn, K.A., Mayer-Pinto, M., Bugnot, A.B., Coleman, R.A., Morris, R.L. & Johnston, E.L. (2016). *Guiding Principles for Marine Foreshore Developments*. (Report prepared for UrbanGrowth NSW).

Darimont, C.T., Fox, C.H., Bryan, H.M. & Reimchen, T.E. (2015). The unique ecology of human predators. *Science,* 349, 858-860.

Dytham, C. (2017). *Choosing and Using Statistics: A Biologist's Guide*. Third edition, Wiley-Blackwell. 103-111.

Eklöf, J.S., Sundblad, G., Erlandsson, M., Donadi, S., Hansen, J.P., Eriksson, B.K. & Bergström, U. (2020). A spatial regime shift from predator to prey dominance in a large coastal ecosystem. *Communications Biology,* 3(1), 459.

Elmgren, R., Blenckner, T. & Andersson, A. (2015). Baltic Sea management: Successes and failures. *Ambio,* 44, S335-S344.

European Commission (2020). *Bioeconomy Strategy*. https://research-and-innovation.ec.europa.eu/research-area/environment/bioeconomy/bioeconomy-strategy_en [16.03.2024]

European Commission (2021a). *European Green Deal: Developing a sustainable blue economy in the European Union*. https://ec.europa.eu/commission/presscorner/detail/en/ip_21_2341 [16.12.2022]

European Commission (2021b). *The Marine Strategy Framework Directive*. https://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm [16.11.2022]

European Commission (2022). *Blue bioeconomy*. https://research-and-innovation.ec.europa.eu/research-area/environment/bioeconomy/blue-bioeconomy_en [16.03.2024]

European Commission (2023). *EU Mission: Restore our Ocean and Waters*. https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/restore-our-ocean-and-waters_en [16.03.2024]

European Commission (2024). *International ocean governance*. https://oceans-and-fisheries.ec.europa.eu/ocean/international-ocean-governance_en#:~:text=International%20ocean%20governance%20is%20about,of%20current%20and%20future%20generations. [19.05.2024]

European Environment Agency (2021). *What is green infrastructure?* https://www.eea.europa.eu/themes/sustainability-transitions/urban-environment/urban-green-infrastructure/what-is-green-infrastructure [16.05.2024]

Fabi, G., Spagnolo, A., Bellan-Santini, D., Charbonnel, E., Çiçek, B.A., García, J.J.G., Jensen, A.C., Kallianiotis, A. & Neves dos Santos, M. (2011). Overview on Artificial Reefs in Europe. *Brazilian Journal of Oceanography,* 59, 155-166.

FAO (2018). *The State of World Fisheries and Aquaculture 2018 - Meeting the Sustainable Development Goals*.

Franz, M., Barboza, F.B., Hinrichsen, H.-H., Lehmann, A., Scotti, M., Hiebenthal, C., Molis, M., Schütt, R. & Wahl, M. (2019). Long-term records of hard-bottom communities in the southwestern Baltic Sea reveal the decline of a foundation species. *Estuarine, Coastal and Shelf Science,* 219, 242-251.

Gann, G.D., McDonald, T., Walder, B., Aronson, J., Nelson, C.R., Jonson, J., Hallett, J.G., Eisenberg, C., Guariguata, M.R., Liu, J., Hua, F., Echeverría, C., Gonzales, E., Shaw, N., Decleer, K. & Dixon, K.W. (2019). International principles and standards for the practice of ecological restoration. Second edition. *Restoration Ecology. Society for Ecological Restoration,* 27(S1), S1-S46.

Gentry, R.R., Froehlich, H.E., Grimm, D., Kareiva, P., Parke, M., Rust, M., Gaines, S.D. & Halpern, B.S. (2017). Mapping the global potential for marine aquaculture. *Nature, Ecology & Evolution,* 1(9), 1317-1324.

Gephart, J.A., Henriksson, P.J.G., Parker, R.W.R., Shepon, A., Gorospe, K.D., Bergman, K., Eshel, G., Golden, C.D., Halpern, B.S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyedmers, P., Zhang, W., Ziegler, F. & Troell, M. (2021). Environmental performance of blue foods. *Nature,* 597, 360-365.

Golden, C.D., Koehn, J.Z., Shepon, A., Passarelli, S., Free, C.M., Viana, D.F., Matthey, H., Eurich, J.G., Gephart, J.A., Fluet-Chouinard, E., Nyboer, E.A., Lynch, A.J., Kjellevold, M., Bromage, S., Charlebois, P., Barange, M., Vannuccini, S., Cao, L., Kleisner, K.M., Rimm, E.B., Danaei, G., DeSisto, C., Kelahan, H., Fiorella, K.J., Little, D.C., Allison, E.H., Fanzo, J. & Thilsted, S.H. (2021a). Aquatic foods to nourish nations. *Nature* 598, 315-320.

Golden, C.D., Koehn, J.Z., Vaitla, B., DeSisto, C., Kelahan, H., Manning, K., Fiorella, K.J., Kjellevold, M. & Thilsted, S.H. (2021b). *Aquatic Food Composition Database*.

Hawkins, S.J., Sugden, H.E., Mieszkowska, N., Moore, P.J., Poloczanska, E., Leaper, R., Herbert, R.J.H., Genner, M.J., Moschella, P.S., Thompson, R.C., Jenkins, S.R., Southward, A.J. & Burrows, M.T. (2009). Consequences of climate-driven biodiversity changes for ecosystem functioning of North European rocky shores. *Marine Ecology Progress Series,* 396, 245-259.

HELCOM (2014). *Convention on the Protection of the Marine Environment of the Baltic Sea Area, 1992 (Helsinki Convention)*. Baltic Marine Environment Protection Commission

HELCOM (2021). *Baltic Sea Action Plan 2021 Update*: HELCOM.

Helsingborg (2023). *Unique mussel farm in the city centre – but can you eat them?* https://helsingborg.se/makingofasmartercity/unique-mussel-farm-in-the-city-centre-but-can-you-eat-them/ [22.02.2024]

Helsingborgs Stad (2019). *Ansökan om tillstånd för vattenverksamet – Övertäckning av förorenade bottensediment I del av Södra Hamnen, Helsingborg. Miljökonsekvensbeskrivning och teknisk beskrivning*. COWI

Helsingborgs Stad (2021). *PM Geoteknik - Rev i Oceanhamnen*. WSP

Helsingborgs Stad (2023). *Kontrollprogram sedimentövertäckning Södra hamnen*.

Hooper, D.U., Chapin, F.S., Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J.H., Lodge, D.M., Loreau, M., Naeem, S., Schmid, B., Setälä, H., Symstad, A.J., Vandermeer, J. & Wardle, D.A. (2005). *Effects of Biodiversity on Ecosystem Functioning: A Consensus of Current Knowledge*. (Ecological Monographs).

Isaksson, I., Pihl, L. & van Montfrans, J. (1994). Eutrophication-related changes in macrovegetation and foraging of young cod (Gadus morhua L.): a mesocosm experiment. *Journal of Experimental Marine Biology and Ecology,* 177, 203–217.

Jennings, S., Stentiford, G.D., Leocadio, A.M., Jeffery, K.R., Metcalfe, J.D., Katsiadaki, I., Auchterlonie, N.A., Mangi, S.C., Pinnegar, J.K., Ellis, T., Peeler, E.J., Luisetti, T., Baker-Austin, C., Brown, M., Catchpole, T.L., Clyne, F.J., Dye, S.R., Edmonds, N.J., Hyder, K., Lee, J., Lees, D.N., Morgan, O.C., O'Brien, C.M., Oidtmann, B., Posen, P.E., Santos, A.R., Taylor, N.G.H., Turner, A.D., Townhill, B.L. & Verner-Jeffreys, D.W. (2016). Aquatic food security: insights into challenges and solutions from an analysis of interactions between fisheries, aquaculture, food safety, human health, fish and human welfare, economy and environment. *Fish and Fisheries,* 17, 893-938.

Kaskela, A.M. & Kotilainen, A.T. (2017). Seabed geodiversity in a glaciated shelf area, the Baltic Sea. *Geomorphology,* 295, 419-435.

Kautsky, H., Kautsky, L., Kautsky, N., Kautsky, U. & Lindblad, C. (1992). Studies on the Fucus vesiculosus community in the Baltic Sea: Phycological studies of Nordic coastal waters. *Acta Phytogeographic Suecica,* 78, 33-48.

Kautsky, L. & Kautsky, N. (2000). The Baltic Sea, including the Bothnian Sea and Bothnian Bay. In: *Seas at the Millennium: an Environmental Evaluation*. (1). 121-133.

Kautsky, N. (1982). Growth and Size Structure in a Baltic Mytilus edulis Population. *Marine Biology,* 68, 117-133.

Kautsky, N. & Evans, S. (1987). Role of biodeposition by Mytilus edulis in the circulation of matter and nutrients in a Baltic coastal ecosystem. *Marine Ecology Progress Series,* 38, 201-212.

Kerr, L.A., Kritzer, J.P. & Cadrin, S.X. (2019). Strengths and limitations of before–after–control–impact analysis for testing the effects of marine protected areas on managed populations. *ICES Journal of Marine Science,* 76 (4), 1039-1051.

Kilfoyle, A.K., Freeman, J., Jordan, L.K.B., Quinn, T.P. & Spieler, R.E. (2013). Fish assemblages on a mitigation boulder reef and neighboring hardbottom. *Ocean & Coastal Management,* 75, 53-62.

Koivisto, M.E. & Westerbom, M. (2010). Habitat structure and complexity as determinants of biodiversity in blue mussel beds on sublittoral rocky shores. *Marine Biology,* 157, 1463-1474.

Korpinen, S., Meski, L., Andersen, J.H. & Laamanen, M. (2012). Human pressures and their potential impact on the Baltic Sea ecosystem. *Ecological Indicators,* 15, 105-114.

Kotta, J., Futter, M., Kaasik, A., Liversage, K., Rätsep, M., Barboza, F.R., Bergström, L., Bergström, P., Bobsien, I., Díaz, E., Herkül, K., Per R. Jonsson, P.R., Korpinen, S., Kraufvelin, P., Krost, P., Lindahl, O., Lindegarth, M., Lyngsgaard, M.M., Mühl, M., Sandman, A.N., Orav-Kotta, H., Orlova, M., Skov, H., Rissanen, J., Šiaulys, A., Vidakovic, A. & Virtanen, E. (2020). Cleaning up seas using blue growth initiatives: Mussel farming for eutrophication control in the Baltic Sea. *Science of the Total Environment,* 709, 136144.

Kuempel, C.D., Froehlich, H.E. & Halpern, B.S. (2021). An informed thought experiment exploring the potential for a paradigm shift in aquatic food production. *Ocean & Coastal Management,* 206, 105574.

Kuussaari, M., Bommarco, R., Heikkinen, R.K., Helm, A., Krauss, J., Lindborg, R., Öckinger, E., Pärtel, M., Pino, J., Rodà, F., Stefanescu, C., Teder, T., Zobel, M. & Steffan-

Dewenter, I. (2009). Extinction debt: a challenge for biodiversity conservation. *Trends in Ecology & Evolution,* 24, 564-571.

Lauzon-Guay, J.-S., Hamilton, D.J. & Barbeau, M.A. (2005). Effect of mussel density and size on the morphology of blue mussels (Mytilus edulis) grown in suspended culture in Prince Edward Island, Canada. *Aquaculture,* 249, 265-274.

Le Pape, O., Sylvain, B., Nieblas, A.-E. & Fromentin, J.-M. (2017). Overfishing causes frequent fish population collapses but rare extinctions. In: *Proceedings of the National Academy of Sciences of the United States of America*, National Academy of Sciences. 114(31), E6274.

Leggett, C.G. & Bockstael, N.E. (2000). Evidence of the effects of water quality on residential land prices. *Journal of Environmental Economics and Management,* 39, 121-144.

Liénart, C., Garbaras, A., Qvarfordt, S., Sysoev, A.Ö., Höglander, H., Walve, J., Schagerström, E., Eklöf, J. & Karlson, A.M.L. (2021). Long-term changes in trophic ecology of blue mussels in a rapidly changing ecosystem. *Limnology and Oceanography,* 66, 694-710.

Loch, J.M.H., Walters, L.J. & Cook, G.S. (2020). Recovering trophic structure through habitat restoration: A review. *Food Webs,* 25, 2352-2496.

Looström, J., Emanuelsson, A. & Dammand, A. (2023). *Baslinjeundersökning av artificiellt rev och levande havsvägg i Helsingborgs hamn 2023*.

Mannar, V., Micha, R., Allemandi, L., Afshin, A., Baker, P., Battersby, J., Bhutta, Z., Corvalan, C., Di Cesare, M., Chen, K., Dolan, C., Hayashi, C., Fonseca, J., Grummer-Strawn, L., Rao, A., Rosenzweig, C. & Schofield, D. (2020). *2020 Global Nutrition Report: Action on Equity to End Malnutrition*.

Medvedev, I.P., Rabinovich, A.B. & Kulikov, E.A. (2013). Tidal Oscillations in the Baltic Sea. *Oceanology,* 53, 526-538.

Miller, T.L. (1974). *Oceanology in Denmark*. National Technical Information Service, U.S.D.o.C.

National Geographic Society (2024). *Marine Pollution*. https://education.nationalgeographic.org/resource/marine-pollution/ [21.05.2024]

Naturskyddsföreningen (2022a). *Under ytan i Västerhavet: Tips och fakta för unga havsforskare*. Naturskyddsföreningen.

Naturskyddsföreningen (2022b). *Under ytan i Östersjön: Tips och fakta för unga havsforskare*. Naturskyddsföreningen.

Naylor, R.L., Kishore, A., Sumaila, U.R., Issifu, I., Hunter, B.P., Belton, B., Bush, S.R., Cao, L., Gelcich, S., Gephart, J.A., Golden, C.D., Jonell, M., Koehn, J.Z., Little, D.C., H., T.S., Tigchelaar, M. & Crona, B. (2021). Blue food demand across geographic and temporal scales. *Nature Communications,* 12(5413), 1-14.

Norkko, A. & Bonsdorff, E. (1996). Rapid zoobenthic community responses to accumulations of drifting algae. *Marine Ecology Progress Series,* 131, 143–157.

OSPAR (2024). *OSPAR Convention*. https://www.ospar.org/convention [19.04.2024]

Ottinger, M., Clauss, K. & Kuenzer, C. (2016). Aquaculture: relevance, distribution, impacts and spatial assessments - a review. *Ocean & Coastal Management,* 119, 244–266.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R. & Torres Jr., F. (1998). Fishing Down Marine Food Webs. *Science* 279, 860-863.

Pearce, D. (2001). Valuing biological diversity: issues and overview. In: Biller, D. & Bark, R. (eds) *Valuation of Biodiversity Benefits: Selected Studies*. OECD.

Råberg, S., Berger-Jönsson, R., Björn, A., Granéli, E. & Kautsky, L. (2005). Effects of Pilayella littoralis on Fucus vesiculosus recruitment: Implications for community composition. *Marine Ecology Progress Series,* 289, 131-139.

Riggio, S., Badalamenti, F. & D'Anna, G. (2000). Artificial reefs in Sicily: an overview. In: *Artificial reefs in European Seas*. Kluwer Academic Publishers. 65-73.

Rönnbäck, P., Kautsky, N., Pihl, L., Troell, M., Söderqvist, T. & Wennhage, H. (2007). Ecosystem Goods and Services from Swedish Coastal Habitats: Identification, Valuation, and Implications of Ecosystem Shifts. *Ambio,* 36(7), 534-544.

Rueness, J. (1998). *Alger i farger: en felthåndbok om kystens makroalger*. Almater.

Ruiz, G.M., Fofonoff, P., Hines, A.H. & Grosholz, E.D. (1999). Non-Indigenous Species as Stressors in Estuarine and Marine Communities: Assessing Invasion Impacts and Interactions. *Limnology and Oceanography,* 44(3), 950-972.

Serrão, E.A., Brawley, S.H., Hedman, J., Kautsky, L. & Samuelsson, G. (1999). Reproductive success of Fucus vesiculosus (Phaeophyceae) in the Baltic Sea. *Journal of Phycology,* 35(2), 254-269.

Simon, T., Joyeux, J.-C. & Pinheiro, H.T. (2013). Fish assemblages on shipwrecks and natural rocky reefs strongly differ in trophic structure. *Marine Environmental Research,* 90, 55-65.

Snoeijs-Leijonmalm, P. & Andrén, E. (2017). Why is the Baltic Sea so special to live in? . In: *Biological Oceanography of the Baltic Sea*. Springer Science and Business Media Dordrecht. 23-84.

Söderqvist, T. (1998). Why Give up Money for the Baltic Sea? Motives for People's Willingness (or Reluctance) to Pay. *Environmental and Resource Economics,* 12, 249-254.

Söderqvist, T., Eggert, H., Olsson, B. & Soutukorva, Å. (2005). Economic Valuation for Sustainable Development in the Swedish Coastal Zone. *Journal of the Human Environment,* 34(2), 169-175.

Springmann, M., Clark, M., Mason-D'Croz, M., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J. & Willett, W. (2018). Options for keeping the food system within environmental limits. *Nature,* 562, 519-525.

Stockholms Universitet (2005). *Växter & djur i Östersjön: en Fälthandboken* Fourth edition, Stockholms Marina Forskningscentrum.

Støttrup, J.G., Stenberg, C., Dahl, K., Kristensen, L.D. & Richardson, K. (2014). Restoration of a Temperate Reef: Effects on the Fish Community. *Open Journal of Ecology,* 4 (16), 1045-1059.

Strain, E., Morris, R. & Bishop, M. (2017). *Sydney Harbour – enhancing seawall sustainability*.

Taylor, J.J., Rytwinski, T., Bennett, J.R., Smokorowski, K.E. & Cooke, S.J. (2017). The effectiveness of spawning habitat creation or enhancement for substrate spawning temperate fish: a systematic review protocol. *Environmental Evidence,* 6(1), 5.

Thilsted, S.H. (2021). Diversifying aquaculture systems to nourish nations. *Nature Food,* 2, 450-451.

Tilman, D. & Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature,* 515 (7528), 518-522.

Torn, K., Krause-Jensen, D. & Martin, G. (2006). Present and past depth distribution of bladderwrack (Fucus vesiculosus) in the Baltic Sea. *Aquatic Botany,* 84, 53-62.

Troell, M., Pihl, L., Rönnbäck, P., Wennhage, H., Söderqvist, T. & Kautsky, N. (2005). Regime shifts and ecosystem services in Swedish coastal soft bottom habitats: when resilience is undesirable. *Ecology and Society,* 10(1), 30.

United Nations (2024a). *The 17 Goals*. https://sdgs.un.org/goals [19.05.2024]

United Nations (2024b). *Transforming our world: the 2030 Agenda for Sustainable Development*. https://sdgs.un.org/2030agenda [19.05.2024]

Voipio, A. (1981). The Baltic Sea. *Elsevier Oceanographic Series*, 418.

Wahl, M., Hinrichsen, H.-H., Lehmann, A. & Lenz, M. (2013). Natural variability in hard-bottom communities and possible drivers assessed by a time-series study in the SW Baltic Sea: know the noise to detect the change. *Biogeosciences,* 10, 5227-5242.

Waldeck, P. & Larsson, K. (2013). Effects of winter water temperature on mass loss in Baltic blue mussels: Implications for foraging sea ducks. *Journal of Experimental Marine Biology and Ecology,* 444, 24-30.

Wang, W., Gao, H., Jin, S., Li, R. & Na, G. (2019). The ecotoxicological effects of microplastics on aquatic food web, from primary producer to human: A review. *Ecotoxicology and Environmental Safety,* 173, 110-117.

Wikström, S.A. & Kautsky, L. (2007). Structure and diversity of invertebrate communities in the presence and absence of canopy-forming Fucus vesiculosus in the Baltic Sea. *Estuarine, Coastal and Shelf Science,* 72, 168-176.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Sibanda, L.M., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Reddy, K.S., Narain, S., Nishtar, S. & Murray, C.J.L. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet,* 393, 447-492.

Wilms, T.J.G., Norðfoss, P.H., Baktoft, H., Støttrup, J.G., Kruse, B.M. & Svendsen, J.C. (2021). Restoring marine ecosystems: Spatial reef configuration triggers taxon-specific responses among early colonizers. *Journal of Applied Ecology,* 58, 2936-2950.

WorldFish, Lala-Pritchard, T. & Johnstone, G. (2020). *2030 Research and Innovation Strategy: Aquatic Foods for Healthy People and Planet*.

Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson, J.B.C., Lotze, H.K., Micheli, F., Palumbi, S.R., Sala, E., Selkoe, K.A., Stachowicz, J.J. & Watson, R. (2006). Impacts of Biodiversity Loss on Ocean Ecosystem Services. *Science,* 314, 787-790.

Yuan, Z., Nag, R. & Enda Cummins, E. (2022). Human health concerns regarding microplastics in the aquatic environment - From marine to food systems. *Science of the Total Environment,* 823, 153730.

Zhao, K., Gaines, S.D., Molinos, J.G., Zhang, M. & Xu, J. (2024). Effect of trade on global aquatic food consumption patterns. *Nature Communications,* 15, 1412.

Popular science summary

Coastal habitats are increasingly being damaged or developed into ports, harbours and other structures. As these coastal habitats are altered from their natural state, fish are losing their sheltered breeding grounds and fewer seaweed forests are left. Fish populations are getting smaller, threatening the global food supply. Other ecosystem services, such as beautiful coastlines and clean waters, are also being lost.

One solution would be to install more artificial reefs. Artificial reefs can be installed in coastal areas worldwide to support a myriad of different coastal systems. They can provide habitat for young fish, attachment sites for seaweed and mussels, and help to support the vulnerable stages of the foodweb. Artificial reefs can also be attached vertically to manmade structures, such as harbour walls, to give nature a chance to regain a foothold in ports and harbours. These reefs can also make the area nicer for local people to explore and provide recreation opportunities, such as snorkelling, alongside closer access to nature and cleaner waters.

In Helsingborg, an artificial reef consisting of stone boulders was installed to replace lost habitat. Secondly, concrete and ceramic panels, shaped into natural shapes like kelp, were added to the outer seawall to help seaweeds and mussels find places to attach. Additionally, a floating platform was also built to allow the local community to grow mussels on dangling lines underneath. Fieldwork assessments of all these reefs were shown to benefit biodiversity and food provisioning in the local area. A survey of local residents found that they have been enjoying some ecosystem services, such as the harbour area now being nicer to walk around. Some local people were not aware that supporting biodiversity by using artificial reefs can have much wider scale benefits, such as improving aquatic food security, providing ecosystem services and helping towards the United Nations' Sustainable Development Goals (SDGs).

Artificial reefs come in many different forms but they can consistently help provide cleaner, clearer waters (SDGs 6+14), capture carbon (SDG13) and can provide habitat for many plant and animals species which are also part of foodwebs in the wider oceans and on land (SDG 15). They are an innovation (SDG 9) which can be used to produce good quality, local food in coastal urban environments (SDGs 11+12). As such, artificial reefs can help support livelihoods (SDG 1), reduce hunger (SDG 2) and improve nutrition (SDG 3). It would be good to have this information be more widely known in order to gather more public support for projects like this which have the potential to bring positive benefits to marine life and people in coastal areas worldwide.

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Appendices

Appendix 1. GDPR data

Participation in an independent project at SLU – consent and information about the processing of personal data

When you consent to take part in the independent project 'The effects of promoting blue-green infrastructure in coastal areas on biodiversity and aquatic foods', you consent to the Swedish University of Agricultural Sciences (SLU) processing your personal data. Consenting to this is optional. However, if you do not consent, you cannot take part in the project. This form aims to give you all the information you need to decide whether you consent to participating in the project and to SLU processing your personal data.

Consent is the legal basis for processing your personal data. You can withdraw your consent at any time, and you do not have to justify this. However, withdrawing your consent will not affect the processing that has already taken place. SLU is responsible for processing your personal data. SLU's data protection officer can be contacted at dataskydd@slu.se. Your contact person for the project is the student Verity Swift (vesw0002@stud.slu.se). You can also contact the supervisor Lena Bergström (lena.bergstrom@slu.se).

We will collect the following personal data: whether you belong to a local apartment building, office building or specified community project. The purpose of processing your personal data is to allow the SLU student to carry out their independent project 'The effects of promoting blue-green infrastructure in coastal areas on biodiversity and aquatic foods' with good scientific quality. Your personal data will not be transferred to other organisations or companies.

Your personal data will be stored until the independent project has been assessed and the grade registered in the SLU student registry. After that, the data will be disposed of. The data will be handled in a way that prevents unauthorised access.

More information on how SLU processes personal data, and about your rights, is available at www.slu.se/personal-data. You have the right, under certain circumstances, to have your personal data erased, corrected or limited. You also have the right to access the personal data being processed, and you have the right to object to the processing of your data.

If you have any comments, contact the data protection officer at dataskydd@slu.se. If you want to make a complaint, contact the Swedish Authority for Privacy Protection at imy@imy.se. Read more about the Swedish Authority for Privacy Protection at www.imy.se.

☐ I hereby consent to take part in this independent project and to SLU processing my personal data in the manner explained in this text, including any sensitive data I may submit.

____

Signature Date

____

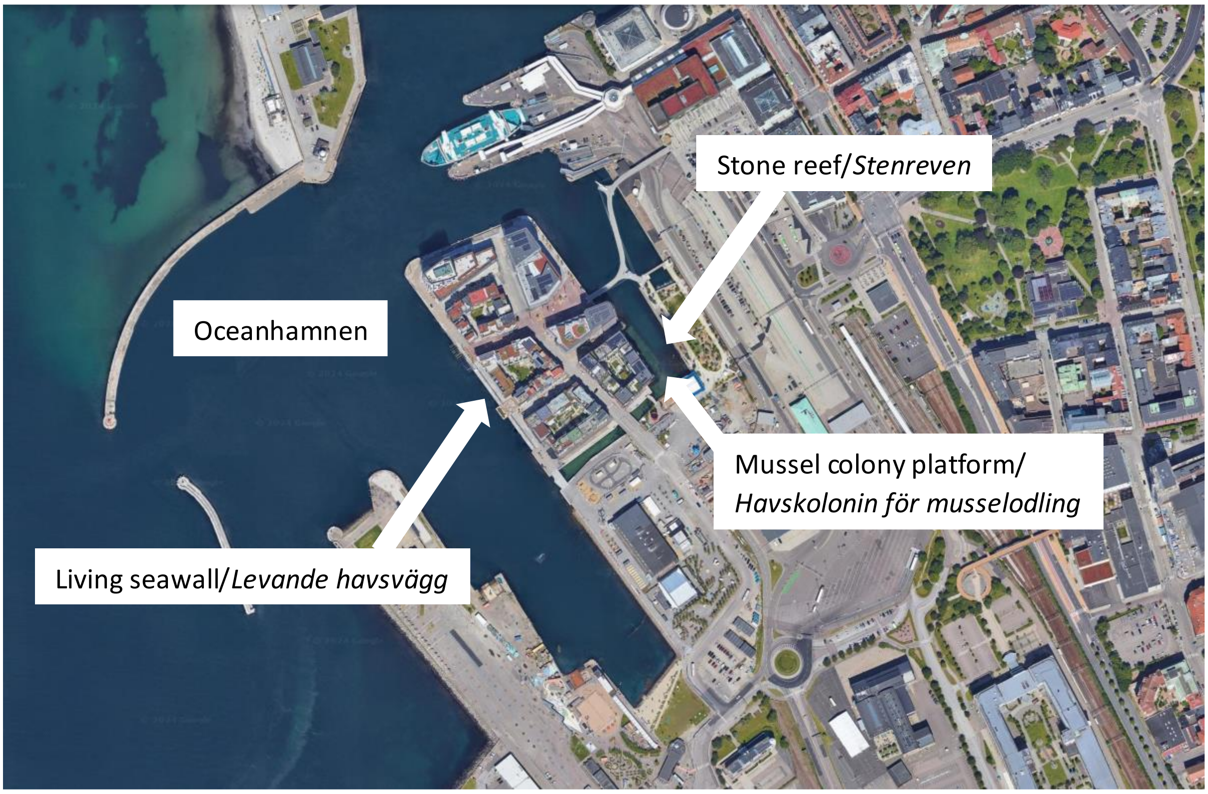
Name in block letters

Appendix 2. Survey

Background/Bakgrund

The City of Helsingborg have developed three marine infrastructure projects in Oceanhamnen. These are the stone reef, living seawall and the floating mussel colony platform, hereafter all three are collectively referred to as the artificial reefs. These structures can be seen on the map below. This survey is being carried out as part of a master's thesis project by a student at the Swedish University of Agricultural Sciences. This survey aims to gather the views of the local people in the immediate vicinity of the artificial reef projects. This survey consists of 20 questions plus the opportunity to provide feedback and should take around 10 minutes to complete.

Helsingborgs stad har utvecklat tre marina infrastrukturprojekt i Oceanhamnen. Dessa är stenreven, levande havsvägg och havskolonin för musselodling, häreefter kallas alla tre gemensamt för de artificiella reven. Kartan här nedanför visar var dessa strukturer finns. Denna undersökning genomförs som en del av ett examensarbete av en student vid Sveriges lantbruksuniversitet. Undersökningen syftar till att samla in synpunkter från människor i närheten av de artificiella revprojekten. Den här undersökningen består av 20 frågor plus möjlighet att ge feedback och bör ta cirka 10 minuter att fylla i.



(Image taken from Google Earth)

General

Q1. Please select any of the following groups that you are associated with:

Vänligen välj vilken av dessa grupper som du är associerad med:

- Oceanhamnen marine project - mussel colony platform/*Oceanhamnens marina projekt - plattform för musselkoloni*
- Local apartment building/*Lokal bostadsrättsförening (Ophelias Brygga)*
- Local office building/*Lokal kontorsbyggnad (Henckels Torg 4)*

- Passerby/*Förbipasserande*

Q2. Please select all options that you are aware of:

Vilka av nedanstående projekt i Oceanhamnen känner du till:

- Stone reef/*Stenreven*
- Living seawall/*Levande havsvägg*
- Mussel colony platform/*Havskolonin för musselodling*

Q3. How did you become aware of the artificial reefs in Oceanhamnen?

Hur fick du kännedom om de artifciella reven i Oceanhamnen?

Q4. Why are you interested in the artificial reefs? Please select all that apply:

Varför är du intresserad av de artificiella reven? Vänligen välj alla som stämmer:

- General interest/*Generellt intresse*
- Education/*Vill öka min allmänbildning*
- Potential food source/*Möjligheten att få lokal sjömat*
- Aesthetic improvement of the area/*Möjlighet till estetisk förbättring av området*
- Connection to nature/*En ökad känsla av närhet till naturen*
- Access to nature/*En ökad möjlighet att vistas i naturen*
- Concerned about habitat loss/*Oro över förlust av livsmiljöer*
- Concerned about biodiversity loss/*Oro över förlust av biologisk mångfald*
- I am not particularly interested in the artificial reefs/*Jag är inte särskilt intresserad av de artificiella reven*
- Other/*Annat*

Please score how strongly you agree with the following statements (0-5, 0 = strongly disagree, 5 = strongly agree)

Betygsätt hur starkt du håller med om följande påståenden (0-5, 0 = håller inte med alls, 5 = håller starkt med)

<u>Biodiversity/*Biologisk mångfald*</u>

Q5. The addition of the reef has increased my awareness of biodiversity

Närvaron av revet har ökat min medvetenhet om biologisk mångfald

Q6. I am more aware of ocean health since the reef installation

Reven gör att jag har blivit mer medveten om havsmiljön

Q7. I have learnt more about marine species since the reef installation

Reven har medfört att jag har lärt mig mer om marina arter

Q8. The addition of the reefs has made me think more about marine habitat loss

Reven har fått mig att bli mer medveten om problem med förlust av naturliga livsmiljöer i havet

Food security/*Matsäkerhet*

Q9. I am aware of recreational fishing occurring locally (Scale: never – on a daily basis)

Jag känner till att de förekommer fritidsfiske i närområdet (Skala: aldrig – dagligen)

Q10. It is important to me that seafood comes from local sources

Det är viktigt för mig att sjömat, som fisk och skaldjur, är från lokala källor

Q11. I like to eat blue mussels

Jag äter gärna blåmusslor

Q12. I am willing to eat blue mussels that are cultivated in urban environments provided they pass food security checks

Jag skulle kunna tänka mig att äta blåmusslor som odlas i stadsmiljö så länge de klarar livsmedelssäkerhets-kontroller

Q13. I would prefer to cultivate my own blue mussels rather than buy them from a shop

Jag skulle föredra att odla mina egna blåmusslor istället för att köpa dem i en butik

Ecosystem services/*Ekosystemtjänster*

Q14. The presence of the reefs has improved the local area

De artificiella reven har förbättrat närområdet

Q15. I appreciate the presence of the artificial reefs

Jag uppskattar närvaron av de artificiella reven

Q16. The presence of the reefs has increased my connection to the sea

Närvaron av reven har ökat min känsla av närhet till havet

Q17. The development of artificial reefs in Oceanhamnen has increased opportunities for recreation in the area

Utvecklingen av de artificiella reven i Oceanhamnen har ökat möjligheterna till rekreation i området

Q18. I think that the presence of the reefs attracts visitors to the area

Jag tror att närvaron av reven lockar fler besökare till området

Q19. I think that the reefs help people to learn more about marine species and the marine environment

Jag tror att reven hjälper människor att lära sig mer om marina arter och den marina miljön

Non-specific/*Ospecifika*

Q20. I would recommend that artificial reefs be installed in other similar areas

Jag skulle rekommendera att artificiella rev installeras även i andra stadsnära miljöer

Feedback

Q21. Do you have any further comments?

Har du något ytterligare som du vill tillägga?

Q22. Do you have any feedback on this survey?

Har du någon feedback på denna undersökning?

Thank you for taking the time to fill in this survey!

Stort tack för att du tog dig tid att fylla i denna undersökning!

What's happening under the water at Oceanhamnen?

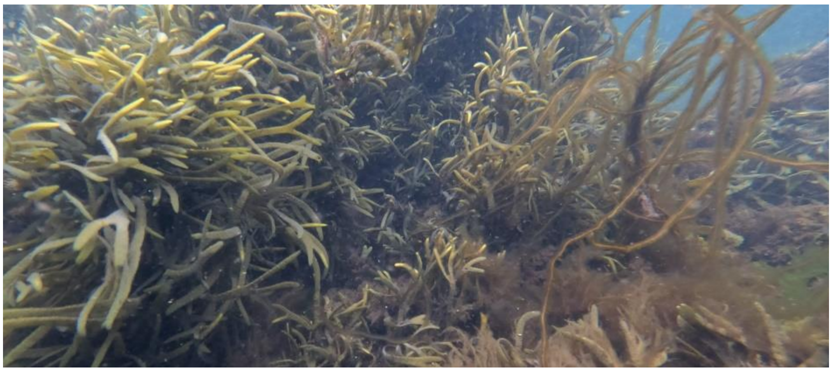
A factsheet for local residents

The stone reef was installed in 2022 by the City of Helsingborg to help introduce natural marine life back into the harbour area.

This artificial reef is large, covering a rectangular area roughly 35 metres by 20 metres. It extends from just above the surface to 3 metres deep.

The large boulders that make up the stone reef provide a home for many aquatic plants and animals.

Seaweed, mussels and barnacles can attach directly to the rocks. Fish can shelter and feed on the reef and smaller species like mud snails and periwinkles also live here.

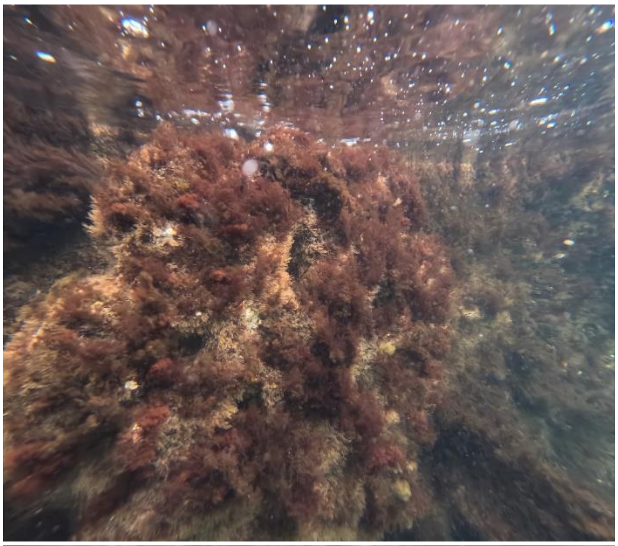


The rocks are now well covered with different marine vegetation. The type of seaweed also changes as you get deeper on the reef, as you can see in the picture on the left.

The reef is very accessible for swimming so bring your snorkel and come take a closer look!

An area of the harbour wall has been made into a living seawall. It is 15 metres long and extends 5 metres deep.

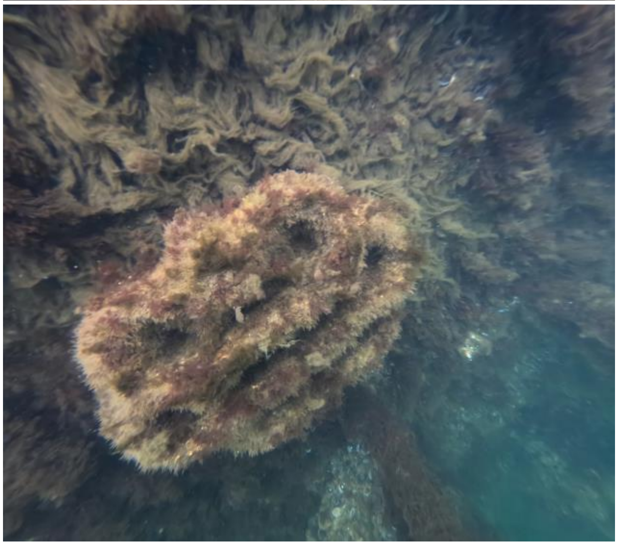
Different shaped panels like the ones in the picture on the left were installed. The panels are designed to copy natural shapes like kelp or irregular rock crevices. This is to help marine plants and animals attach to the harbour wall and has helped to bring a bit more nature back into Oceanhamnen!



The City of Helsingborg installed the living seawall in 2022 and expanded it again in 2023.

As you can see in the pictures, the artificial reef panels add more dimension to an otherwise fairly boring wall. The panels provide a larger surface area for different marine plants and animals to anchor themselves to.

The panels below the waterline are now covered in different seaweeds and many small creatures like crabs and mussels have also found a home here.



There is a ladder down to the living seawall for those feeling brave enough to snorkel but the current is stronger here so always take a buddy with you!

For those who feel safer on land, you can take a closer look at the living seawall by using a static camera that has been installed as part of the wall! The camera is always active and can be found using this QR code.

The mussel colony is tucked away under the floating platform next to the stone reef in Oceanhamnen. The colony was set up by the City of Helsingborg in 2023 to see how well it would work to grow mussels in an urban harbour area.

The mussels grow on the long cultivation nets that can be seen in the image on the right. There is quite a lot of water movement under the platform but the mussels are tightly attached so they don't fall off!

This colony is cared for by a group of local Helsingborg citizens who volunteered to help with this project. They visit regularly to clean algae from the mussels as this helps them to grow faster.

If you visit the platform, there is a trapdoor which lifts up so that you can take a sneak peek at the mussels below. Take care not to lean too far though or you may end up joining the mussels in the water for a really close up viewing!

The picture to the left shows blue mussels. They come in different shapes and sizes. The youngest ones are the smallest but they grow very quickly.

Mussels are useful because they feed by filtering the water. Large amounts of plankton can make water cloudy but mussels take these in as food and so make the water in the harbour clearer for us to enjoy!

Blue mussels are also quite tasty. Mussels take three years to grow large enough for eating. This means that the first harvest from the mussel colony will be in summer 2025! The hard working volunteer group will finally be able to taste the mussels they have cared for after a three year wait.

If you want to know more information about the activities happening in the harbour, information can be found using the QR codes below to reach the Instagram pages run by the City of Helsingborg.

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