Master of Science in Environmental Management

ENVM8004 Dissertation

香 港 大 學

THE UNIVERSITY OF HONG KONG

A critical investigation into the potential value of establishing an Oyster Shell Recycling (OSR) programme in Hong Kong

Author:

Matthew Roberts

(3035716957)

Supervisor:

Dr. Bayden Russell

Disclosure statement: This dissertation represents the author's own work conducted for the purposes of this MSc in Environmental Management programme. All significant data or analysis used in this dissertation from other sources – including work the author may have carried out for purposes other than for this programme – has clearly been identified as such.

Signed: ________________________________

Printed Name: Matthew Roberts

Date: 28/05/21

Acknowledgements

Firstly, I want to express my deep gratitude to my supervisor, Dr Bayden Russell for his tireless support, encouragement and enthusiasm. Bayden's expertise and guidance throughout this study has been invaluable and I can't thank him enough for all that he has done.

Secondly, I would like to show my sincere appreciation to the Tai Tam Tuk Foundation and more specifically, Jenna Ho Marris and Andy Niven. Tai Tam Tuk is a beautiful and special ecosystem and I feel privileged to have conducted my research there.

I would also like to thank Dr Sam Crickenberger for his friendship and counsel in many parts of this study. Sam was a guiding light throughout this experience.

As always, I am immensely grateful for the love and admiration of my parents, brother and family. They have provided me the confidence to follow my passion and nurtured my aspirations into fruition.

Lastly, a special thank you to my field and life partner Sarah Taylor, her passion and talent inspire me daily. Without her knowledge, love and support this dissertation would not have been possible.

Abstract

Worldwide, Oyster Shell Recycling (OSR) is the process of recovering waste shell material and OSR programmes have been used as a successful mechanism for procuring otherwise lost oyster shells that are crucial to restoring oyster populations. Oyster shells are considered waste in Hong Kong and currently there is no active Oyster Shell Recycling programme. Hong Kong generated an estimated 3671 tonnes of shell material in 2020; therefore the opportunity to create circularity through recycling is feasible. Oyster populations in Hong Kong have the potential to generate considerable ecological and economic value. Oysters have been harvested extensively for their shells to make by-products for at least 700 years and combined with the continued decline of the oyster aquaculture industry, face extinction without immediate restorative action. Unfortunately, restoration efforts face shortages in shell material that is used as a hard substrate for oyster spat (larvae), on which they are dependent for settlement and survival. As the global shell deficit continues alternative materials in restoration are being explored. This study undertook the following process; first, experimentally validated shell as a preferred substrate for oyster spat and secondly, identified the extent of oyster shell available in Hong Kong to evaluate the cost-benefit and feasibility of implementing an OSR programme. This study offers a context under which OSR programmes can contribute efforts to mitigating waste issues in Hong Kong, by repurposing "waste" shells for the restoration of oyster populations, therefore enhancing the ecosystem services they provide.

Table of Contents:

Acknowledgements **3**

Abstract **4**

Table of Contents: **5**

List of Figures **7**

List of Tables **8**

1.0 Introduction **9**

1.1 Framing the problem 11

1.2 Aims and Objectives. 13

2.0 Literature Review **14**

2.1 Function and Ecosystem Services 14

2.1.2 Water Quality Services 14

2.1.3 Increase biodiversity 15

2.1.4 Shoreline Stabilisation & Coastal defense 16

2.1.5 Carbon sequestration 17

2.2 Oyster Reef Formation/ Larvae Settlement. 17

2.2.1 Waterborne chemical cues 19

2.2.2 Substrate type 20

2.3 Substrate in restoration 20

2.3.1 Alternative Materials: 20

2.3.2 Oyster Shell 22

2.4 Oyster Reef Restoration- Case Studies 23

2.4.1 United States - Chesapeake Bay 23

2.4.2 Oyster Restoration Limitations 27

2.4.3 Oyster Shell Waste 27

2.4.4 Oyster Shell Recycling (OSR) Process and case studies 28

2.4.4.1 Billion Oyster Project, USA 29
2.4.4.2 North Carolina Shell Recycling, USA 31
2.4.4.3 South Carolina Oyster Restoration & Enhancement (SCORE), USA 33
2.4.4.4 Xiamen University, “Trash to Treasure” (Dawu, China) 33
2.4.4.5 The Nature Conservancy, Australia 34
2.5 Hong Kong Oysters 36
2.5.1 Hong Kong Oyster Ecology 37
2.5.2 The Hong Kong Oyster Industry: 40
2.5.3 Hong Kong Oyster restoration 40
2.6 Shell as a commodity 42
3.0 Methodology 44
3.1 Field Study 44
3.1.2 Site description 44
3.1.3 Experimental design and sampling 46
3.1.4 Sampling analysis 47
3.1.5 Statistical analysis. 48
3.2 Desktop study 49
3.2.1. Primary Literature 49
3.2.2 Grey Literature 49
3.2.3 Data analysis 49
3.2.4. Costs of Oyster Shell Recycling Programmes 49
3.2.5 Value of shell material 50
3.3 Cost-Benefit Evaluation 50
3.3.1 Value of ecosystem services 53
4.0 Results 58
4.1 Ecological Survey: 58
4.2 Shell Valuation 59

4.3 Oyster ecosystem services valuation 60
4.4 Cost for OSR 61
4.4.1 Operational costs analysis 62
4.4.2 Partnerships 65
4.5 Hong Kong Oyster Shell Recycling Cost-Benefit Evaluation 67
5.0 Limitations and further suggestions: 68
5.1 Field study 68
5.2 Cost-Benefit Evaluation 68
6.0 Discussion and Limitations 70
6.1 The value of restoring oyster reefs in Hong Kong 70
6.2 Oyster Shell should be the preferential tool for restoration 74
6.3 Shell a lost resource 76
6.4 Oyster Shell Recycling Programmes 77
7.0 Conclusion 80
References 82
Appendix 96

List of Figures

Figure 1. Basic Oyster Life Cycle Diagram.
Figure 2. Photo providing an example of an oyster reef.
Figure 3. Photo providing an example of oyster reef formation.
Figure 4. History of commercial oyster landings in the Chesapeake Bay.
Figure 5. Photo example of The Billion Oyster Project using recycled shells for restoration.
Figure 6. Photo example of The Billion Oyster Project conducting reef restoration.
Figure 7. Photo of oyster beds in Pak Nai, Deep Bay, Hong Kong.
Figure 8. Map showing areas of Oyster Production and Fishponds in Hong Kong.

Figure 9. Photo of study site at Tai Tam Harbour, Hong Kong with experimentally survey units.

Figure 10. Map showing Tai Tam Harbour extracted from the Agriculture, Fisheries and Conservation Department with location of the study site added.

Figure 11. Photo showing experimental survey units in water at the study site in Tai Tam Harbour.

Figure 12. Photo showing dense oyster cluster at the study site in Tai Tam Harbour.

Figure 13. Graph showing Global Carbon Tax analysis adapted from the World Bank Group.

Figure 14. Output table for PERMANOVA

Figure 15. Output table for PERMANOVA 'Pair-wise' Test.

Figure 16. Bar chart highlighting the mean oyster spat recruitment density per m2 of substrate.

Figure 17. Bar chart showing average shell valuation in USD per tonne based on shell market/use.

Figure 18. Bar chart showing the estimated potential value of ecosystem services provided by Hong Kong oyster reefs per year in USD$.

Figure 19. Graph showing amount of shell volume recycled per programme per year vs amount of programme partners.

Figure 20. Bar Chart showing shell volume recycled vs programme funding mechanism.

Figure 21. Graph showing Cost-Benefit Evaluation of establishing an Oyster Shell Recycling programme in Hong Kong.

List of Tables

Table 1. List of common alternative substrate and synonyms

Table 2. North Carolina Division of Marine Fisheries, Oyster Shell Recycling operating costs.

Table 3. Analysis of Oyster Shell Recycling Programmes

1.0 Introduction

It is estimated that 85% of oyster reefs worldwide have been lost, driven by centuries of resource extraction and habitat degradation (Beck et al, 2011). Oyster populations are historically valued as a fisheries resource, but more recently, focus has been placed on the broad range of critical ecosystem services they provide. Described as ecosystem engineers, oysters create heterogeneous reef structures that foster biodiversity (Mann & Harding, 2001). In addition to increasing biodiversity through habitat creation, oysters can improve water quality through active filtration, enhance nutrient cycling, provide shoreline stabilisation by reducing wave energy, and sequester carbon (Grabowski, 2012). These services create substantial environmental, economic and social value. Oyster reefs are now considered functionally extinct and their decline follows a common pattern (Beck et al, 2011). Historical overharvesting and removal of shells for processing of calcium carbonate results in the loss of complex reef structure. This loss directly impacts the success of the next generation of oyster populations that rely upon the hard substrate for settlement and growth.

Oyster reefs are pivotal to ecosystem functionality and the valuation of their services can contribute needed evidence towards the importance of restoration (Grabowski, 2012). Typically, oysters provide the only hard substrate in the predominantly soft-sediment environments in which they are found (Grabowski, 2012). Oysters display natural gregarious settlement by which they provide other individuals a suitable surface for attachment (Chinzei, 2013). Oysters will settle upon other oyster shells due to the chemical cues admitted from juvenile and adult conspecifics, as well as natural biofilms found on the shell material that enhance larval settlement (Green et al, 2013, Crisp, 1967). Therefore, the loss of oyster shells and the associated habitat, leaves less hard substrate that is vital for the settlement and survival of oyster larvae. Providing hard substrate for larvae is fundamental to the success of restoration, therefore the emphasis of many restoration projects is to place shell material back into the water (Tamburri, 2008).

The world currently faces a shell deficit with the vast majority of shells either processed into by-products or lost as waste (FAO, 2016). As a result, restoration efforts have been hampered by a lack of shell material and forced to explore alternative materials. As the deficit continues, creating pathways to procure much needed oyster shells will be critical to the success of restoration projects.

The Chesapeake Bay Foundation in the United States America (USA), represents one of the world's most renowned oyster restoration projects. During the 1800s, the bay was dominated by nearly half a million acres of oyster beds (CBF, 2020). However, a common theme of overharvesting, disease and poor water quality caused by human activity has put oyster populations at 1% of historic levels (CBF, 2020). Once the bay’s most valuable fishery, there is much recognition that the regeneration of oyster populations is critical, not only as an economic resource but also as an equally important ecological resource. Founded in 1967, The Chesapeake Bay Foundation has been recycling oyster shells to create habitat and expand reefs with much success. CBF’s Oyster Shell Recycling (OSR) programme collects shells via state-wide ‘shell drop-off’ locations and also partners with restaurants and other volunteers who can supply shells. Each recycled shell is used in restoration and can become home to dozens of oyster larvae, otherwise known as ‘spat’ (Nalesso, 2008). The shell replenishment programme continues today and has contributed crucial restoration with an estimated 80% of harvested oysters being sourced from areas the Department of Natural Resources (the agency responsible for the protection and enhancement of the USA fisheries) has planted recycled shell (UNC, 2005). The Chesapeake Bay Foundation's project provides a model example of using Oyster Shell Recycling to enhance oyster restoration.

1.1 Framing the problem

In Hong Kong, the native oyster species, *Crassostrea hongkongensis*, has been cultivated for over 700 years and represents a valuable economic, social and environmental resource. In 2018, Hong Kong's oyster production was 141 tonnes (meat only) and valued at HKD$17 million (AFCD, 2020). Oyster reefs in Hong Kong were critically overharvested in the past for the production of lime and today are essentially extinct (Morton and Wong, 1975). Hong Kong's oyster aquaculture industry also faces a similar fate due to declining water quality caused by human development. While the populations of Hong Kong oyster species has not been well documented, it can be estimated that China has also had similar reductions given global data combined with the known overharvesting and explosion of coastal development (Fang et al. 2007). Without immediate restorative action, Hong Kong faces the continuing loss of fisheries and the collapse of a vital ecosystem engineer. Of the 141 tonnes of oyster meat that was procured by aquaculture, no post-consumed oyster shells have been recovered from oyster farms, restaurants or packaging centers. This shell material is currently being lost to the landfills.

Concurrently, Hong Kong is facing a waste crisis and currently generates over 5.95 million tonnes of Municipal Solid Waste (MSW) each year, with 70% of this being sent to landfill (HK Gov, 2020). MSW comprises solid waste from households, commercial and industrial sources (HK Gov, 2020). Resource space in Hong Kong's landfills continues to reduce and the rate of waste production is not sustainable even in the short term (HK Gov, 2020). Therefore, the Environmental Protection

Department (EPD) has placed a high priority on promoting waste reduction and recycling, as well as developing programs and facilities to reduce bulk waste volume, recover energy and repurpose recycled source-separated waste (EPD, 2021).

To help address waste issues, Hong Kong has recently established several types of waste recycling facilities. Unfortunately, oyster shells are considered a special type of food waste that is not accepted by these facilities and thus, will continue to make unwanted contributions to landfill (FWMG, 2017). Furthermore, Waste Producer Responsibility Schemes (on hold due to Covid-19) are soon to be implemented, under which waste producers will pay the cost of Municipal Solid Waste collection, recycling, and disposal by weight (HK Gov, 2020). As a consequence of this policy, producers will soon pay to send discarded oyster shells to landfill.

Due to the high consumption of local and imported oysters in Hong Kong, oyster shells contribute to the waste produced by the city's food and restaurant industries. Oyster shell waste is further produced by the oyster aquaculture farmers themselves. As a result of the cultivation methods used, shells are often discarded directly after harvesting and result in excess aquaculture debris along the shoreline. This is particularly problematic in Deep Bay where shells contribute to the habitat degradation of important species such as the endangered Chinese horseshoe crab (*Tachypleus tridentat*us) (Cheung et al 2019). The Nature Conservancy Hong Kong uses volunteers to gather shells on the mudflats near Deep Bay. However, given the insufficient volume of shell collected for restoration activities, they are exploring various ways to repurpose the shell and will pilot shell-based products such as fertilizer to donate to local vegetable farms (Thomas, M ‘personal communication’, 2020).

1.2 Aims and objectives.

I seek to show the following; oyster shell should be the focal point of restoration efforts in Hong Kong as it is a preferential substrate for spat recruitment and that Oyster Shell Recycling programmes are a cost-effective solution to enhance oyster restoration and provide a valuable waste recovery service. However, to effectively proceed with shell-based restoration activities in Hong Kong there are some key knowledge gaps. Firstly, information on whether shell is substantially better for oyster spat recruitment than other commonly used substrates for population restoration (terracotta and concrete); and secondly, to determine the cost-effectiveness of establishing an Oyster Shell Recycling programme in Hong Kong and method that would underpin effective shell procurement.

Therefore, this study proceeded in two steps. First, I experimentally tested the spat recruitment rates on different types of substrate (including oyster shell) to be used as restoration material in Hong Kong. A cost-benefit evaluation was then conducted using quantifiable data from global case studies, literary and legislative sources as well as financial reports to demonstrate the feasibility and potential value of implementing an OSR programme in Hong Kong. Furthermore, the investigation discusses and makes suggestions on the best method of investment for OSR in Hong Kong. Based on this, I seek to provide evidence that OSR programmes provide a cost-effective method to source shells for enhancing oyster population restoration efforts, whilst also reducing Hong Kong's waste and helping to capitalise on a valuable wasted resource.

2.0 Literature Review

2.1 Function and Ecosystem Services

Historically, oysters were only appreciated as a commercial fishery resource. However, they are ecosystem engineers which play a critical function and provide vital services. Oysters create complex structural habitats that sustain large, abundant and diverse populations of species across all trophic levels (Mann and Harding, 2001). Not only do oysters foster a biodiverse environment, healthy reefs support large populations of recreationally and commercially valuable fish (Mann and Harding, 2001). Oyster reef morphology and size can vary considerably with reefs ranging from small fragmented intertidal reefs, less than 1 m^2, to continuous subtidal reefs that extend over 1 km (Eggleston, 1999). Their abundance and distribution are limited to specific physicochemical conditions. Salinity and water temperature are the dominant factors that affect population distribution (Sehlinger et al, 2019). Additionally, factors limiting the distribution of oysters are dissolved oxygen, food concentration and water movement (Burrell, 1986). Oysters are found all over the world and different species can survive in a wide range of temperatures and depths close to shorelines (Baggett et al, 2014).

2.1.2 Water quality Services

Oyster populations contribute valuable water quality services for other species and habitats that often go unrecognized. Oysters are efficient filter feeders that help regulate water quality and nutrient cycling (Konrad, 2014). In Hong Kong, oyster reefs are able to provide filtration services up to 31.7ML/hour (Lau et al, 2020). Dissolved carbon, nitrogen, and phosphorus actively promote the growth of phytoplankton and eutrophication. As blooms of phytoplankton become progressively larger, their eventual decomposition consumes high amounts of dissolved oxygen which can lead to serious environmental impacts such as hypoxia (Konrad, 2014). Oyster aquaculture has been demonstrated to have mean nitrogen removal rates of 235.86 kg per acre per year (Rose et al, 2015). Wild or cultured oyster populations can therefore influence nutrient dynamics and help manage the effects of eutrophication by consuming phytoplankton and other suspended solids in the water column before depositing them as pseudofeces (Grabowski & Peterson, 2007; Eggleston, 1999). The minimizing of eutrophication effects also allows for deeper light penetration into the water column that promotes healthy sub aquatic vegetation (SAV) habitats (Grabowski & Peterson, 2007). Therefore, healthy oyster populations can provide beneficial services to coral reefs and SAV, like seagrasses, by acting as a filter for pollution runoff, thereby ensuring that ecosystems maintain lower levels of nutrients that prevent degradation (Baggett et al, 2015).

2.1.3 Increase biodiversity

Similarly to their influence in water nutrient dynamics, oyster reefs also have the potential to regulate population dynamics (Breitburg, 1999). Oyster reefs provide critical habitat that can support large populations of juvenile and adult marine species that are dependent on the reef structure for shelter, feeding and reproduction (Breitburg, 1999, Tolley & Volety, 2005, Coen et al, 2007). Areas where oyster shell dominates the substrate have been shown to support fish densities up to 14 times greater than habitat areas lacking shell (Harding & Mann, 2001). With this biomass enhancement, 10 m^2 of restored oyster reef in the USA yields an additional 2.6 kg of fish and large mobile crustaceans yearly, for the functional lifetime of the reef (Peterson et al., 2003). This finding is common, with the density, biomass and richness of other species being greater with shell-bottom compared with sand-bottom (no-shell) (Tolley & Volety, 2005).

2.1.4 Shoreline stabilisation & coastal defense

Oyster reefs absorb wave energy and have the potential to grow large vertical reef structures that can function as natural living coastal defense (Grabowski et al, 2012). In Hong Kong waters, piers and seawalls occupy a significant portion of the shoreline defense of Hong Kong (Chow, Leung, & Lee, 2017). These structures protect valuable human infrastructure by re-directing wave energy but the costs of constructing and maintaining these defenses are expected to increase due to sea-level-rise caused by climate change (Chow, Leung, & Lee, 2017). Oyster reefs reduce the need and cost of these structures as they can also reduce wave damage on coastlines (Morris et al, 2019). This could prove to be a critical utility in mitigating the impacts of climate change on human developments as unharvested oyster reefs can maintain vertical growth rates that exceed estimated sea-level-rise (Morris et al, 2019). The ability of oyster reefs to maintain these growth rates is seen as an important advantage compared to man-made engineering structures. In fact, arguments have been made that oyster reefs are more valuable than other engineered devices due to them being a more resilient option to sea-level-rise (Rodriguez et al 2014 & Walles et al, 2016). However, location is critical to the potential value of oyster reefs (Grabowski et al, 2012). In locations where shoreline protection is required, oyster reefs can be a direct substitute or supplement for man-made devices and their value as a coastal defense will obviously be significantly higher in these areas opposed to areas without a need. For example, one hectare of oyster reef habitat is estimated to provide USD$85,998 of annual value in the USA (Grabowski et al, 2012). The coastal risks associated with climate change like shoreline erosion, habitat loss and property damage or loss could be reduced by using oyster reefs as a substitute defense (Morris et al, 2019).

2.1.5 Carbon sequestration

Oysters can contribute carbon sequestration services via filtration and biodeposition of carbon (Pi-hai et al., 2014). In the latest report from the UN Intergovernmental Panel on Climate Change, clear ambitions are outlined about the critical importance of putting a price on carbon to create pathways that limit warming (IPCC, 2018). Approximately 40 national and 20 sub-national governments have already implemented or scheduled emissions trading schemes or carbon taxes (The WBG, 2020). Each jurisdiction prices carbon dependent on various characteristics and goals of their region. For instance, the United States developed a benchmark estimate of USD$50 per ton of carbon dioxide in 2019 and a recent International Monetary Fund estimate suggests carbon per ton should be taxed globally at USD$75 in order to meet targets set in the Paris Agreement (IMF, 2019). Carbon contributes 12g for every 100g of shell and oyster carbon sequestration rates can be in the range of between 1,400 to 2,500 kg per hectare (Pi-hai et al., 2014).

2.2 Oyster reef formation and larvae settlement

Oyster larvae use a wide variety of habitat site characteristics when selecting a settlement location. Figure 1 shows that larva oysters are free swimming veliger for roughly 2-3 weeks until they metamorphs into pediveliger (Norton, 2001). The pediveliger life cycle stage is characterised by the appearance of the eyespot and foot (Lodeiros et al, 2017). Their movements are then aided by the foot which probes substrate until it finds a suitable place for permanent attachment (Baggett et al, 2015). Once settled, the oyster larvae permanently cement to the surface and are thereafter referred to as oyster 'spat' (Norton, 2001). Larval settlement behaviour and choice of final substratum for attachment is critical to the success of the adult organism (Turner et al 1994). Settlement is influenced by a number of chemical and physical factors including but not limited to substrate type, natural biofilms and waterborne chemical cues.

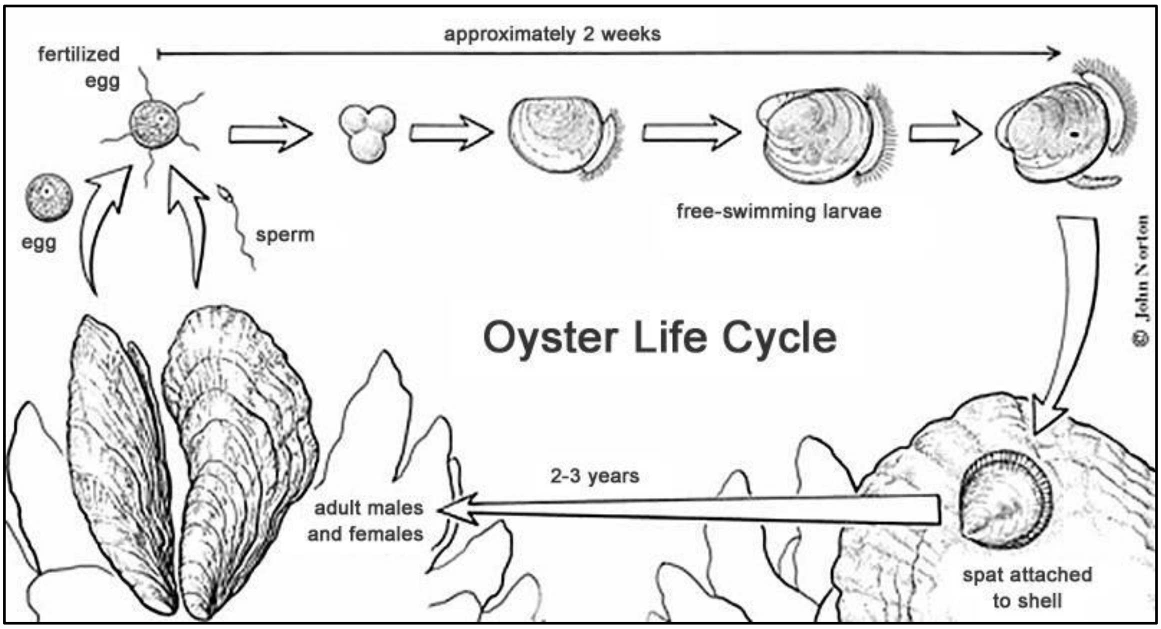

Figure 1. Basic Oyster Life Cycle Diagram (Norton, 2001).

Figure 2. Example of Oyster Reef (TNC, 2018)

Figure 3. Oyster reef formation (TNC, 2018)

2.2.1 Waterborne chemical cues

Multiple chemical cues, especially those related to the shell, play a critical role in larvae settlement. Oysters utilise chemical cues in the water column during settlement (Burke, 1986). Like communication found in other animals, oysters omit waterborne chemical cues that elicit a response from juveniles and act as a mechanism for site selection (Veitch & Hidu, 1971, Crenshaw, 1972). Waterborne chemical cues are not species specific and are found to enhance substrate attachment across all oyster larval forms (Tamburri et al, 2008). Some of the earliest studies on oyster larvae settlement were conducted because of depleted oyster fisheries and a need for restorative action (Cole and Knight Jones, 1949). These centered around larval settlement behaviour and were conducted by placing similarly shaped shells in tanks containing settling larvae. During the experiment, one shell was allowed to continuously accumulate larvae and the other shell was cleared daily. The settlement rates observed were higher on shell containing spat (Cole and Knight Jones, 1949) suggesting that spat also release pheromones that promote larval settlement (Hidu, 1969). Additionally, larvae have been known to recognize both the insoluble organic layer of the adult conspecific shells and soluble material emanating from living oysters (Crisp, 1967). The extrapallial fluid is enclosed between the inner surface of the shell meaning that water filtered through an adult oyster, as well as the liquid within the shell, contain thyro proteins that attract larval settlement (Veitch & Hidu, 1971, Crenshaw, 1972). All oyster shells are rich in the chemical compound calcium carbonate that increases pH (Green et al, 2013). Oyster larvae in both lab and field settings have been shown to prefer higher levels of pH when settling (Green et al, 2013). The significance of this is that even post-mortem shell material will attract oyster larvae through chemical cues.

2.2.2 Substrate type

Availability of hard substrate is the principal factor governing recruitment success of oyster populations (Rodriguez-Perez et al, 2019). Natural oyster reefs can thrive even in unfavourable conditions if high numbers of oysters are present in the community that can provide a hard substrate for settlement (Korringa, 1946). Oysters rely upon hard substrate for larvae settlement (Smyth et al, 2018) but in the absence of available shell substrate, oysters have been found to settle upon a variety of other available hard surfaces. Alternative substrates are being explored in oyster restoration but it is repeatedly shown that larvae will preferentially settle on substrate composed of oyster shell material (Crisp, 1967; Veltch & Hindi, 1971; Bonar et al., 1990; Lok & Acarli, 2006; Nestlerode et al., 2007; Tamburni et al., 2008; Quan et al., 2017; Christianen et al, 2018; Smyth, 2018).

2.3 Substrate in restoration

2.3.1 Alternative materials

Alternative or artificial substrate is an umbrella term that encompasses any substrate used for oyster restoration other than oyster shell (Table 1; Goelz et al, 2020). Alternative materials have been shown to provide analogous qualities to those of natural oyster reefs in spat recruitment (George et al, 2015). For example, many alternative materials can provide the same hard structural qualities that provide the foundation for oyster larvae settlement (George et al, 2015). However, the recruitment of oyster spat varies among substrate.

One evident alternative to oyster shells is the shell from another sessile bivalve. Clam shell has been shown to support similar levels of spat recruitment to oyster shell (Goelz et al, 2020). However, post settlement mortality of spat was observed at higher levels on clam shell compared to oyster shell, mosty likely because clam shell offered less structural complexity which is important for refuge from predation (Nestlerode, 2007). Other restoration efforts have focused on using material such as porcelain, limestone, non-calcium stone and concrete (Goelz et al, 2020 and Soniat & Burton, 2005).

Table 1. Alternative substrate and synonyms (Goelz et al, 2020)

Alternative Substrate	Synonyms
Porcelain	None
Limestone	None
Noncalcium stone	Granite, rocks, stone
Concrete	Block, blocks, cement, cinder, rip rap
Non Oyster shell	Surf, Mussel, clamshell, conch
Dredge shell	Dredged, fossilized
Engineered reefs	Castles, reef balls

Using alternative materials as substrate for oyster reef restoration can be successful (George et al 2015). When comparing the impact of substrate on recruitment between four different substrates (oyster shell, clam shell, limestone, and clay brick), for the first two years after deployment of the substrata, oyster and clam shell had greater recruitment and abundance of oysters compared with limestone and clay bricks (Quan et al, 2017). However, after 3 years, all substrate types had similar oyster abundances and size distributions of oysters. These results are not entirely surprising as oysters will dominate most substrates over a long time period which could relate to the overall success of alternative materials (George et al 2015).

Alternative materials have been shown to encounter recruitment issues as a result of competition for space from other sessile bivalves and the lack of chemical cues that provide a map to settlement (Metz et al, 2015). Terracotta as a substrate has been shown to recruit equal amounts of spat to oyster shell (Metz et al 2015). Cement and limestone riprap recruit spat but not at a rate close to oyster shell (Burke, 2010). Furthermore, spat recruitment per surface area ratio for limestone was three to nine times lower than oyster shell material (Kuykendall et al, 2015). The common and key finding is that the initial substrate preference was for oyster shells over alternative materials. Whilst this does indicate that different types of substrate material can be used to successfully develop viable, self-sustaining oyster populations, it remains clear that the most efficient substrate for restoration projects is oyster shell (Quan et al, 2017).

2.3.2 Oyster shell

The loss of oyster populations directly affects the success of the next generation. The accumulation of shell material through growth and recruitment is essential in the sustainability of healthy oyster reefs (Walles et al, 2016). Any loss of the accumulated oyster shell (e.g. through dredging for the shells or other means) reduces the amount of suitable hard substrate that is vital for the settlement and survival of oyster larvae (Baggett et al, 2015). Due to the morphology and chemical cues emitted, oysters preferentially settle on oyster shells relative to other substrates which suggests that there are opportunities in restoration to augment spat recruitment through the addition of shell substrate (McAfee & Connell, 2020). Restoration generally begins with the addition of a hard substrate that serves as a base for oyster spat attachment and growth (O'Beirn et al, 2000 & Nestlerode et al, 2007). No matter if the shell is native or non-native, oysters predominantly use shell as settlement substrate (Christianen, 2018). Some studies indicate that restoration success may vary between the use of live oyster shells and post-consumed shells, however most literature remains clear that regardless of its state (live or post-mortem), shell material is pivotal (Christianen, 2018). From a practical basis, the shell is far lighter than some alternative substrates making it the preferred tool for reconstructing reefs for restoration. In soft-sediment environments where substrate may sink, a large volume of shell base would be required and in some situations only the top layer will be covered with shell; utilizing an alternative substrate beneath (Nestlerode, et al 2007). Oyster restoration efforts are predominantly limited by the availability, cost, and suitability of substrates, in particular oyster shells, which are becoming increasingly scarce and expensive.

2.4 Oyster reef restoration case study

2.4.1 Chesapeake Bay, USA

By the late 1880s, The Chesapeake Bay, located on the US east coast, was the greatest oyster-producing region in the world. The region was home to a thriving commercial oyster industry whose products were sought globally and its oyster harvest was two times greater than anywhere else in the world (Mann, 2000). The fishery, which included 450,000 acres of subtidal reefs in the bay, represented 39% of the U.S. oyster harvest, 17% of all U.S. fisheries, and employed 20% of all

Americans who worked in the fishing industry (Oyster Recovery, 2020, National Research Council, 2004). Dense and tall oyster reefs, consisting of large deposits of shell rose meters off the bay bottom and were capable of sustaining years of commercial harvest. Oyster farmers would remove shells before canning the meat for preservation and shipment (Tarnowski, 1999). As a consequence, farmers would generate large volumes of waste oyster shells and surplus to requirements, shells were deposited back into estuaries and the ocean from where they were originally farmed (Tarnowski, 1999). Oysters were so abundant at the time, seed oysters were exported to other states in 500,000 bushels quantities to combat fishery collapses in those states (Kirby, 2004). The estimated weight of a bushel of post-consumed oyster shells is 50 pounds meaning there are 44.1 bushes in a tonne or 22.67 kg per bushel (Street et al, 2005). Unrecognized oyster restoration efforts started as early as the 1890's in the USA in an attempt to increase production (Schulte, 2017). Following years of thriving oyster populations and commercial fishery success, federal regulations that prohibited waste dumping into marine environments (including shell material) stopped farmers from returning shells (Tarnowski, 1999). Oyster harvests peaked in the Chesapeake Bay around 1880 at 6.3 million bushels of market oysters and 1.9 million bushels of "seed" oysters (Schulte, 2017). As harvests declined, state exports were reduced and by 1930 quantities ranged from 100,000 to 150,000 bushels and declined continuously until 1950 when legislation was passed to prohibit the shipment of seed oysters outside the state (Schulte, 2017).

The long-term decline in abundance of oysters since the 1890s has been attributed mainly to habitat loss associated with pollution, overfishing and dredging (Rothschild et al, 1994). Years of poor commercial fishing practices including dredging, tore key hard substrate (oysters) from the bottom, leaving soft mud bottom unsuitable for oyster spat attachment (Newell, 1988, Rothschild et al, 1994). As oyster populations declined, as did water quality, only further perpetuating oyster population decline (Newell, 1988, Rothschild et al, 1994).

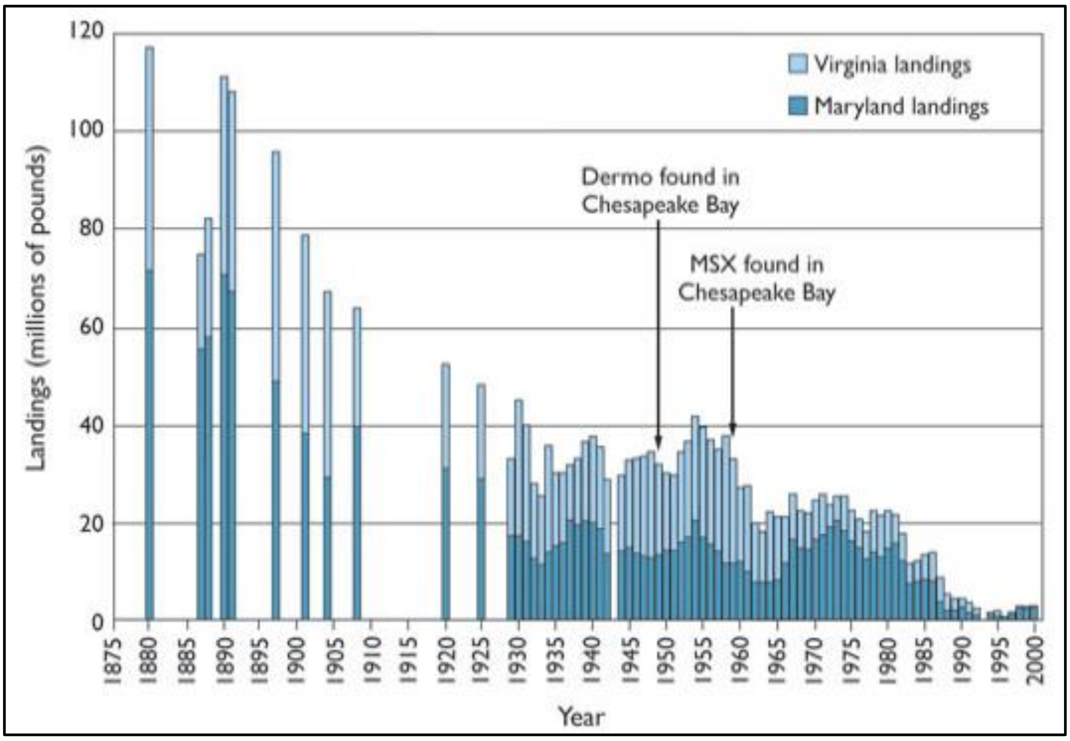

Figure 4. History of commercial oyster landings in the Chesapeake Bay (National Research Council, 2004).

In 1929, the first shell replenishment programme was initiated in the hopes of combating the fishery decline through habitat enhancement and augmented species production (Schulte, 2017). The main objective of the program was to plant at least 500,000 bushels (22,600 m^3) of shells per year. Though this goal was achieved, harvests continued to decline over the years and in response shell planting efforts were increased to 676,000 (30,555 m^3) bushels of shells/year (Schulte, 2017). Harvests declined further and evidence suggests replenishment efforts did not have the desired effect as any accumulated shell substrate was quickly exhausted again by a damaging and more efficient fishing practice, dredging (Schulte, 2017). In 1947, State funds were invested in the replenishment program for the first time, which prior to then was funded solely by license fees on the oyster industry (Schulte, 2017).

In the late 1980s, the first no-take sanctuaries within the bay were protected to allow the oyster populations to thrive unharvested (Burke, 2007). The Maryland Department of Natural Resources (DNR) currently has 24 sanctuary sites throughout the bay area and 19 sites as Compromise Reserves, where sites are closed for five years then re-opened for managed harvests until they are closed again, acting as a storehouse for healthy oysters (UNC, 2005). The restoration activities in Maryland are considered under two categories, habitat improvement and population enhancement; habitat improves the substrate for recruiting oysters and the population enhancement is the increase of successful individuals (Paolisso et al. 2006). The DNR plants an average of 2.5 million bushels of seed oysters from aquaculture and 200,000 bushels of fresh shell captured from the seafood industry per year (DLS, 2009). Shell replenishment has contributed crucial shell material to the ongoing restoration initiatives in the Chesapeake Bay. However, shell availability is continually declining and as a consequence, the use of alternative materials are being tested for ongoing and future restoration efforts in Maryland (DLS, 2009). In an effort to conserve remaining shell, strategies have been modified to create bases of alternative material that are then covered in a layer of shell material to promote oyster settlement (Burke, 2007). Restoration strategies are based on the foundation of providing suitable substrate for oyster larvae but as the footprint of oyster restoration work continues to expand, the need to source more substrate material increases.

2.4.2 Oyster restoration limitations

In many instances, restoration efforts are constrained by the availability, cost and transportation of material used to provide the hard substrate that underpins reef formation by oysters. Along the US East Coast, using oyster shells as the material for restoration activities has been successful for over 50 years. Unfortunately, as oyster populations continue to decline, the amount of available shells for restoration also declines. Alternative substrate materials can be successful as restoration tools, though studies do show inconsistencies in their success and economically, alternative materials are more costly than oyster shells (George et al 2015). The type of material used as well as the distance and method of transportation are usually the key factors attributing to the variability in success and cost (Goelz et al, 2020). The decline in available material has increased the need for accountability over each harvested oyster to be recycled. Oyster Shell Recycling programs are designed to capture valuable shell waste for restoration.

2.4.3 Oyster shell waste

As a consequence of exponential global population growth, the demand for industrialization of food production, particularly aquaculture has seen significant growth with ~16.1 million tons of molluscs (19 billion USD) produced annually (FAO, 2016). Oyster aquaculture production has also increased rapidly in recent decades but has received limited attention (Botta et al, 2020). Oyster aquaculture production is dominated by China, who accounted for 86% of global production (Botta et al, 2020). At a conservative estimate across most common species, the shell represents more than 70% of their total weight (Morris et al 2019). A key barrier to sustainability in shellfish production remains shell waste. The amount of shell 'waste' generated is directly related to the volume of oyster produced.

Most waste shells are currently deposited in landfills, abandoned on land, or returned to the ocean without any form of biosecurity practices taking place leading to broad environmental impacts (Silva et al, 2019). Globally, shell waste is seen as a costly environmental nuisance but in most jurisdictions it is unregulated. If uncontrolled, shell waste can contribute to high levels of visual pollution, odors and local environmental contamination (Silva et al, 2019). In the United Kingdom (UK), under HM Revenue and Customs landfill Tax, disposal of shell material to landfill could cost as much as GBP80 per tonne (Morris et al, 2019). Waste oyster shells have the potential to come from many different sources but governing all sources of discarded shell to recapture the material is incredibly difficult and potentially a contributing factor to the overall waste issue.

2.4.4 Oyster shell recycling (OSR) process and case studies

Shell recycling has been implemented as a method for procuring shell material throughout the United States of America. In areas where wild harvests or oyster aquaculture take place, shell material will be produced and thus shell is available to be sourced. Oyster Shell Recycling typically follows this process:

1) Recruitment of shell recycling partners

In order to procure shells, it is imperative that any OSR programme recruits partners who can provide a source of shell material. In most examples, partners are volunteers or members of the public who donate waste shells to programmes via 'shell drop-off 'locations and/or restaurants where shell is collected regularly after being discarded post-consumption (Branigan et al, 2020). Programmes also engage oyster farmers themselves to capture shell material that might otherwise be lost during harvest (Branigan et al, 2020)

2) Storage and biosecurity

Although storage of waste oyster shells will be different in each jurisdiction, the biosecurity risks and mitigation methods are recommended to be standardised across all geographies. A standard practice, well established in the United States is the curing and weathering of shells (NOAA, 2012). Once collected, shells are washed clean of debris and other organisms and then dried in sunlight for up to six months to kill any pathogens or parasites that may be present on the oyster shells (NOAA, 2012). An additional safeguarding measure to mitigate biosecurity risks is to turn shell piles periodically (up to twice a month) allowing all shells to be thoroughly exposed to sunlight (Branigan et al, 2020).

3) Restoration

Once cured, shells are ready to be used in restoration activities. The recycled shells that would typically be lost are bagged or caged and placed as settlement substrate for oysters larvae (Branigan et al, 2020). Other programmes utilise 'spat-on-shell' restoration methods whereby recycled shells are put into water tanks in oyster hatcheries containing millions of microscopic oyster larvae which then attach to the shells (Burmester & McCann, 2019). Pre-settling spat on shell is a further method for enhancing recruitment of oyster spat. Once pre-settling has been completed, 'spat-on shells' are provided to restoration projects to grow and expand oyster reefs.

2.4.4.1 Billion Oyster Project, USA

The Billion Oyster Project (BOP) has reinvigorated global interest in oyster restoration and is one of the most well renowned operations currently operating. Through public education initiatives supported by shell recycling programmes, the project aims to put over 1 billion shells back into New

York Harbor, USA, by the year 2035 in order to restore its lost oyster reefs (Burmester & McCann, 2019). In 2015, Billion Oyster Project started a Shell Collection Program aimed at reclaiming valuable shell resources from both the general public and local restaurants and utilising the material in its restoration projects (Burmester & McCann, 2019). The project adopts many methods including spat-on-shell, bagged shell, concrete discs with shell attached and mesh cages filled with oyster shell (Burmester & McCann, 2019). The Project is a member of the New York Alliance of Shell Collectors (NYASC), which promotes collaboration between shell collecting organizations across the state (Burmester & McCann, 2019). The programme partners with over 70 restaurants to source shell material as well as over 10,000+ volunteers including from over 100+ local schools (Burmester & McCann, 2019). Shell collection and equipment is provided by Billion Oyster Project to all partners and collected on a regular schedule before being taken to be cured and cleaned for restoration (Burmester & McCann, 2019). To date the project has diverted over 1.6 million pounds (680,000 kg) of shell from landfill and has restored 15 acres of reef using recycled oyster shell (Burmester & McCann, 2019). The BOP aims to restore 200 acres to New York Harbour by 2035 and to date, restored sites have shown rapid growth resulting in high density oysters and promising trends in survival and reproduction (Burmester & McCann, 2019)

Figure 5. Billion Dollar Oyster Project, reef restoration using recycled shells. (BOP, 2021).

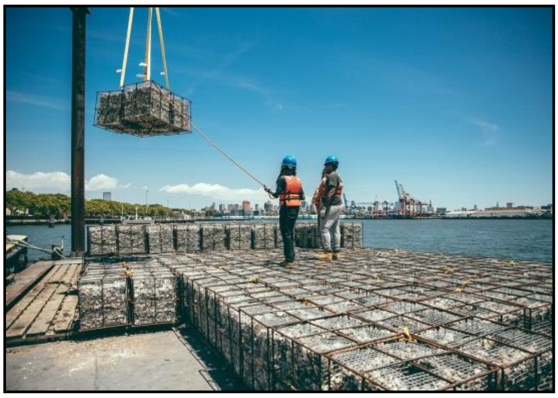

Figure 6. Billion Dollar Oyster Project oyster restoration using recycled shells (BOP, 2021).

2.4.4.2 North Carolina Shell Recycling, USA

North Carolina, USA, is home to the second-largest estuarine system on the US East coast (NCDMF, 2014). In 2003, provisions were made for large scale shell replanting to address drastically declining oyster populations and the State utilised a tax credit to underpin it's procurement of oyster shells (NCDMF, 2014). Tax credits have been used as a means of further promoting oyster shell recycling programs. Taxpayers who donate oyster shells to the North Carolina Department of Marine Fisheries (NCDMF) were eligible for a tax credit of $1 per bushel (~22.67kg) of shells (North Carolina Coastal Federation, 2020). The State of North Carolina ran a state-funded OSR programme from 2003 to 2013 (NCDMF, 2014). A 2007 statute passed by the State of North Carolina banning the disposal of oyster shells in landfills further promoted the programme (NCDMF, 2014). The NCDMF adopted centralised 'shell drop-off' locations and provided collection, transportation and maintenance services (NCDMF, 2014). This provided the public and restaurants an easy and cost-efficient service that handled excess shell waste and promoted shell recycling. The program had a total of over 55 restaurant partners & 116 public recycling locations Statewide (NCDMF, 2014). Shells were diverted from landfills and used to supplement restoration activities that were currently using alternative materials (NCDMF, 2014). Prior to the start of the programme, approximately 3000 bushes were collected from 2001-2003 (NCDMF, 2014). After establishment and funding of $35,000 annually, the amount of recycled shell increased 86% from 3000 to 22,000 bushels (NCDMF, 2014). While operating from 2003-2013 an estimated 211,255.41 bushels (7,941 tonnes) of oyster shells were recycled (NCDMF, 2014). The program operated under an annual funding allocation of USD$35,000 USD but in 2013, legislators removed programme funding from the State budget (NCDMF, 2014).

After funding was withdrawn, shell collection in 2014 decreased 66% to 9,419 bushels (NCDMF, 2014). As a result of reduced shell availability, the NCDMF had to compensate by purchasing shell material or using alternatives (NCDMF, 2014). The costs of these and associated operations from 2009-2013 are highlighted in the table below. The NCDMF was spending an average of $40.17 per tonne of shell material and $44.52 per tonne of alternative material to supplement their de-funded restoration initiatives (NCDMF, 2014). In contrast, when operating the OSR programme, the state acquired recycled shell at a cost $12.15 making it the most cost-effective substrate. A scaled down programme continued to operate between 2013 to 2018 before eventually, all state-run oyster shell recycling programs were halted due to a lack of available funding (NCDMF, 2014).

Table 2: NCDMF, OSR cost of operations. Adapted from: NCDMF, 2009-2013

Year	OSR Operating Costs	Purchased Shell Costs	Alternative Material Costs
2009	$11,945	$179,092	$339,462
2010	$21,410	$233,618	$339,750
2011	$21,410	$435,554	$371,800
2012	$24,929	$194,691	$458,200
2013	$9,038	$206,335	$798,090
Total Cost	$88,732	$1,249,290	$2,307,302
Total Tonne	4650.95	31,385	50,531.38
Average cost per tonne	$19.72	$40.17	$44.52

2.4.4.3 South Carolina Oyster Restoration & Enhancement (SCORE), USA

The State of South Carolina, USA, has been managing their shell resource specifically for oyster restoration since the early 2000's. The South Carolina Department of Natural Resources (SCDNR) implements it's OSR programme by funding generated from Saltwater Recreational Fishing Licenses (SCDNR, 2021). The Department of Natural Resources actively governs the State's oyster shell resource through a recycling programme which is able to replant 100% of recycled shells as hard substrate. The state manages over 30 public drop-off locations and partners with 50 restaurants as well as the public to procure shells (SCDNR, 2021). The state has established one of the most efficient shell recycling programs in the United States with over 400 reefs across 44 sites restored (SCDNR, 2021).

2.4.4.4 Xiamen University, "Trash to Treasure", China

In China, researchers from Xiamen University started the "Trash to Treasure'' project in the village of Dawu. Dawu's community is largely dependent on oyster harvesting and currently has no waste disposal process for discarded shells (Enactus, 2015). Waste shell was causing many local environmental issues and researchers partnered with the Government to construct an oyster shell processing factory that repurposes shell into by-products such as fertilizers and construction materials (Enactus, 2015). Over 4,000 tonnes of shucked shells are processed each year with a value of 82.8 million Yuan (~13,965,047 USD). In addition, the processing factory has created jobs, helped manage local waste issues and provided local water quality improvements (Enactus, 2015). Shell by-product used for construction material offers a solution based on the reuse and recycling of oyster shells. Not only does new product innovations such as this add commercial value to oyster shell waste, it also reduces resource extraction demand for natural stone and is an excellent example of a circular economy for local producers (Silva et al, 2019).

2.4.4.5 The Nature Conservancy, Australia

The TNC Australia recently implemented the 'Shuck Don't Chuck' project, a shell recycling programme inspired by the efforts of similar schemes in the United States. The organization outlined the primary steps involved in setting up a shell recycling project: (adapted from Branigan et al, 2020). These steps included the following:

- *(i)* *recruitment of shell recycling partners,*
- *(ii)* *transport and logistics,*
- *(iii)* *shell storage sites,*
- *(iv)* *biosecurity and curing protocols,*
- *(v)* *hatchery use,*
- *(vi)* *reef deployment,*
- *(vii)* *community engagement.*

In this case study, existing waste recycling incentives meant that oyster shell recycling was an attractive alternative to landfill for restaurants, businesses, or any shell disposers (Branigan et al, 2020). Partners were further attracted to the programme, citing the dual appeal of waste reduction and biodiversity conservation (Branigan et al, 2020). Establishing partners to supply otherwise discarded shells was the critical first to collect sufficient volumes of material.

Transportation and logistics are typically one of the major project costs of recycling programs and highly dependent on the distribution and storage capacity of the shell recycling partners (Branigan et al, 2020). Odor and storage determine the frequency of shell collection and expected volume of shell will determine the collection method (Branigan et al, 2020). Many recycling programmes use community volunteers, however, The Nature Conservancy in Australia sub-contracted this task to an established recycling business due the high expected shell volume and oversight needed to manage the project (Branigan et al, 2020). Special purpose containers designed to prevent liquids and residue escaping were provided to recycling partners (Branigan et al, 2020). These containers are used to store post-consumed shells until collection.

Under the TNC's guidance notes, several criteria exist to be considered in the selection of storage sites for oyster shell recycling programmes. A suitable site should be at least 1 hectare minimum per 1000 cubic meters of shell to be stored to allow for movement of vehicles (Branigan et al, 2020). Ideally, the site will also be located away from residential properties and waterways due to mild odor and runoff (Branigan et al, 2020). One key criteria that is likely to impact the success of the program is the proximity of the shell storage site relative to its recycling partners. Sites located close to partners (shell sources) will ultimately reduce the transportation cost (typically the largest cost) and increase the ability to manage large volumes of shell material (Branigan et al, 2020).

Recycled shells are required to be cured for at least six months and turned over approximately every two months as a biosecurity measure (NOAA,2020). Regulatory approval and protocols regarding this aspect may differ between jurisdictions which means any OSR Programmes established in other locations will need to adhere to local environmental permits. Once cured, the shells are cleaned and used either as oyster seed or to rebuild reef bases.

In the Australian programme, 225 m^3 of recycled shells have been used to restore two hectares of reef with another 550 m^3 to be used by October 2020, but no information is currently available on the restoration amount (Branigan et al, 2020). As with OSR programmes in the USA, the TNC programme in Australia is heavily reliant on community involvement and engagement. There are many ways to engage volunteers in oyster shell recycling programmes throughout the supply chain from partners to restoration. Activities include; the actual supply of shell material itself, collection of shells, cleaning, bagging and even restoration (Branigan et al, 2020).

The project has over 15 partner organisations and continues to generate high levels of interest from restaurants and wholesalers who would like to establish partnerships (Branigan et al, 2020). The programme operates at a cost of $83,436 per year however this is not inclusive of the biggest portion of costs which is attributed to salary for TNC employees (Branigan et al, 2020). Currently it is free for restaurants to participate and it is currently being investigated whether the program is scalable to a national level (Branigan et al, 2020). 'Shuck Don't Chuck' offes a successful framework for oyster shell recycling that could be applied in other jurisdictions to help establish shell recycling programmes.

2.5 Hong Kong Oysters

2.5.1 Hong Kong Oyster Ecology

In the revision of 'The Oysters of Hong Kong', Morton & Lam, 2004 identified twelve species of oysters found in Hong Kong including *Crassostrea hongkongensis*, a then newly described species native to Hong Kong. The results showed that two species of cultured oyster were present in the oyster farms of Hong Kong. One is a genetically identified new species, *C. hongkongensis* and the other *C. ariakensis*, otherwise known as the 'Suminoe oyster' the species is large and flat in appearance and almost identical in gross morphology to *Crassostrea virginica* or 'Eastern Oyster' found on the East Coast of the United States of America (Morton & Lam, 2004). In contrast, the status of Hong Kong's oyster reefs are unknown in comparison to their well-documented loss in other global regions. Any remaining natural reefs in Hong Kong are sparsely distributed and highly in the shallow intertidal coastal waters of Hong Kong (Lau et al., 2020). These habitats are highly degraded and in need of vital restoration but have adequate larval supply for restoration (Lau et al., 2020). This conclusion means that restoration can be achieved with the addition of a hard substrate.

2.5.2 The Hong Kong Oyster Industry:

Crassostrea hongkongensis and C. ariakensis are commercially cultivated using culture rafts in Deep Bay in northwestern Hong Kong (Figure 8). Deep Bay is situated on the Eastern side of the Pearl River Estuary and is approximately 17 km in length, 115 km^2 in area and with an average water depth of 2.9 meters (AFCD, 2017). Outer Deep Bay is characteristically sandy substrate, while Inner Deep Bay is almost exclusively mud substrate (EPD, 2002). Oysters were traditionally cultivated by the method of 'bottom culture', a method used for at least 700 years (Morton & Wong, 1975). The tidal mudflats at Deep Bay are not suitable for oyster settlement because of the lack of hard substrate, and therefore 'cultch' (a hard substrate placed in the mud) was used to collect spat (EPD, 2002). Typical clutch material include; concrete posts, concrete tiles, concrete blocks or stone with the most common type of clutch being bamboo sticks coated with concrete (Morton & Wong, 1975). Clutches are inserted into the tidal mudflats allowing spat to settle naturally and grow to market size, with farmers regularly clearing other organisms to reduce competition (Morton & Wong, 1975). However, more modern raft culture techniques are now the most common commercial culture method in Hong Kong (AFCD,2020). Bamboo or wood rafts are used to suspend oysters on ropes above the seabed which reduces growth time compared to clutches on the mudflats (AFCD,2020). Typically, oysters take three years to mature to market size (AFCD,2020). There are over 1000 ha of mudflats within Deep Bay and roughly 75% of them extend from Tsim Bei Tsui to Ha Pak Nai (747 ha) (AFCD,2020). The size of intertidal mudflats was surveyed to be about 747 ha, of which about 176 ha (approximately 24%) consisted of oyster beds (EPD, 2015). This figure represents the total area of HKSAR mudflat available for oyster farming as shown in Figure 7 (EPD,2002).

Figure 7. Oyster beds in Pak Nai, Deep Bay, Hong Kong (TNC,2020).

The oyster industry in Deep Bay has been decimated by serious declines in water quality caused by high pollution and land reclamation (Kwan et al, 2018). Environmental conditions have deteriorated so drastically that little oyster spat can be collected from the wild in local waters and oyster farmers have shifted to fattening of imported seed oysters purchased from China (FAO, 2016). As a consequence, local production of oysters represents only a small proportion of the total oysters consumed in Hong Kong. Production has been exceeded by imports from the mainland and around the world. In 2020, local production was 119 tonnes (meat only) valued at HKD$15 million (AFCD, 2020). The site was declared a Water Pollution Control Zone in 1991 (FAO, 1994) and whilst there have been noticeable improvements in water quality since then, Hong Kong still faces many pollution challenges that are impacting both oyster populations and oyster aquaculture.

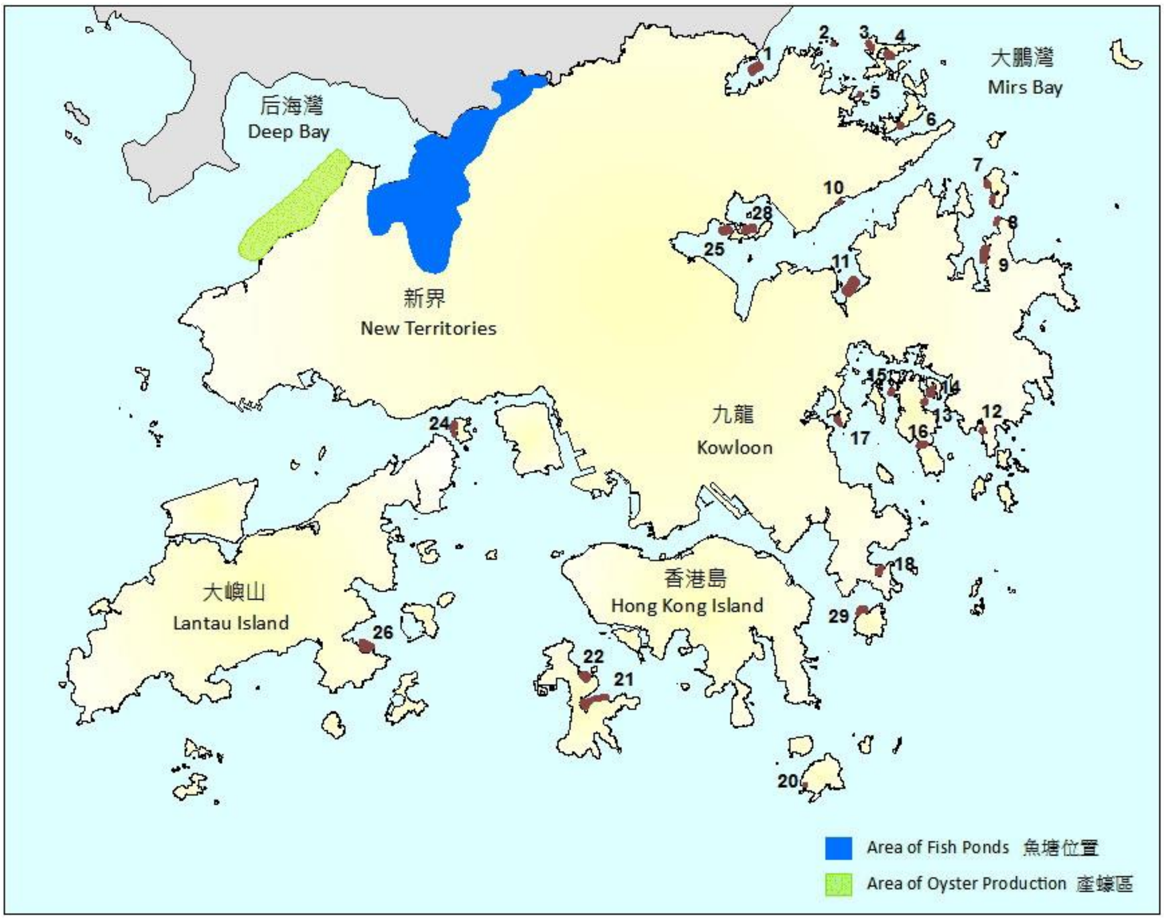

Figure 8. Map showing areas of Oyster Production and Fishponds in Hong Kong (AFCD, 2017)

2.5.3 Hong Kong Oyster restoration

In Hong Kong, there has been little done to restore oyster populations. The only active restoration is being conducted by The Nature Conservancy (TNC) in Pak Nai, near Deep Bay and Hong Kong's oyster production zone (TNC, 2021). The TNC uses volunteers for the purpose of shell gathering on the mudflats of Deep Bay (Thomas, M 'email communication' 2020). The shell is aquaculture debris from the local oyster farms and activity serves a dual purpose in that it provides shell material to the TNC and also improves vulnerable Horseshoe Crab habitat (Kwan et al, 2018). Oyster shells have been known to negatively affect horseshoe crab density and foraging behaviour (Kwan et al, 2018). Due to the low volumes of shells collected, the TNC investigated using alternative materials such as terracotta tile for substrate enhancement and further exploring various ways to repurpose shell into by-product to donate to local vegetable farms (Thomas, M 'email communication' 2020). The TNC's efforts more broadly go into investigating how oyster reefs can positively impact Hong Kong's marine environment and engaging the aquaculture industry to help revive the community (TNC, 2021)

Hong Kong Context

Hong Kong's 700-year old oyster industry holds cultural and historical heritage and it's loss would be significant. Hong Kong is also concurrently facing a waste crisis (EPD, 2021). The production and imports of oysters generates thousands of tonnes of waste each year (Silva et al, 2019). Waste loads in Hong Kong have mirrored economic growth, similar to many developed nations, but whilst waste increases are common, unfortunately Hong Kong's issue is unique and further compounded by limited land resource availability (EPD, 2021). Landfills are a crucial element to any sustainable waste management plan but to date, Hong Kong has closed 13 of its existing landfills to minimize potential health and safety risks (EPD, 2017). Three strategic landfills remain but they are similarly under tremendous pressure (EPD, 2017). The short-term solution is to expand Hong Kong's three major waste facilities to accommodate incoming waste (EPD, 2021). These facilities include the South-East New Territories landfill (SENT), the North-East New Territories landfill (NENT), and the West New Territories landfill (WENT) (EPD, 2017). Another new government facility, the Waste Electrical and Electronic Equipment (WEEE) has been developed to handle recyclables of electric hazardous waste and the Organic Resources Recovery Centre (OPARK) has been established to handle 200 tonnes of food waste generated from the commercial and industrial sectors per day (EPD, 2017). OPARK is the first facility of its kind in Hong Kong and adopts anaerobic digestion technology to convert food waste into biogas as renewable energy as well as compost for agricultural use (EPD, 2017). Unfortunately, oyster shell material can not be processed at OPARK and therefore discarded oyster shells will still contribute to Hong Kong's ongoing landfill and waste issues.

In February 2021, the "Waste Blueprint for Hong Kong 2035" was announced that outlines the Government's goals and strategies to tackle waste management with the vision of "Waste Reduction. Resources Circulation, Zero Landfill" (Environment Bureau, 2021). The blueprint highlighted two major goals: Reduce per capita Municipal-Solid-Waste (MSW) disposal rate by 40-45% and raise the recovery rate to about 55% by implementing Municipal-Solid-Waste Charging (MWCS) and reduce dependency on landfills by developing adequate waste-to-energy facilities (Environment Bureau, 2021). Initially introduced in 2018, the MWCS is premised on the "polluter-pays" principle by which Hong Kong residents will be taxed based on their waste disposal (Environment Bureau, 2021). The charges proposed are applicable to almost all residential and commercial premises and they will be calculated under two modes; 1) charging by designated trash bags currently set at HKD$0.11 per litre and will account for 80% of daily MSW sent to landfills and 2) charging by weight-based “gate-fee” for private waste collectors who dispose of MSW at landfills (Environment Bureau, 2021). The second method will cover the remaining 20% of Municipal-Solid-Waste (Environment Bureau, 2021). The scheme is currently postponed due to the Covid-19 Pandemic but once revived, households and restaurants will have to pay by the volume of waste they contribute, regardless of the actual volume, oyster shell waste will soon come at a cost (Environment Bureau, 2021).

2.6 Shell as a commodity

Shells have been a prominent feature throughout human history. Initially used as primitive tools and more recently as a globally traded currency in the mid-19th, shells have always held intrinsic value to society (Morris et al., 2019). Today, shells are valued for their structure and properties and there are already a number of well-established markets for shells. Composed of 95% to 99.9% calcium carbonate, shell material has a wide range of applications, particularly as a replacement for energy intensive and ecologically damaging calcium carbonate (CaCO3) mining. (Morris et al., 2019).

Oyster shells, and more specifically the calcium derived from them, have been used as a means of improving livestock health as a replacement for $CaC0_3$ which is more commonly mined from limestone (Silva et al, 2019). Shell is comparable, and in some instances a better quality material to limestone in respect of calcium supplementation (Silva et al, 2019). Shells are further applied in the agricultural sector as a liming agent to treat soil or water to reduce its acidity which in turn increases oxygen levels and improves fertility (Silva et al, 2019). Most commonly, shells are used as material for construction or aggregate Silva et al, 2019). Whole oyster shells can be incorporated into wall construction or mixed into aggregate for pathways. Furthermore, shells can act as pH buffer for wastewater in aquatic systems (Waldbusser et al, 2011). In more practical terms, crushed oyster shells are sold as a biofilter substrate that can prevent or rectify dramatic acidification (Waldbusser et al, 2011).). It should be noted that shell applications will be limited by the costs associated with aggregating enough mass material that could provide suitable quantities. (Morris et al, 2019). In locations where shells are produced in high quantities, there are sustainable and economically viable applications to change shells from an unnecessary waste product into a valuable commodity (Morris et al, 2019).

Oyster shell is a valuable commodity that doesn't require high energy processing to generate value. Shell can be turned into by-products and sold in many markets. However, it’s greatest value may lie in returning shell to its natural environment to enhance restoration of oyster populations. Therefore, an effective method for procuring waste shells needs to be established.

3.0 Methodology

3.1 Field study

A field study was undertaken to test spat recruitment rates and evaluate whether Hong Kong oyster spat show a preference in the selection of substrate during settlement.

Figure 9. Study site at Tai Tam Harbour, Hong Kong with experimentally survey units.

3.1.2 Site description

The study site is located on the Southern side of Hong Kong Island, in Tai Tam Harbour, in the innermost part of Tai Tam Bay. Tai Tam Harbour is roughly 3.2 km in length and 500 m wide (AFCD, 2020). The coastal habitat was also awarded as a Site of Specific Scientific Interest (SSSI) (AFCD, 2020). It has a diverse ecosystem that encompasses mangroves and an intertidal mudflat consisting of oyster populations. The site was selected due to it's high density oyster populations and shallow water depth that provided convenient access. The bottom is predominantly soft muddy sand with fragmented oyster habitat.

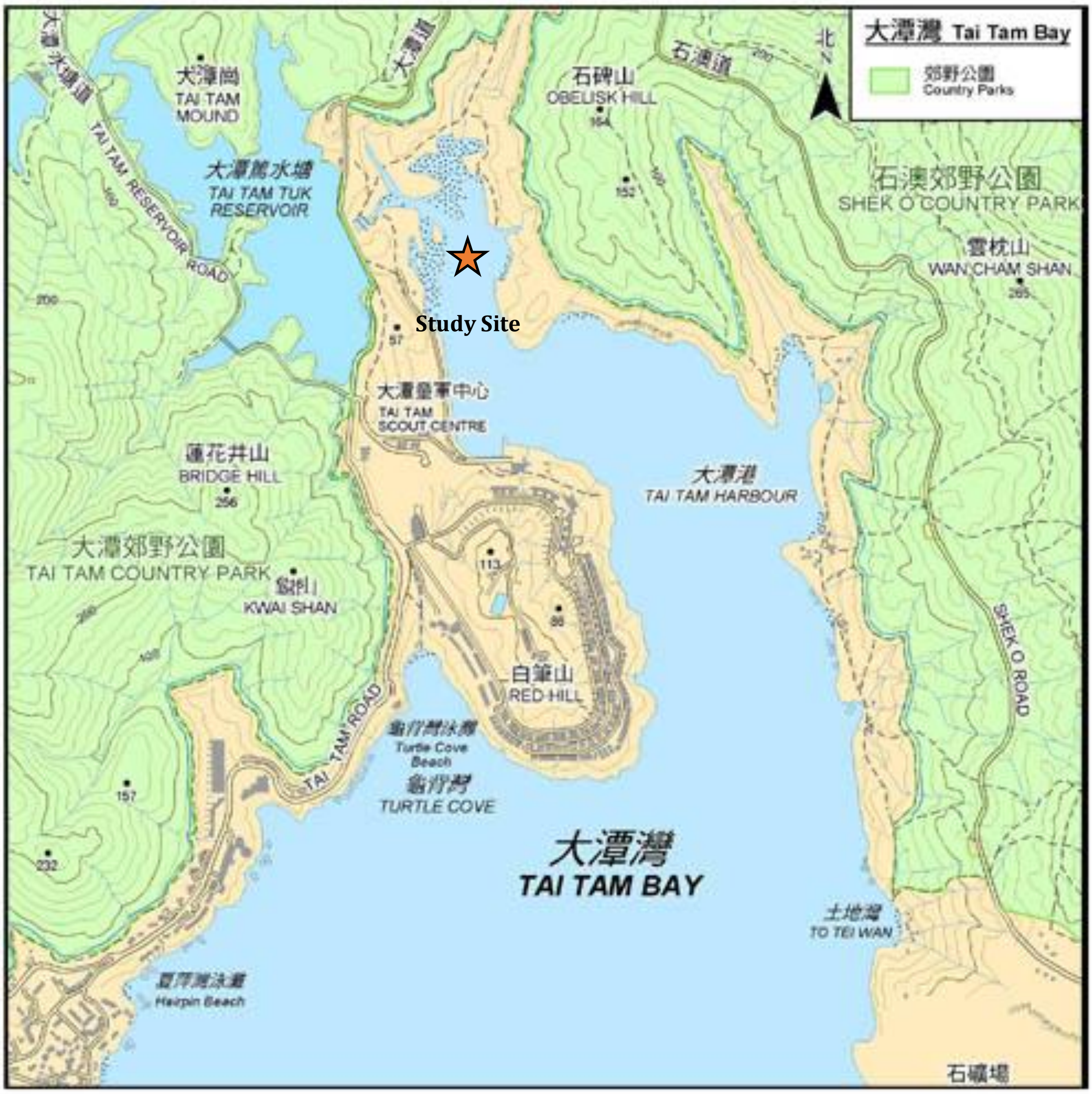

Figure 10. Map showing Tai Tam Harbour extracted from the Agriculture, Fisheries and Conservation Department with location of the study site added (AFCD, 2020).

3.1.3 Experimental design and sampling

Sampling units were created using PVC piping to hold 3 different substrates suspended in the water column. The substrates used were; post-consumed oyster shell, terracotta and concrete. The post-consumed oyster shells were acquired from a local restaurant and underwent all necessary biosecurity protocols needed to reduce the risk of the spread of invasive species and diseases through the relocation of bivalve shells (NOAA, 2012). The terracotta tiles are identical to the alternative substrate used by The Nature Conservancy in their oyster restoration investigations. The concrete was collected from construction debris and is representative of a common alternative substrate used for oyster reef restoration. The substrates were suspended >15cm above the bottom and tilted to a 45 degree angle to avoid a buildup of sedimentation which can negatively impact spat settlement. Eight (n=8) survey units were built, each supporting at least 1 of each substrate and a maximum of 4 substrates. Each substrate was separated by >60 cm using 'arms' designed for this purpose. Oyster shells were threaded together through drilled holes in the center of the shells. Each thread held 4 to 5 oysters. The sampling units were placed during a low tide period (i.e. tidal level < 1.2 m) in the water at Tai Tam Harbour in late August 29th 2020. Observations continued for a period of seven weeks before the units were removed on October 18th 2020.

Figure 11. Survey unit under water at the study site in Tai Tam Harbour.

Figure 12. Oyster cluster at the study site in Tai Tam Harbour.

3.1.4 Sampling analysis

Following removal, each survey unit was taken immediately to the laboratory and visually observed for spat recruitment. All substrates were frozen to maintain the condition of attach spat for observation. The colonization of fouling organisms such as barnacles and other bivalves were identified, removed and not counted. To standardize the estimate of total spatfall in this experiment, the total surface area of the substrate was used. The application of density in this study follows absolute density as applied for distribution and abundance in ecological studies. Spat density was described as the number of spat per unit (substrate) area. The terracotta tiles and concrete had fixed surface area sizes of 380.25 cm2 and 574.36 cm2, respectively. However, the individual oysters shells had variable sizes. The surface area of the oyster shells was calculated by creating aluminum molds to press over the shell surface and into mounds; ridges, depressions and crevices (Morales-Alamo, 1993). Any excess foil was removed without distorting the shape and surface area (mm2) was measured from the resulting piece of foil using measured grid paper. Foil has been previously used to measure surface area of corals (Marsh, 1970) and other bivalve mollusks (Mackie, 1992, Beckett et al, 1996, Werner & Rothhaupt, 2007, Sousa et al,2011).

3.1.5 Statistical analysis.

Differences between recruitment rates were analyzed by the Kruskal-Wallis test and post-hoc Permutational Analysis of Variance (PERMANOVA). Statistical tests were performed using SPSS software. Differences were considered significant when $p<0.05$.

3.2 Desktop study

A desktop study was then conducted to identify quantifiable data regarding, the costs of oyster shell recycling programmes, the value of oyster shells and the estimated value of ecosystem services provided by oyster populations in Hong Kong. Data and descriptions were taken from multiple sources including: 1) primary literature (published peer-reviewed scientific literature, annual financial reports), 2) grey literature (scientific reports and technical summaries) and 3) online descriptions (e.g. blogs and websites describing programmes).

3.2.1. Primary literature

Multiple search engines were used to achieve coverage across scientific literature. The main source or primary literature was found using Google and Google Scholar with the keywords "oyster + shell + recycling or restoration" and "oyster + ecosystem +services". Because the field is dominated by studies, specific studies that highlighted the value of oyster ecosystem services, the value of shell and/or costs of oyster shell recycling programmes were selected.

3.2.2 Grey literature

To achieve further coverage, various other sources were consulted including; Government reports, legislation, EIA reports, NGO technical reports, company annual reports, financial statements and tax returns. This was supplemented with reports listed in the reference lists of other papers and reviews found during online searches.

3.2.3 Data analysis

Due to the high heterogeneity of information available from such a diverse range of sources, the study was precluded from performing quantitative statistical analysis. However, a comprehensive review and cost-benefit evaluation were conducted using summary statistics to evaluate and compare different oyster shell recycling programme operation costs vs the estimated value of oyster ecosystem services in Hong Kong.

3.2.4. Costs of Oyster Shell Recycling Programmes

The costs of oyster shell recycling programme data has been extracted from 14 case study projects sampled worldwide. Along with costs of operating per year in USD$, the scope of the programme in terms of number of shell supplier partners, the amount of shell volume generated, the type of organisation and the funding mechanism were recorded. In total, 7 projects had cost data available, 12 had data on shell volume generated and all had information on the scope or operating mechanism of the programme. This review has focused on both the largest scale oyster shell recycling programmes as well as smaller scale efforts by community-based organizations. To access this information, I conducted online searches on Google, using the search terms “Oyster Shell Recycling”.

3.2.5 Value of shell material

Data on the value of shell across different products was gathered by using online Google searches entering ‘oyster+shell’ + the specific shell use, i.e animal feed, liming agent, etc. Multiple sources from different global locations were analyzed and the valuation selected based on the most reliable source. In many cases, this was either online retailers or e-commerce platforms. The raw material shell price was obtained directly from the Habitat Project Coordinator at The Delaware Estuary Organization priced at USD$10 a bushel (Bouboulis, S. ‘personal email’, 2021). Bushels were converted to an average weight of 50 lbs (Street, et al, 2005) and 50 lbs converted to 22.67 kg. All prices were converted into USD$ per tonne and the estimated value was calculated by multiplying the USD$ per tonne by 3671, which is the estimated tonnes of shell Hong Kong generated in 2020. Any price per shell valuations were calculated by approximating 12,500 shells per 1 tonne (Morris et al, 2019).

3.3 Cost-Benefit Evaluation

A Cost-Benefit Evaluation (CBE) can be a useful method to inform decision makers of the benefits and costs between existing and future programme choices, such as oyster shell recycling. The cost and benefits evaluated involved both tangible and intangible, non-market and marketed services with economic and environmental aspects. The benefits of restoring oyster populations in Hong Kong mainly involve ecosystem services that are not traded in the market, such as water quality improvements. Without evaluating these non-marketed aspects, the total value of OSR programmes would likely be undervalued and therefore conducting a cost-benefit evaluation is essential for decision makers. The study gives a preliminary estimate of the costs and benefits of establishing an Oyster Shell Recycling programme in Hong Hong that could serve as a reference for further studies or policy considerations. To calculate the impacts of benefits per each year from an enhanced Hong Kong oyster population, peer reviewed studies were used to approximate the potential benefit per ha of oyster reef. This was multiplied by the cumulative production area (ha) reported in Hong Kong. Any benefits were adjusted to 2021 dollars and both minimum and maximum averages of ecosystem services values were included. The annual benefits and costs were compared using discounting to calculate the net present value (NPV) and Benefit-Cost Ratio (B/C). The Hong Kong Government recommends a 4% discount rate for environmental projects (HKMA, 2021). NPV was calculated as: $\sum(P/ (1+i)t) – C$, where P = Net Period Cash Flow, i = Discount Rate, t = Number of years, and C = Initial Investment. The Net Present Value and Benefit-Cost Ratio are the decision rules for the evaluation. If the NPV is positive and the B/C >1 then the programme is deemed beneficial. i.e the benefits outweigh the costs.

A ‘baseline” scenario was first established to describe what the policy site (Hong Kong) would look like without a shell recycling programme. The assumption is that without establishing a shell recycling programme, oyster populations will continue to decline due to a lack of shell material to underpin restoration. It is important to note that some restoration activity using alternative materials such as those already mentioned may still occur. However, our assumption is that oyster shell provides the most effective and preferred substrate for larvae settlement and therefore without suitable investment to return shell material to strategic locations, it's assumed that populations will continue to decline.

A relevant time horizon was also identified. For the analysis, the year 2046, or 25 years beyond the first year of activity (e.g. 2021) was selected. Justification for this time horizon was to allow enough time for oysters to yield multiple high value benefits beyond one year. Costs and benefits are influenced by varying factors and therefore selecting just one year does not account for this variation.

Once the total Hong Kong oyster production hectare as well as total shell production was determined, non-market valuation methods were chosen to estimate a value against the benefits of oyster reefs as reported in the peer-reviewed studies. These studies focused on policy sites in the USA and China. Using pre-existing estimates to measure benefits at another project site is known as the benefit transfer approach to non-market valuations. This method transfers an estimated value and the range of benefits from the original site (referred to as the "study site") to the site of interest (referred to as the "policy site"). The main advantage of benefit transfer is its low-cost approach to non-market valuation approaches. We acknowledge the disadvantages of this approach are the differences in the policy (USA) and study site (Hong Kong). In recognition of the limitations associated with the valuation methods, sensitivity analysis was performed to provide a range of lower and upper estimates of the benefit-cost. The detailed calculations of the CBE are demonstrated in the appendix.

3.3.1 Value of ecosystem services

Ecosystem system services were valued using a variety of valuation methods. The impact of ecosystem service in kgs per hectare (Ha) of oyster reef was calculated and multiplied by the total Ha production area of oysters in Hong Kong. The total kg was then valued in USD$ using common environmental economic evaluation methods.

A combination of market-based and value transfer approaches were utilised to estimate the value of water quality improvements. Oyster populations are capable of nitrogen removal and there is evidence for the price of nitrogen. Nutrient trading programs are currently adopted and recognised by the US Environmental Protection Agency (EPA,2021). They operate by issuing permits to point source polluters such as sewage treatment plants (EPA,2021). This mechanism allows entities that achieve targets and have net-positive pollution levels, to sell credits to those who need to meet compliance regulations. Wastewater buffers such as oyster reefs could generate value through trading nitrogen credits; rather coincidentally, nutrient credits are a part of the Chesapeake Bay's restoration strategies for enhancing water quality (CBF, 2020). The current value, based on global nutrient trading credit programs, is USD$29 for 1kg of nitrogen removal (Rose et al, 2015). By using a value transfer approach, this existing value is used to estimate the value of the 'policy site' (Hong Kong). Studies provided information on nitrogen removal rates in lbs per Ha. This was converted to kg per Ha. Multiplying the estimated nitrogen removal rate by the Ha of oyster production area in

Hong Kong gave an approximate amount of nitrogen removal in kg. By comparing the removal rates of nitrogen and then multiplying by the trading price per kg, we estimated the value of nitrogen removal from Hong Kong oyster populations. The replacement and avoidance cost methods were also considered. The replacement-cost approach was a potential valuation method to estimate value based on water quality improvement technologies in Hong Kong. This evaluation method assigns replacement costs for a treatment plant to compensate for lost nitrogen sequestration as a consequence of lost oyster populations. However, given the detailed data needed to accurately estimate the replacement costs in Hong Kong, this was not possible.

To estimate the value of augmented commercial fish species production, again a value function transfer approach was used with information provided by peer reviewed literature (Harding & Mann, 2000). It was concluded that 10 m2 of restored oyster reef habitat creates an additional 2.6 kg of fish and large mobile crustacean production annually (Harding & Mann, 2000). Although these estimates were derived from studies in the USA, the peer-reviewed study involved multiple valuation studies across several different study sites to synthesize a value that is widely applicable. In 2020, Hong Kong produced an estimated 116,000 tonnes from it's fisheries valued at USD$347m (AFCD,2020). Using these figures, the data was extrapolated to achieve a per tonne amount of USD$2,990 and adjusted to fit the policy site i.e the size of the oyster production area in Hong Kong (176Ha).

Evaluation of the value of oysters' primary production in Hong Kong was taken from available market prices. Oyster production in Hong Kong was 119 tonnes (meat only) valued at USD$1.5 million. The Hong Kong Agricultural, Fisheries and Conservation Department makes available the amount of commercial oysters harvested and amount of oysters imported annually. They provide two quantities for these: economical value in USD and total weight in kg (tonnes).

For coastal defense cost estimates, proxy measures were relied upon for providing the same ecosystem service through an alternative option. The costs used for this exercise were based on the recently available values of the construction costs for seawall in Hong Kong, which are estimated to be USD$112 per metre (Chow et al, 2017). Data from peer-reviewed studies indicates that 5 m2 of oyster reef is needed to protect 1m of shoreline (Grabowski et al, 2014). The avoided-cost is assumed based on the total production area of oysters to approximate the amount of potentially enhanced oyster reef that would be available to provide coastal defense services. The total area is then multiplied by the cost per metre of using alternative materials, in this instance, seawall. This figure then relates to shoreline protection per 1 m of oyster reef (USD$22.4 per metre).

The amount of harvested and imported oysters can be used to estimate abundance and value of available shell material in Hong Kong. Estimates suggest shell accounts for at least 70% of the total organismal weight of an oyster (Morris et al, 2019). The production volume was 119 tonnes and the import volume of oysters to Hong Kong was 6000 tonnes in 2020 (FAO, 2020). Using a highly conservative estimate to account for species variation, we can suggest that shell accounts for at least 60% of the total weight of oysters. By extrapolating this figure from oyster production and import volumes in Hong Kong, it can be estimated that Hong Kong created 3671 tonnes of shell material in 2020. Whilst there may indeed be other sources of shell available, it is beyond the scope of this investigation to discover the circumstances of all oyster shell in Hong Kong but commercial harvests and imports are likely to be the source with the highest shell production. The estimates of total shell material available were multiplied by the mean market price per tonne of oyster shells to estimate the total potential value of recaptured waste oyster shells in Hong Kong.

Lastly, to estimate the value of carbon sequestration, the study combined a value transfer method with market prices. Using a value transfer from peer-reviewed literature a carbon sequestration rate of 0.83 tonnes per Ha per year of oyster reef (Hickey, 2008) was multiplied by the total oyster production area in Hong Kong. This calculation provided the estimate of total carbon sequestration by oyster reefs in Hong Kong. An analysis of all global carbon pricing initiatives was undertaken to achieve an average carbon price of USD$27.10. (WBG,2020 & S&P Global, 2018). When considering more relevant study sites to the policy site, the average carbon cost for China's potential policies is USD$4.60 per tonne of carbon. Both this value and the average global carbon price were used to estimate the value of carbon removal by oysters in Hong Kong.

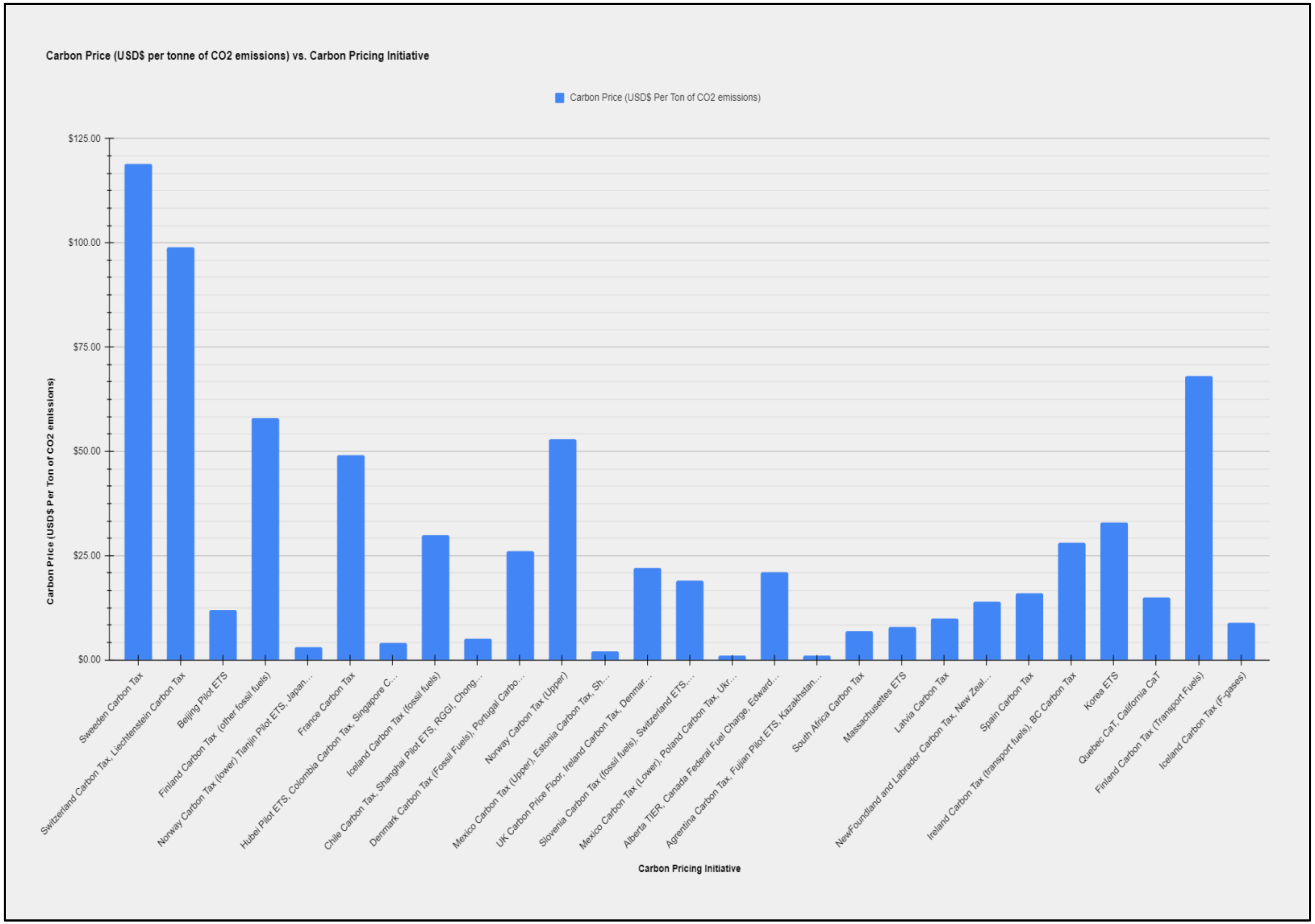

Figure 13. Global Carbon Tax analysis adapted from World Bank Group (WBG), (2020)

4.0 Results

4.1 Ecological survey

Source	df	SS	MS	Pseudo-F	P(perm)	perms
Su	2	6.38E+05	3.19E+05	5.6246	0.008	999
Res	58	3.29E+06	5.62E+04			
Total	60					

Figure 14. Output table for PERMANOVA

Groups	t	P(perm)	perms
Shell, Tile	1.4112	0.151	995
Shell, Concrete	3.0748	0.005	995
Title, Concrete	2.8333	0.008	300

Figure 15. Output table for PERMANOVA 'Pair-wise' Test

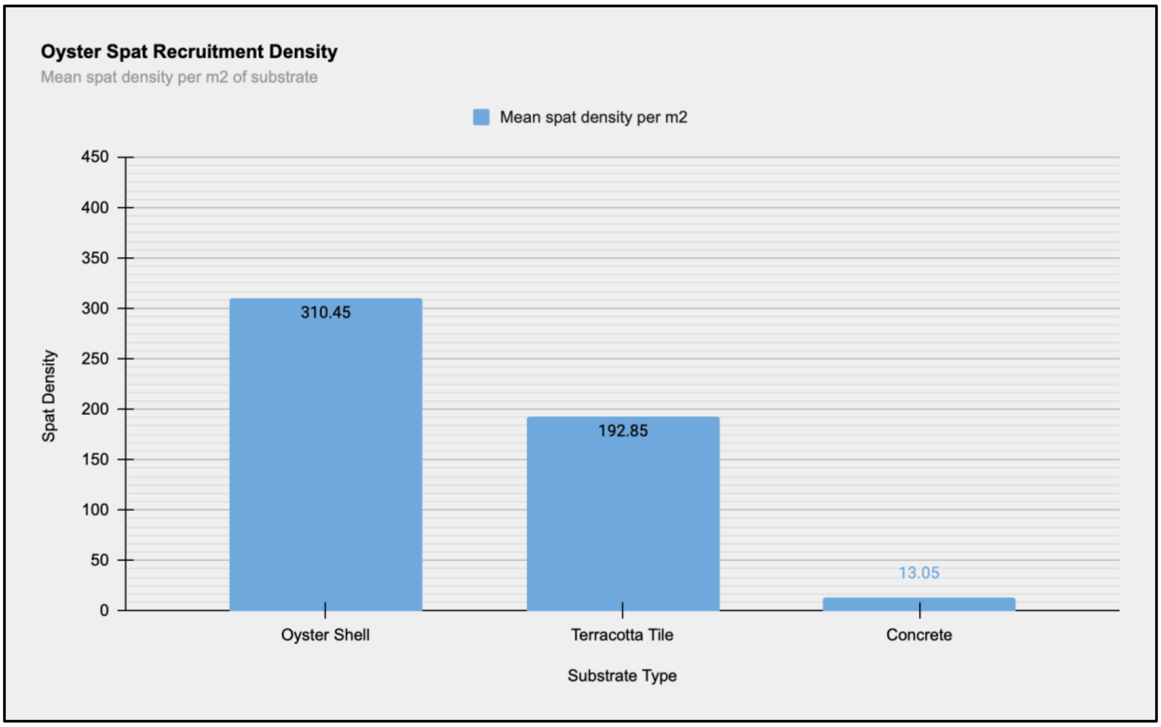

Figure 16. Mean oyster spat density per m2 of substrate

The p-value (0.008) shown in Figure 14 indicates that there is an effect of substrate type on oyster spat recruitment. Figure 15, highlights the pairwise comparisons of the different substrate types. The analysis shows that Oyster Shell spat recruitment rates are not statistically significantly different from Terracotta Tile ($p = 0.151$). However, spat recruitment rates to Oyster Shell are significantly different from Concrete ($p = 0.005$), and Terracotta Tile is also significantly different from Concrete ($p = 0.008$). Figure 16 highlights the mean density of spat per m2 across the different substrates. Oyster Shell had the highest mean spat density of 310.45 m2 ± 65.4 m2 (mean ± Standard Error (SE)). Terracotta Tile recruited spat at a density of 192.85 m2 ± 51.2 m2 and Concrete at 13.05 m2 ± 5.45 m2. The boxplot in Figure 17, emphasizes the significantly greater density of recruits on Oyster Shell and Terracotta Tile than the Concrete, but the Shell and Tile do not significantly differ from each other, largely because of the high variation.

4.2 Shell Valuation

Across 6 different shell product markets. Shell valuation ranged from USD$113 to USD$3,977 per tonne. The highest value form of oyster shell was animal feed at USD$3,997. Aggregate used in concrete was also highly valuable, estimated to be USD$2120 per tonne. These higher values may be in part attributed to the additional shell volume needed to create fine shell powder.. Shell used as a liming agent or pH buffer ranged from USD$550 to USD$840. Shell in raw material form was estimated to be worth USD$442 per tonne whilst oyster shell used for restoration was comparatively the cheapest form of shell available. This is likely a result of the need to keep restoration costs low and indicative of a willingness to provide shells at lower costs to enhance restoration activities. The mean price of oyster shell across the 6 different markets available was estimated to be USD$1931 per tonne. Under Hong Kong's MWCS, oyster shell send to landfill would come at a cost of USD$110 per tonne.

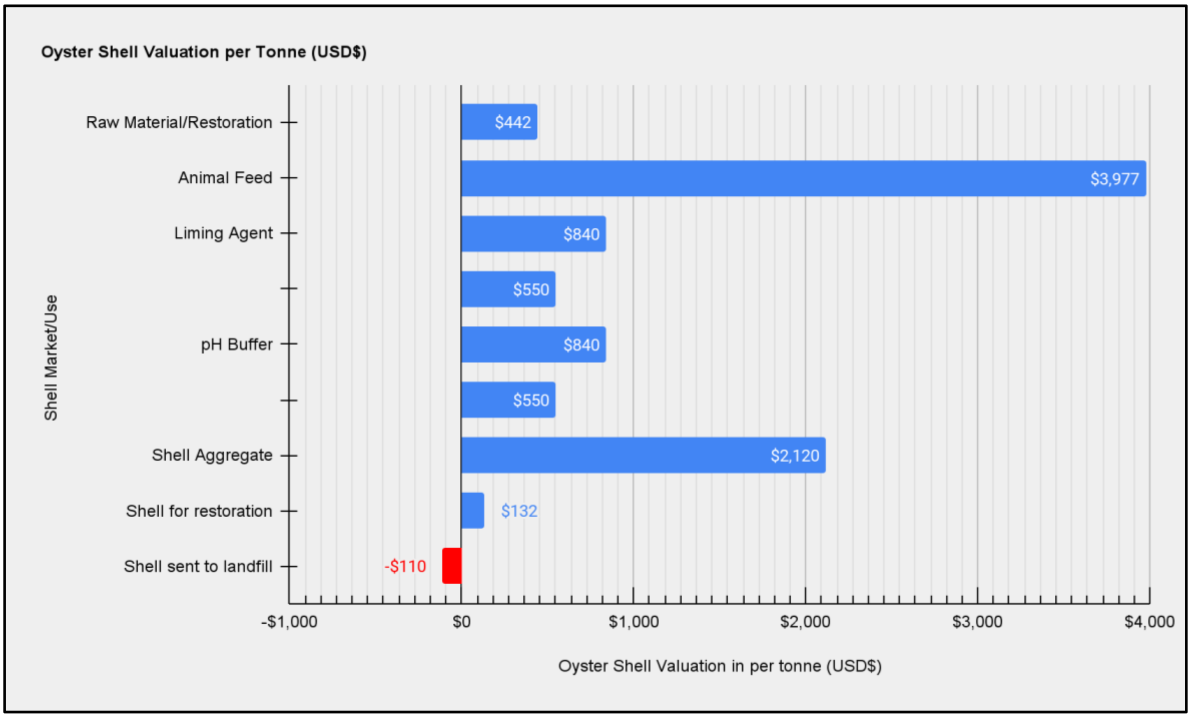

Figure 17. Average shell valuation in USD per tonne based on shell use.

4.3 Oyster ecosystem services valuation

The oyster fisheries themselves provide the most reliable valuation of ecosystem services provided to Hong Kong, at an estimated value of USD$1,386,550 per year as shown in Figure 19. However, the value of augmented fisheries production is comparably higher and estimated to be USD$13,718,848. In contrast, carbon sequestration as an ecosystem service provides the least value at USD$3,956 per year. Improvements in water quality were estimated to be valued at USD$120,350, whilst oyster reef as a coastal defense service has a highest potential value of USD$39,424,000. Oyster shell production estimates in Hong Kong are linked to the total raw material oyster shell value and the results estimate that recovering raw material oyster shells to either sell or produce by-products would bring a total value of USD$7,088,701 per year. The total estimated value of benefits enhanced oyster reefs in Hong Kong could provide per year is USD$61,742,405.

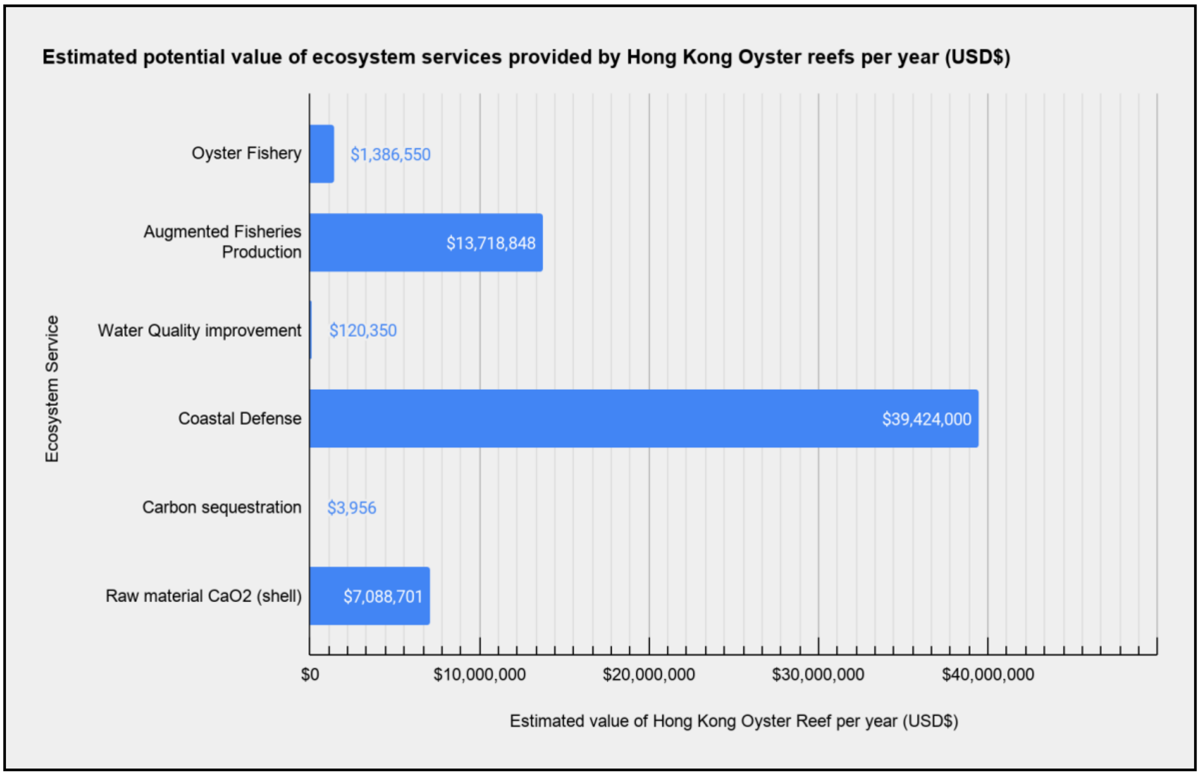

Figure 18. Estimated potential value of ecosystem services provided by Hong Kong oyster reefs per year.

4.4 Cost for OSR

4.4.1 Operational costs analysis

Data on the operating costs of Oyster Shell Recycling programs was available from 7 of the 14 programmes analysed and costs ranged from USD$17,746 to USD$1,578,318 per year. The average cost of operations across programmes was USD$306,532 per year. The North Carolina Division of Marine Fisheries surprisingly had the lowest cost of operations but generated the second highest volume of shells at 930.1 tonnes. Notwithstanding the fact that some cost data was unavailable, this is still comparatively low especially when considering the costs of other programmes such the Billion Oyster Project. The BOP is a privately funded programme and operates at a per year cost of USD$144,000. The programme recycles less than 10% of the amount of shell volume per year, compared to the per year rates of the North Carolina state-run programme. Government operated oyster shell recycling models yielded the highest volume of shell per year. This indicates that programmes backed by federal funding and/or policy instruments are the most effective mechanism for OSR Programmes to procure shells. Of the programmes with shell volume data, the average volume of shells recycled was 452.5 tonnes per year and the average cost of operation per year was USD$306,532. The result indicates that the average operating cost per tonne of recycled shell is USD$677 per year. Assuming that Hong Kong generates at least 3671 tonnes of shell per year, the estimated cost of recycling this amount based on averages from existing global OSR programmes is USD$2,486,804 per year.

Table 3. Analysis of Oyster Shell Recycling Programmes

Oyster Shell Recycling Programme	Costs /year (USD$)	Scope of programme	Shell volume recycled / year (tonnes)	Operating Model	Funding Mechanism
The Nature Conservancy 'Shuck don't Chuck' (Australia)	$83,436	15 partners	55	NGO	Private funding
Oyster Recovery Partnership (USA)	N/A	350 partners	816	Non-profit	Private funding and Tax Credit
The Coastal Conservation Association (New Hampshire)	N/A	22 partners	360.7	Non-profit	Private funding
The Massachusetts Oyster Project (Massachusetts)	N/A	0	0	Non-profit	Volunteer
Wellfleet SPAT (Massachusetts)	N/A	23 partners	250	Non-profit	Volunteer

Nantucket Shellfish Association (Massachusetts)	N/A	30	N/A	Non-profit	Volunteer
Billion Oyster Project (New York)	$144,000	75 partners	60.4	Non-profit	Private funding
The Chesapeake Bay Foundation (Virginia)	$1,578,318	Statewide	45.3	Non-profit	Private funding
The North Carolina Division of Marine Fisheries (North Carolina)	$17,746.40	State-wide	930.1	Government	Federal funding - Tax credit and Legislation
South Carolina Department of Natural Resources (South Carolina)	N/A	State-wide	1750	Government	Federal funding - Tax Credit and Legislation
Choctawhatchee Basin Alliance (CBA)(Florida)	$18,000	12 Partners	N/A	Non-profit	Private funding

Santa Rosa County (Florida,USA)	N/A	2 partners	3.22*	Government	Federal funding and Legislation
Galveston Bay Foundation (Texas,USA)	$64,223	12 partners	10	Non-profit	Private funding
Coalition to Restore Coastal Louisiana (CRCL) (Louisiana, USA	$240,000	31 partners	700	Non-profit	Private funding

4.4.2 Partnerships

OSR programmes with greater amounts of partners tended to recycle higher volumes of oyster shells as shown in Figure 20. This unsurprising result is presumably because of the greater supply of shells to the programme. On average, non-profit or privately funded organizations recruited less partners and recycled less shells. Government operated programmes recycled significantly more shells, with the exception of the Santa Rosa County programme. This is likely explained by the fact the programme only started in 2020 and has been on hold to Covid-19.

Government run programmes operated by federal funding and with the use of a policy instrument were able to procure significantly high volumes oyster shells. In locations where policies such tax credits were used, privately funded programmes also were able to recycle more shells. OSR programmes that were privately funded without any supporting policies recycled less than half the volume of shells. Volunteer run programmes procured the least amount of shell per year.

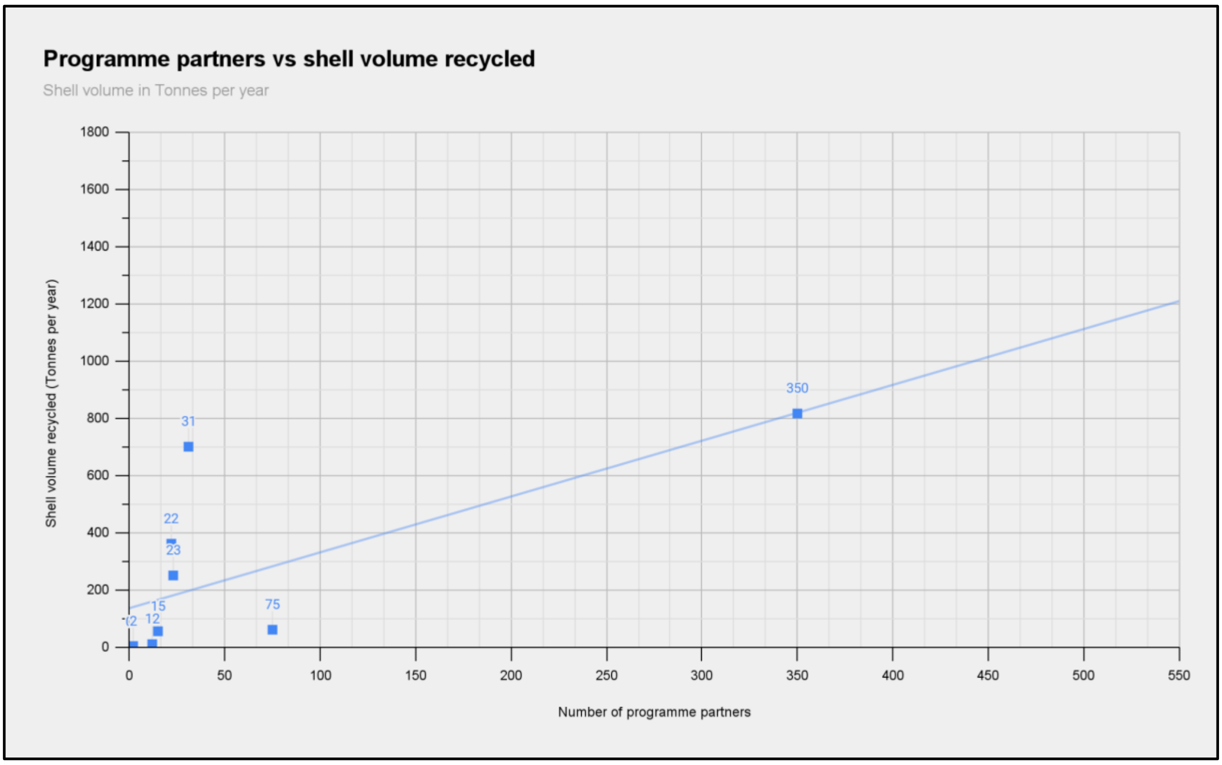

Figure 19. Amount of shell volume recycled per programme vs number of programme partners.

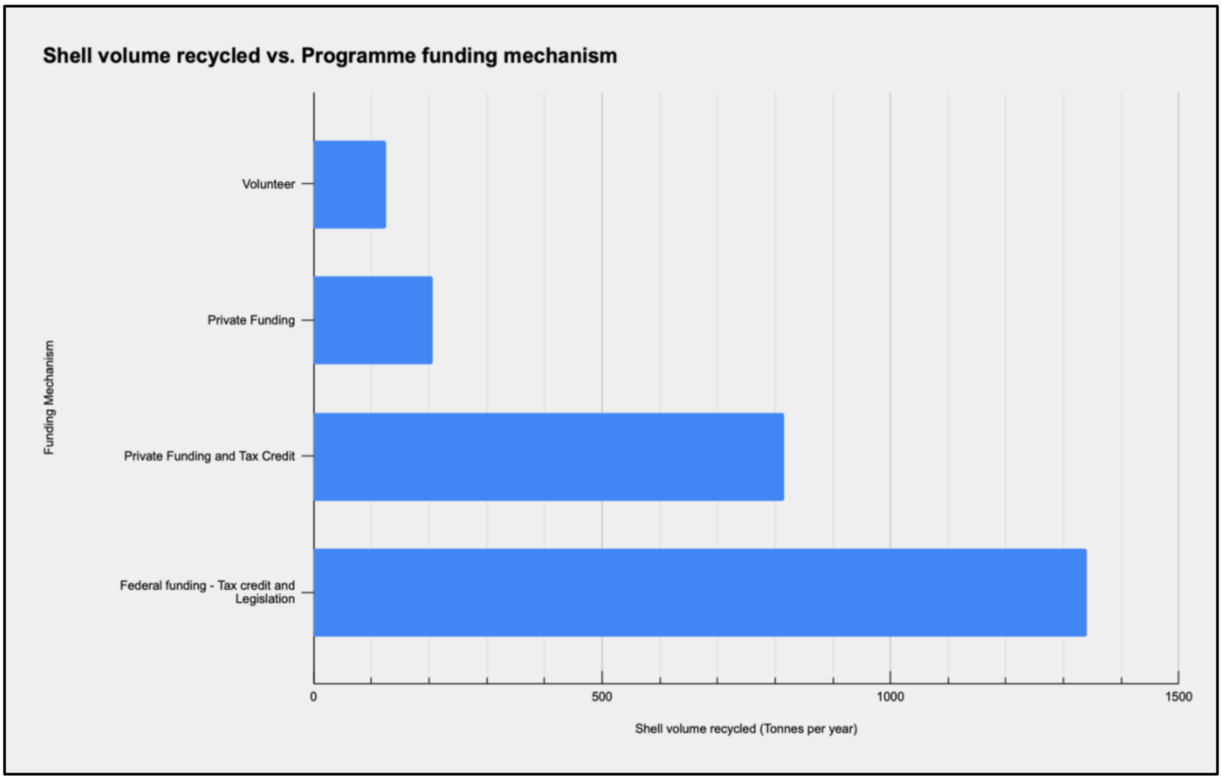

Figure 20. Shell volume recycled vs funding mechanism

4.5 Hong Kong, Oyster Shell Recycling Cost-Benefit Evaluation

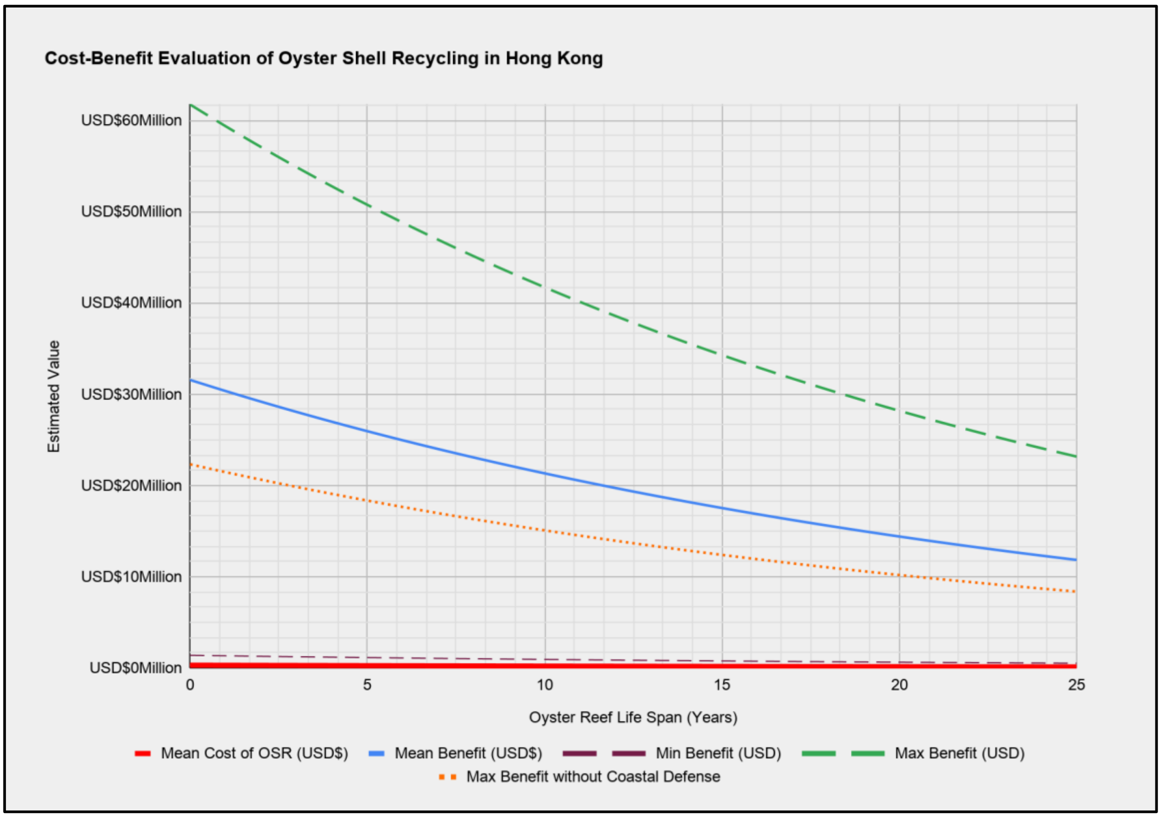

Figure 21. Cost-Benefit Evaluation of establishing an Oyster Shell Recycling programme in Hong Kong

Potential oyster shell recycling activities passed the cost-benefit test. The Net Present Value (NPV) created by establishing an Oyster Shell Recycling programme in Hong Kong over the next 25 years is USD$519,572,078, indicative of being highly beneficial in terms of the cost-benefit evaluation. The Benefit-Cost Ratio is 102.9, showing the benefits far exceed the costs and meaning for every $1 invested in an OSR is expected to yield $102 in benefits. Even when examining the minimum estimated benefits of enhanced oyster reefs in Hong Kong, this scenario would still provide benefits over the costs with a BCR of 4.5. As a further sensitivity measure, the speculative valuation of coastal defense was removed and the analysis still concluded a high positive BCR of 72.8. The result indicates that even without such services, OSR programmes would still be a beneficial investment.

Potential oyster shell recycling activities passed the cost-benefit test. The CBE resulted in a positive NPV and a BCR, showing that establishing an Oyster Shell Recycling programme in Hong Kong is economically viable. Therefore, the total benefits of ecosystem services provided by enhanced oyster reefs would outweigh the mean cost of running an oyster shell recycling programme. Even when considering the applied sensitivity analysis i.e the minimum and maximum benefits, the NPV is still positive. This highlights that even in situations where the full benefits of ecosystem services were not provided, OSR programmes would still be acceptable investments in Hong Kong.

5.0 Limitations

5.1 Field study

Genetically identifying the species of oyster present at the study site or the attached spat was not possible. To further understand the requirements for settlement of Hong Kong species, more sites should be selected whilst repeating the same methodology in each site to provide more information. The lack of data around spat recruitment variables specifically in Hong Kong would be useful to further validate the results of the effect of substrate.

5.2 Cost-Benefit evaluation

It was beyond the scope of this investigation to quantify the total amount of oyster reef in Hong Kong. As a consequence, the total oyster production area as reported by the AFCD was used to represent a conservative estimate of oyster populations capable of being restored and therefore provide beneficial services to Hong Kong. Estimates were based on the unit area (ha) of oysters over the total production area. Given the value of ecosystem services can be largely dependent on the exact location of oyster reefs, it is recommended that wider surveys be conducted to identify furter sites with the potential for restoration. However, given the limited data available in Hong Kong, the total production area figure was selected as the most appropriate foundation to value the services oysters provide to Hong Kong. Historical or cultural valuations were not included as part of the evaluation as these values would require extensive research into the Willingness-to-Pay (WIP) for such services. However, anecdotal comments and news coverage regarding Hong Kong’s oyster industry would suggest the WIP in these areas is high (Farmer, 2021). Where possible, the analysis selected valuation methods that were not location dependent as to provide a more accurate and transferable value.

Data regarding the operating costs of various OSR programmes was also missing in some cases. Furthermore, the running cost and programmed details were outdated for The Department of Marine Fisheries, North Carolina. There are potentially more OSR programmes that were not accessible based on the content being in a different language (non-English) as well as unreported non-scientific community based endeavors.

6.0 Discussion

6.1 The value of restoring oyster reefs in Hong Kong

Ecosystem services provided by oyster reefs are well documented, but their value is relatively unknown and unquantified in Hong Kong. This analysis supports the theory that healthy oyster reefs in Hong Kong would bring highly valuable ecosystem services that could provide mitigation against some of the country's most pressing environmental issues (Lau et al, 2020). When considering that oyster primary production has a known market value of USD$1,386,550 in Hong Kong, it is surprising that more has not already been done to restore oyster populations. In close association, secondary production in the form of augmented species production was appraised as the third highest valued service. Literature demonstrated that oyster reefs have the potential to increase commercial fisheries species by 2.6 kg per 10 m^2 of oyster reef (Harding & Mann, 2000). Given the ability to perform this function is closely tethered to primary production, it suggests that oysters reefs should be valued for their cumulative production power. The value of secondary production from a unit of oyster reef will be dependent on location and the associated specific ecological and environmental factors, but oyster reefs located on mudflats, such as those in Deep Bay, have been shown to have a far greater effect at augmenting juvenile fish than other habitats (Grabowski et al, 2012) This information provides more validity to the estimated valuation of secondary production.

The potential of oyster reefs to provide coastal defence services in Hong Kong was also highly valued in the evaluation. This result is in line with literature, which implies oysters reefs have the potential to provide replacement services for protecting coastline (Grabowski et al, 2012). The investigation relied heavily upon proxy measures based on the cost of performing the same service via alternative means, in this case, the construction costs of a seawall in Hong Kong. The value of protective services however, is highly dependent on what exactly oyster reefs are protecting. Therefore, this is likely the most speculative valuation. Environmental valuation methods, such as 'Hedonic Pricing', which evaluates ecosystem services that directly impact housing prices, could be used as part of further studies to more accurately estimate the value of coastal protection provided by oyster reefs in Hong Kong. However, estimates in this study were based on the unit area of oysters for the total production area of Hong Kong and not specific oyster reef habitat with characteristics. This means oysters were valued as a transferable defence tool that could be utilised in strategic locations where protection services are demanded.

That said, the location of Hong Kong's oyster production area does provide protection of valuable coastline including the Mai Po Inner Deep Bay Ramsar Site, Pak Nai SSSI & Tsim Bei Tsui SSSI, and Hong Kong Wetlands Park. Mai Po features the largest dwarf mangrove habitat in Hong Kong and is listed as of International conservation importance due to it providing habitat for over 400 species of birds including over 50 that are globally threatened (EPD, 2019). The two SSSI's of Pak Bai & Tsim Bei Tsui, located behind the oyster cultivation area of Deep Bay are also of high scientific and educational value. Tsim Bei Tsui encomposses a mature and uncommon mangrove community whilst Pak Nai provides important nursery and breeding habitats for Horseshoe Crabs and Seagrasses (Cheung, 2019). Furthermore, with the rapid infrastructure development in Deep Bay, combined with increasing risk of shoreline erosion and sea level rise due to climate change, it is reasonable to suggest the cost of coastal protection services in Hong Kong will increase. This has knock-on implications for the potential value of oyster reefs. In locations where such services are demanded, oyster reefs can provide analogous qualities to alternative structures and will likely be highly valued (Morris et al, 2019).

Many water quality issues exist in Hong Kong and recent studies on oysters populations in Hong Kong indic ate they are capable of providing filtration rates of 31.7ML/hour (Lau et al, 2020). As demonstrated in this evaluation, services that can contribute to water quality improvements will be valuable (USD$120,350 per year). The lower value of this estimate may in part be explained by the method of using nitrogen removal and credits as a proxy measure for water quality improvements. Currently, there is no nutrient trading programme in Hong Kong, but in the context of Hong Kong's 2050 climate targets, it is not unreasonable to suggest that nutrient trading will likely be a future mechanism to facilitate improvements in water quality. Thereby, placing a value on nitrogen removal in Hong Kong. The EPD already sets strict parameters that total Nitrogen does not exceed mg/L 0.7 in Deep Bay which demonstrates a further Willingness-To-Pay for these services (EPD, 2021). As highlighted in the literature review, oysters are capable of nitrogen removal but given the relatively low average value of nutrient trading credits, the total valuation ranked low amongst the ecosystem services value provided to Hong Kong.

Water quality services do provide another illustration of the importance of site characteristics when determining the value of oyster reefs. Similarly to coastal protection, higher values will be gained from oyster reef services in places that require water quality improvements. Upgrades to the Shek Wu Hui Sewage Treatment works are designed to improve water quality in Deep Bay and estimated to cost HK$481 million (LegCo, 2014). A replacement-cost valuation was not used in this evaluation, but it does provide evidence of the high Willingness-To-Pay for water improvements in areas where oysters could provide a similar service. Future research could utilise this or the damage-cost approach to achieve more valuation estimates. A damage-cost method could be a particularly useful context in which to understand the value of water quality improvements in Hong Kong. In 1998, a red tide event killed 3400 tonnes of fish, comprising nearly 80% of the total cultured fish stock and caused a direct economic loss of HK$250 million (Dickman, 1992; Yang et al, 2000). Red tides are an increasing regular occurrence in Hong Kong with roughly 14 instances per year. Oyster populations have the potential to reduce the impacts of eutrophication and therefore the impact of this service would be highly valuable in regions such as Hong Kong where red tide events are becoming more frequent.

Oysters have been shown to sequester an average of 830 kg of carbon per Ha per Year (Hickey, 2008). The estimates in this evaluation suggest carbon sequestration would be the lowest value ecosystem service provided to Hong Kong. Carbon pricing initiatives are set up with large scale carbon reduction goals in mind and the price per tonne of carbon is also a reflection of these goals. Therefore, unless large quantities of oyster populations could be enhanced in Hong Kong, it’s unlikely to contribute high value carbon reduction services (Pi-hai et al, 2014). Hong Kong is yet to establish a price on carbon so the valuation was estimated based on an extensive analysis of all global carbon pricing initiatives (see appendix). Though the global average was used for the total valuation, this does not account for the varying characteristics that impact the price a country places upon carbon. China has several carbon pricing trials in place and taking the average price across these initiatives in further studies may provide a more accurate evaluation given the similar policy characteristics to Hong Kong. The average carbon price for China’s initiatives is significantly lower than the global average at USD$4.60 and therefore, it’s possible that this study has overestimated the value of carbon sequestration services in Hong Kong by using the global average. That said, within the context of global climate change, any carbon reduction services should be viewed as meaningful and valuable.

6.2 Oyster shell should be the preferential tool for restoration

In Hong Kong, there is no baseline for recruitment rates of wild oysters spat across various substrates. Therefore, it was critical to investigate the preferential substrate choice of oysters in Hong Kong. The results in this study build upon the knowledge that oyster larvae are gregarious and will preferentially settle on oyster shell substrate. Interestingly, recruitment rates were not significantly different from terracotta, which also performed exceptionally well at recruiting spat. Oyster shell substrate exhibited a high variation in spat recruitment which may be as a consequence of the experimental design of the survey units or other factors at the study side that were not included in the scope of this investigation. This data supports existing evidence that terracotta can successfully recruit equivalent amounts of spat to oyster shell (Metz et al 2015). This result is not surprising but does warrant further investigation. Oysters will dominate most surfaces over a long period of time and this could be a plausible explanation for high levels of recruitment on terracotta. Daily monitoring of the substrates was not conducted during this study and therefore it’s not possible to know if recruitment rates differed over varying timeframes or if there was an initial substrate preference. Further studies should include more frequent monitoring to gather more insights on the patterns presented here.

Debate also exists in literature regarding recruitment rates on live vs post-mortem oyster shells. This is an important factor when considering the most likely source of shell material in Hong Kong will come from post-consumed oysters. Post-consumed oyster shells were used as the substrate in this experiment and were successful at recruiting spat.

The field study's most significant result is the difference between recruitment rates of oyster shell and terracotta in comparison to the concrete substrate. The poor performance of concrete is surprising given its use in restoration but most importantly, this result provides evidence of the effect of substrate on spat recruitment in Hong Kong. Oyster populations in Hong Kong are characterized by strong recruitment potential (Lau et al, 2020), which suggests spat are subjected to substrate limitations. Therefore the focus of restoration should be the addition of hard substrate. Concrete is often chosen as a substrate for restoration, mainly due to its low cost and high availability. However, whilst it may be practically advantageous in restoration, the results demonstrated indicate it is not the most effective substrate for recruiting spat. Given the choice, oyster spat in Hong Kong preferentially chose to settle upon oyster shell or terracotta, further emphasising the importance of the appropriate substrate selection in restoration.

When comparing the two, oyster shells have many ecological and economical advantages over terracotta. Terracotta, or any alternative substrate for that matter, lack the chemical cues present in oyster shell that signal and provide a map for spat settlement. Although the results do suggest the terracotta can provide a similar service in terms of recruitment levels, other considerations such as cost should be considered when deciding the best tool for restoration. Oyster shell is currently a wasted resource in Hong Kong and alternative material will typically come at a cost. The overall impact of these findings would suggest that oyster shell is the most cost-effective restoration substrate and implies the need to create pathways to capture shell material that is currency lost.

6.3 Shell a lost resource

Oyster shells are treated as a waste product in Hong Kong and contribute unwanted Municipal-Solid-Waste to landfills. However, as demonstrated, shell material provides analogous qualities to a number of highly valued services in well established markets. Across six different shell product markets, an average shell value of USD$1,338 per tonne was calculated and indicates that oyster shells are capable of being recycled into widely applicable and valuable products. This value is unsurprising but is unfortunately not well recognised in Hong Kong. Shells are a potentially valuable commodity that do not necessarily require high-energy processing to create value but are currently not accepted at any waste recycling facilities. The data collected from the Delaware Estuary Organization (USA), confirmed that shell was being sold for restoration activities at a cost of $0.04 per oyster shell. The non-profit organization was established and designated by the United States congress and therefore provides indicative evidence towards the value the USA places on its shell resources.

By studying the commercial production and import volumes of oysters in Hong Kong, it was possible to estimate the amount of shell waste currently generated to be 3671 tonnes in 2020. Import and production volumes are likely to be the largest contributors to shell generation but shell waste can come from a variety of sources. For instance, Hong Kong oyster aquaculture farmers typically remove ('shuck') shell at the point of harvest before the meat is dried and sold. Imported oysters are also commonly provided to restaurants in full shell as well as being consumed in half shell. During the analysis, a highly conservative estimate of 60% of total weight was used to account for shell weight. This estimate is below estimates regularly used in literature with a view to incorporate any variation in shell density of species found in Hong Kong. Therefore, it is highly probable that Hong Kong generates more waste shells than the estimated figure. Further research would be needed to understand the source of all shell material available in Hong Kong.

Evidently, many markets exist for Hong Kong to capitalise on its waste shell resources and because of the high estimated volume, if all available waste shells were captured it could yield financial returns upwards of USD$7,088,701 per year. Even if Hong Kong were to export its waste shell material to other countries for use in their own oyster population restoration efforts, it could be expected to generate USD$484,572. This however would be counter intuitive to Hong Kong's own ecological needs and when coupled with the potential value of oyster ecosystem services (USD$$61,742,405), suggests that the most inherent value of the shell lies in being returned to its source, the marine environment.

6.4 Oyster Shell Recycling programmes

The results highlight the value of both oyster shells and the ecosystem services that healthy oyster populations can provide in Hong Kong. Therefore, a mechanism designed to capture waste shell resources for restoring oyster populations is needed. The Cost-Benefit Evaluation in this study combined with literary research, demonstrates that Oyster Shell Recycling programmes can provide a cost-effective solution. A potential OSR programme in Hong Kong passed the Benefit-Cost test with the results indicating that for every USD$1 invested in OSR operations would yield USD$102 in benefits.

Following an investigation into various global OSR recycling programmes, the mean average cost of operations was USD$305,532 per year. Of the programmes studied, the two highest shell yields per year came from North Carolina and South Carolina's respective state-run programmes which were supported by federal funding and underpinned by legislation that promotes oyster shell recycling. In contrast, privately funded programmes without a policy instrument were shown to be less capable of generating high volumes of recycled shells. Whilst all shell recycling efforts should be commended and encouraged, the results highlight that the most effective mechanism for Oyster Shell Recycling programmes is Government funded programmes that implement policy instruments such as legislation banning the disposal of oyster shells or a tax credit to incentivise recycling shells. Even in large scale case studies, such as the The Nature Conservancy OSR Programme in Australia and The Billion Oyster Project, privately funded programmes do not capture the highest volume of recycled shells, both projects currently recycle 55 and 60 tonnes per year, respectively (Branigan, 2020). Government programmes are presumed to have stronger enforcement capabilities in the procurement of shell as well as a further reach to connect with more partners who can provide shell. As evidence of this, a trend emerged between recycled shell volumes and the number of partners participating in a programme. Because of this, establishing recycling partners seems to be critical to procuring enough shells to be effective as a restoration tool. This pattern indicates that overarching governance of shell resources will be more effective in capturing large quantities. This is further demonstrated if we look at the Nantucket Shellfish Association (Table 3). The non-profit organisation has struggled to establish a recycling programme due a lack of resources although being active in oyster restoration and knowing the benefits of shell recycling (Massachusetts Oyster Project, 2020). The organisation is pushing the State Government for support, citing that other States with successful OSR programmes have policy mechanisms in place to subsidise the programme (Massachusetts Oyster Project, 2020). The NCDMF is an exemplary case study of how Government policies are necessary to underpin OSR programmes. After the removal of federal funding and without adequate resources, the programme could not procure enough shells and as a consequence, alternative materials were purchased to enhance restoration which actually proved to be more costly than operating its OSR programme (NCDMF, 2014).

Hong Kong has many advantages and characteristics that make it suitable for an oyster shell recycling programme. In other countries, the most successful oyster shell recycling programmes involved a policy instrument that promoted recycling of waste shells. Government policy instruments that either penalizes discarding of oyster shells or incentivises recycling will increase the willingness to recycle oyster shells. A higher Willingness-To-Pay can assist in reducing the overall costs of programmes whilst increasing the volume of shells recycled. Hong Kong has many potential partners with a high WIP. The Hong Kong Government themselves are incentivised to recycle shells, not only to benefit the community with the wide range of valuable ecosystem services provided by healthy oyster populations but also as a means of creating waste reduction pathways to achieve 2050 carbon neutrality targets. Due to the current waste crisis in Hong Kong, waste reduction forms a large part of Hong Kong’s climate strategy (Environmental bureau, 2021). The likely impact of increasing regulatory requirements and waste charging should also provide adequate incentive to restaurants and commercial entities to participate in shell recycling programmes. Environmental regulations associated with Hong Kong’s carbon targets will call upon all industries and a variety of stakeholders to help achieve its climate commitments. Furthermore, the Municipal-Waste-Charging scheme places Hong Kong in a unique position whereby it could also provide a net benefit to producers by establishing an oyster shell recycling programme that could help commercial entities meet potential waste obligations, as well as provide cost-savings associated with the scheme. The motivation for oyster farmers themselves should be self-evident, oyster shell recycling can provide the mechanism to enhance oyster restoration and therefore oyster populations whilst alsoalso providing an alternative source of income.

7.0 Conclusion

New research in Hong Kong has emphasised the value of restoring Hong Kong's lost oyster populations and provides evidence that the natural recruitment of oysters in Hong Kong is high (Lau et al, 2020). Oyster shell is a preferred substrate for settling spat in Hong Kong, and Oyster Shell Recycling programmes are a cost-effective tool for procuring shell material for restoration. Whilst Hong Kong's natural oyster reefs have long been decimated, aquaculture plays a prominent role in both the production and imports of oysters. By virtue of this, Hong Kong generates significant amounts of waste shell material that can be utilised in restoration. It was necessary to quantify the value of ecosystem services provided by enhanced reefs in Hong Kong so as to demonstrate the potential value of effective restoration. As a result, there is a substantial need and value to establishing an OSR programme in Hong Kong that would reclaim post-consumed oyster shells from local restaurants and aquaculture to use in restoration. Oyster shell is a preferable substrate for oyster spat and indicates that population restoration initiatives should be focused on capturing this currently lost and valuable resource.

Establishing an Oyster Shell Recycling (OSR) programme in Hong Kong would simultaneously address the economic losses of the oyster industry, reestablish vital ecosystem services by restoring oyster populations and help create a circular economy through better governance of natural resources.

References

Baggett, L. P., Powers, S. P., Brumbaugh, R. D., Coen, L. D., DeAngelis, B. M., Greene, J. K., & Zu Ermgassen, P. S. (2015). Guidelines for evaluating performance of oyster habitat restoration. Restoration Ecology, 23(6), 737-745.

Beck, M. W., Brumbaugh, R. D., Airoldi, L., Carranza, A., Coen, L. D., Crawford, C., & Guo, X. (2011). Oyster reefs at risk and recommendations for conservation, restoration, and management. Bioscience, 61(2), 107-116.

Beckett, D. C., Green, B. W., Thomas, S. A., & Miller, A. C. (1996). Epizoic invertebrate communities on upper Mississippi River unionid bivalves. American Midland Naturalist, 102-114.

Billion Dollar Oyster Project. (2021). Image of oyster reef restoration using recycled shells. Available from: billionoysterproject.org

Bonar, D. B., Coon, S. L., Walch, M., Weiner, R. M., & Fitt, W. (1990). Control of oyster settlement and metamorphosis by endogenous and exogenous chemical cues. Bulletin of marine Science, 46(2), 484-498.

Botta, R., Asche, F., Borsum, J. S., & Camp, E. V. (2020). A review of global oyster aquaculture production and consumption. Marine Policy, 117, 103952.

Bouboulis, S. (2021).“Hong Kong University study – price of oyster shells”. Message to Matt Roberts. Delivered on 3/5/2021 at 21:00 via Google Mail.

Branigan, S., Fitzsimons, J., & Gillies, C. L. (2020). Modern middens: Shell recycling for restoring an endangered marine ecosystem in Victoria, Australia. 21 (3), 198-204.

Breitburg, D. L. (1999). Are three-dimensional structure and healthy oyster populations the keys to an ecologically interesting and important fish community. Oyster reef habitat restoration: a synopsis and synthesis of approaches. Virginia Institute of Marine Science Press, 239-250.

Burke, R. D. (1986). Pheromones and the gregarious settlement of marine invertebrate larvae. Bulletin of marine science, 39(2), 323-331.

Burmester, E.M., and McCann, M.J. (2019). New York City Oyster Monitoring Report: 2018. Billion Oyster Project and The Nature Conservancy. Accessed from: https://www.nature.org/content/dam/tnc/nature/en/documents/new-york-city-oyster-monitoring-report-2018.pdf

Burrell, V. G. (1986). Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (South Atlantic): American oyster.

Cheung, S, G,, Wong, W. T., Chan, H.K, & Kwan, B.K.Y. (2019). Oyster rubble reduces the home range and disturbs the foraging behaviour of Tachypleus Tridentatus. International Workshop on the Science and Conservation of Horseshoe Crabs, 4, 80.

Chinzei, K. (2013). Adaptation of oysters to life on soft substrates. Historical Biology, 25(2), 223-231, DOI: 10.1080/08912963.2012.727412

Chow, A., Leung, T., & Lee, F. (2017). Benefit–cost analysis on coastal structures design for climate change adaptation in Hong Kong. Coastal Engineering Journal, 59(02), 1740005.

Coen, L. D., Brumbaugh, R. D., Bushek, D., Grizzle, R., Luckenbach, M. W., Posey, M. H., & Tolley, S. G. (2007). Ecosystem services related to oyster restoration. Marine Ecology Progress Series, 341, 303-307.

Crenshaw, M. A. (1972). The inorganic composition of molluscan extrapallial fluid. The Biological Bulletin, 143(3), 506-512.

Crisp, D. J. (1967). Chemical factors inducing settlement in Crassostrea virginica (Gmelin). The Journal of Animal Ecology, 329-335.

Dickman, M. D. (1998). Hong Kong's worst red tide. Environmental Hydraulics., 641-646.

Eggleston, D. B. (1999). Application of landscape ecological principles to oyster reef habitat restoration. Oyster reef habitat restoration: a synopsis and synthesis of approaches. Virginia Institute of Marine Science Press, 213-227.

Enactus. (2015). Finding value in discarded oyster shells – China. Available from: https://enactus.org/project/finding-new-value-in-discarded-oyster-shellls/

Farmer, H. (2021). The declining oyster trade of Lau Fau Shan – HKU project to revive the 700 year old industry. Accessed from: https://industrialhistoryhk.org/

Fang, E., Li, W. & Yu, J. (2007). Sustainable use of live oyster reef in Bohai Gulf. Modern Fisheries Information, 22, 12–14.

Food and Agriculture Organization of the United Nations (FAO). (1994). Report on a Regional Study and Workshop on the Environmental Assessment and Management of Aquaculture Development. Annex II Country Reports (Cont.) Annex II-4:HONG KONG. Accessed from: http://www.fao.org/3/ac279e/AC279E10.htm#annII4

Food and Agriculture Organization of the United Nations (FAO). (2016). The State of World Fisheries and Aquaculture 2016. Contributing to Food Security and Nutrition for All; FAO: Rome, Italy, 2016; ISBN 9789251091852.

George, L. M., De Santiago, K., Palmer, T. A., & Pollack, J. B. (2015). Oyster reef restoration: effect of alternative substrates on oyster recruitment and nekton habitat use. Journal of Coastal Conservation, 19(1), 13-22.

Goelz, T., Vogt, B., & Hartley, T. (2020). Alternative substrates used for oyster reef restoration: a review. Journal of Shellfish Research, 39(1), 1-12.

Grabowski, J. H., & Peterson, C. H. (2007). Restoring oyster reefs to recover ecosystem services. Ecosystem engineers: plants to protists, 4, 281-298.

Grabowski, J. H., Brumbaugh, R. D., Conrad, R. F., Keeler, A. G., Opaluch, J. J., Peterson, C. H., & Smyth, A. R. (2012). Economic valuation of ecosystem services provided by oyster reefs. Bioscience, 62(10), 900-909.

H Silva, T., Mesquita-Guimarães, J., Henriques, B., Silva, F. S., & Fredel, M. C. (2019). The potential use of oyster shell waste in new value-added by-products. Resources, 8(1), 13.

H.A., Cole and E.W., Knight-Jones. (1949). Settling Behaviour of the Oyster Larva. Nature, 164, 1085.

Harding, J. M., & Mann, R. (2000). Estimates of naked goby (Gobiosoma bosc), striped blenny (Chasmodes bosquianus) and eastern oyster (Crassostrea virginica) larval production around a restored Chesapeake Bay oyster reef. Bulletin of Marine Science, 66(1), 29-45.

Harding, J. M., & Mann, R. (2001). Oyster reefs as fish habitat: opportunistic use of restored reefs by transient fishes. Journal of Shellfish Research, 20(3), 951.

Hidu, H. (1969). Gregarious setting in the American oyster Crassostrea virginica Gmelin. Chesapeake. Science, 10(2), 85-92.

Hong Kong Special Administrative Region Government (HK Gov). (2020). Municipal Solid Waste. Accessed from: https://www.gov.hk/en/residents/environment/waste/treatment/msw.htm

Hong Kong Special Administrative Region, Agricultural, Fisheries and Conservation Department (AFCD). (2020). Marine fish culture, pond fish culture and oyster culture. Accessed from: https://www.afcd.gov.hk/english/fisheries/fish_aqu/fish_aqu_mpo/fish_aqu_mpo.html

Hong Kong Special Administrative Region, Environment Bureau. (2021). Waste Blueprint for Hong Kong 2035. Available from:
https://www.enb.gov.hk/sites/default/files/pdf/waste_blueprint_2035_eng.pdf

Hong Kong Special Administrative Region, Environmental Protection Department (EPD). (2002). EIA Report 082/2020 - Shenzhen Western Corridor. Available from:

https://www.epd.gov.hk/eia/register/report/eiareport/eia_0822002/EIA%20main%20report/EIA%20Report.htm

Hong Kong Special Administrative Region, Environmental Protection Department (EPD). (2015). EIA Report 248/2016 - Hung Shui Kiu New Development Area. Accessed from: https://www.epd.gov.hk/eia/register/report/eiareport/eia_2482016/EIA/TOC%20-%20Text%20(pdf).pdf

Hong Kong Special Administrative Region, Environmental Protection Department (EPD). (2017). Code of Practice on Separating, Collecting and Transporting Food Waste to Organic Resources Recovery Centre Phase 1. Available from: https://www.epd.gov.hk/epd/sites/default/files/epd/english/environmentinhk/waste/prob_solutions/

Hong Kong Special Administrative Region, Environmental Protection Department (EPD). (2021). An overview on challenges for waste reduction and management in Hong Kong. Accessed from: https://www.epd.gov.hk/epd/english/environmentinhk/waste/waste_maincontent.html

Hong Kong Special Administrative Region, Environmental Protection Department (EPD). (2021). An overview on challenges for waste reduction and management in Hong Kong. Available from: https://www.epd.gov.hk/epd/english/environmentinhk/waste/

International Monetary Fund (IMF). (2019). Carbon Calculus. Finance & Development. 56(4). Available from:https://www.imf.org/external/pubs/ft/fandd/2019/12/the-true-cost-of-reducing-greenhouse-gas-emissions

Konrad, C. P. (2014). Approaches for evaluating the effects of bivalve filter feeding on nutrient dynamics in Puget Sound, Washington. US Geological Survey Scientific Investigations Report 2013, 5237, 22.

Korringa, P. (1946). The decline of natural oyster beds. Basteria, 10, 36-41.

Kuykendall, K., P. Moreno, E. Powell, T. Sonait, S. Colley, R. Mann & D. Munroe. 2015. The exposed surface area to volume ratio: is shell more efficient than limestone in promoting oyster recruitment? J. Shellfish Res. 34, 217–225.

Kwan, B. K., Chan, H. K., & Cheung, S. G. (2018). Habitat use of globally threatened juvenile Chinese horseshoe crab, Tachypleus tridentatus under the influence of simulated intertidal oyster culture structures in Hong Kong. Aquatic Conservation: Marine and Freshwater Ecosystems, 28(1), 124-132.

Lau, S. C., Thomas, M., Hancock, B., & Russell, B. D. (2020). Restoration potential of Asian oysters on heavily developed coastlines. Restoration Ecology, 28(6), 1643-1653.

Legislative Council of Hong Kong Special Administrative Region (LegCo). (2014). Shek Wu Hui sewage treatment works – further expansion phase 1A. 14-21. Available from: https://www.legco.gov.hk/index.html

Lodeiros, C., Marquez, A., Revilla, J., Rodríguez, D., & Sonnenholzner, S. (2017). Spat production of the rock oyster Striostrea prismatica. Journal of Shellfish Research, 36(3), 729-735.

Lok, A., & Acarli, S. (2006). Preliminary study of settlement of flat oyster spat (Ostreaedulis L.) on oyster and mussel shell collectors.

M. J. A. Christianen, W. Lengkeek, J. H. Bergsma, J. W. P. Coolen, K. Didderen, M. Dorenbosch, F. M. F. Driessen, P. Kamermans, E. Reuchlin-Hugenholtz, H. Sas, A. Smaal, K. A. van den Wijngaard & T. M. van der Have. (2018).Return of the native facilitated by the invasive? Population composition, substrate preferences and epibenthic species richness of a recently discovered shellfish reef with native European flat oysters (Ostrea edulis) in the North Sea. Marine Biology Research, 14(6), 590-597, DOI: 10.1080/17451000.2018.1498520

Mackie, G. L. (1992). Biology of the Zebra Mussel (Dreissena polymorpha) and Observations of Mussel Colonization on Unionid Bivalves. Zebra mussels. Biology, Impacts, and control, 153.

Mann, R. & E. N. Powell. (2007). Why oyster restoration goals in the Chesapeake Bay are not and probably cannot be achieved. J. Shellfish Res. 26, 905–917.

Mann, R. L. (2000). Restoring the oyster reef communities in the Chesapeake Bay: a commentary. Journal of Shellfish Research, 19(1), 335.

Marsh Jr, J. A. (1970). Primary productivity of reef-building calcareous red algae. Ecology, 51(2), 255-263.

McAfee, D., & Connell, S. D. (2020). Cuing oyster recruitment with shell and rock: implications for timing reef restoration. Restoration Ecology, 28(3), 506-511.

Metz, J. L., Stoner, E. W., & Arrington, D. A. (2015). Comparison of substrates for Eastern oyster (Crassostrea virginica) spat settlement in the Loxahatchee River Estuary, Florida. Journal of Shellfish Research, 34(3), 861-865.

Morales-Alamo, R. (1993). Estimation of oyster shell surface-area using regression equations derived from aluminum foil molds. Journal of Shellfish Research, 12(1), 15.

Morris, J. P., Backeljau, T., & Chapelle, G. (2019). Shells from aquaculture: a valuable biomaterial, not a nuisance waste product. Reviews in Aquaculture, 11(1), 42-57.

Morris, R. L., Bilkovic, D. M., Boswell, M. K., Bushek, D., Cebrian, J., Goff, J., & Swearer, S. E. (2019). The application of oyster reefs in shoreline protection: Are we over-engineering for an ecosystem engineer?. Journal of Applied Ecology, 56(7), 1703-1711.

Morton, B., & Wong, P.S. (1975). The Pacific Oyster Industry in Hong Kong (香港的蠔業). Journal of the Royal Asiatic Society Hong Kong, 15:139–149

National Oceanic and Atmospheric Administration Fisheries Service (NOAA). (2012). Decontamination of Shells used for Habitat Restoration. Available from: oyster-restoration.org

National Research Council (2004). Nonnative Oysters in the Chesapeake Bay. Washington, DC: The National Academies Press. https://doi.org/10.17226/10796.

Nestlerode, J. A., Luckenbach, M. W., & O'Beirn, F. X. (2007). Settlement and survival of the oyster Crassostrea virginica on created oyster reef habitats in Chesapeake Bay. Restoration Ecology, 15(2), 273-283.

North Carolina Coastal Federation. (2020). Oyster Shell Recycling Program. Available from: https://www.nccoast.org/project/oyster-shell-recycling-program/

North Carolina Division of Marine Fisheries, (NCDMF) (2014). Shellfish Rehabilitation Programs Annual Report 2009-2014. North Carolina: Department of Environmental and Natural Resources. Available from: www.ncleg.gov

North Carolina, Division of Marine Fisheries (NCDMF). (2009). Shellfish Rehabilitation Programs Annual Report. North Carolina: Department of Environmental and Natural Resources.

North Carolina, Division of Marine Fisheries (NCDMF). (2010). Shellfish Rehabilitation Programs Annual Report. North Carolina: Department of Environmental and Natural Resources.

North Carolina, Division of Marine Fisheries (NCDMF). (2011). Shellfish Rehabilitation Programs Annual Report. North Carolina: Department of Environmental and Natural Resources.

North Carolina, Division of Marine Fisheries (NCDMF). (2012). Shellfish Rehabilitation Programs Annual Report. North Carolina: Department of Environmental and Natural Resources.

North Carolina, Division of Marine Fisheries (NCDMF). (2013). Shellfish Rehabilitation Programs Annual Report. North Carolina: Department of Environmental and Natural Resources.

North Carolina, Division of Marine Fisheries (NCDMF). (2014). Shellfish Rehabilitation Programs Annual Report. North Carolina: Department of Environmental and Natural Resources.

Norton, J. (2001). Figure1 Basic Oyster Life Cycle. Maryland Sea Grant. Accessed from: http://www.mdsg.umd.edu/oysters/garden/seed.html

O'Beirn, F. X., Luckenbach, M., Nestlerode, J. A., & Coates, G. M. (2000). Toward design criteria in constructed oyster reefs: oyster recruitment as a function of substrate type and tidal height. Journal of Shellfish Research, 19(1), 387.

Peterson, C. H., Grabowski, J. H., & Powers, S. P. (2003). Estimated enhancement of fish production resulting from restoring oyster reef habitat: quantitative valuation. Marine Ecology Progress Series, 264, 249-264.

Pi-hai, G. O. N. G., Jiao, L. I., Chang-tao, G. U. A. N., Meng-jie, L. I., & Chao, L. I. U. (2014). Estimation and experiment of carbon sequestration by oysters attached to the enhancement artificial reefs in Laizhou Bay, Shandong, China. Yingyong Shengtai Xuebao, 25(10).

Quan, W., Fan, R., Wang, Y., & Humphries, A. T. (2017). Long-term oyster recruitment and growth are not influenced by substrate type in China: implications for sustainable oyster reef restoration. Journal of Shellfish Research, 36(1), 79-86.

Rodriguez, A. B., Fodrie, F. J., Ridge, J. T., Lindquist, N. L., Theuerkauf, E. J., Coleman, S. E., & Kenworthy, M. D. (2014). Oyster reefs can outpace sea-level rise. Nature climate change, 4(6), 493-497.

Rodriguez-Perez, A., James, M., Donnan, D. W., Henry, T. B., Møller, L. F., & Sanderson, W. G. (2019). Conservation and restoration of a keystone species: Understanding the settlement preferences of the European oyster (Ostrea edulis). Marine pollution bulletin, 138, 312-321.

Rose, J. M., Bricker, S. B., & Ferreira, J. G. (2015). Comparative analysis of modeled nitrogen removal by shellfish farms. Marine pollution bulletin, 91(1), 185-190.

Rothschild, B. J., Ault, J. S., Goulletquer, P., & Héral, M. (1994). Decline of the Chesapeake Bay oyster population: a century of habitat destruction and overfishing. Marine Ecology Progress Series, 29-39.

Schulte, D. M. (2017). History of the Virginia oyster fishery, Chesapeake Bay, USA. Frontiers in Marine Science, 4, 127.

Sehlinger, T., Lowe, M. R., La Peyre, M. K., & Soniat, T. M. (2019). Differential effects of temperature and salinity on growth and mortality of oysters (Crassostrea virginica) in Barataria Bay and Breton Sound, Louisiana. Journal of Shellfish Research, 38(2), 317-326.

Smyth, D., Mahon, A. M., Roberts, D., & Kregting, L. (2018). Settlement of Ostrea edulis is determined by the availability of hard substrata rather than by its nature: implications for stock recovery and restoration of the European oyster. Aquatic conservation.

Soniat, T. M., & Burton, G. M. (2005). A comparison of the effectiveness of sandstone and limestone as clutch for oysters, Crassostrea virginica. Journal of Shellfish research, 24(2), 483-485.

Sousa, R., Pilotto, F., & Aldridge, D. C. (2011). Fouling of European freshwater bivalves (Unionidae) by the invasive zebra mussel (Dreissena polymorpha). Freshwater Biology, 56(5), 867-876.

South Carolina Department of Natural Resources (SCDNR).(2021). The South Carolina Oyster Recycling and Enhancement Program (SCORE). Available from: http://score.dnr.sc.gov/

Street, M. Deaton, A., Chappell, W., Mooreside, P. (2005). North Carolina Habitat Protection Plan. North Carolina Department of Environment and Natural Resources. NCDMF. Morehead City, NC

Tamburri, M. N., Luckenbach, M. W., Breitburg, D. L., & Bonniwell, S. M. (2008). Settlement of Crassostrea ariakensis larvae: effects of substrate, biofilms, sediment and adult chemical cues. Journal of Shellfish Research, 27(3), 601-608.

Tarnowski, M. (1999). A Historical Background for Oyster Landings in Maryland 1916-1998. Maryland Department of Natural Resources, Annapolis, Maryland, 34

The Chesapeake Bay Foundation (CFC). (2020). Chesapeake Bay Foundation: Saving a National Treasure. Accessed from: https://www.cbf.org/

The Nature Conservancy (TNC). (2018). Image: Oyster Reef Restoration. Available from: www.nature.org

The Nature Conservancy (TNC). (2020). Image: Beyond Romantic Sunsets – What We're Doing in Pak Nai. Available from: https://www.tnc.org.hk/en-hk/what-we-do/hong-kong-projects/pak-nai/

The World Bank Group. (WBG). (2020). State and Trends of Carbon Pricing 2020. Available from: https://www.worldbank.org/en/programs/pricing-carbon

Tolley, S. G., & Volety, A. K. (2005). The role of oysters in habitat use of oyster reefs by resident fishes and decapod crustaceans. Journal of Shellfish Research, 24(4), 1007-1012.

Turner, E. J., Zimmer-Faust, R. K., Palmer, M. A., Luckenbach, M., & Pentchef, N. D. (1994). Settlement of oyster (Crassostrea virginica) larvae: Effects of water flow and a water-soluble chemical cue. Limnology and Oceanography, 39(7), 1579-1593.

United Nations, The Intergovernmental Panel on Climate Change (IPCC). (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Accessed from: https://www.ipcc.ch/

United States Environmental Protection Agency (EPA).(2021). National Pollutant Discharge Elimination System (NPDES). Available from: https://www.epa.gov/npdes/water-quality-trading

Veitch, F. P., & Hidu, H. (1971). Gregarious setting in the American oyster Crassostrea virginica Gmelin: I. Properties of a partially purified “setting factor”. Chesapeake Science, 12(3), 173-178.

Waldbusser, G., R. Steenson & M. Green. (2011). Oyster shell dissolution rates in estuarine waters: effects of pH and shell legacy. J. Shellfish Res, 30, 659–669.

Walles, B., Troost, K., van den Ende, D., Nieuwhof, S., Smaal, A. C., & Ysebaert, T. (2016). From artificial structures to self-sustaining oyster reefs. Journal of Sea Research, 108, 1-9.

Werner, S., & Rothhaupt, K. O. (2007). Effects of the invasive bivalve Corbicula fluminea on settling juveniles and other benthic taxa. Journal of the North American Benthological Society, 26(4), 673-680.

Yang, Z. B., Takayama, H., Matsuoka, K., & Hodgkiss, I. J. (2000). Karenia digitata sp. nov.(Gymnodiniales, Dinophyceae), a new harmful algal bloom species from the coastal waters of west Japan and Hong Kong. Phycologia, 39(6), 463-470.

Yang, Z. B., Takayama, H., Matsuoka, K., and Hodgkiss, I. J. (2000).’’Karenia digitata sp. no., a new harmful algal bloom species from the coastal waters of west Japan and Hong Kong. ’’Phycologia, 39(6), 463–470.

Yin, K., Harrison, P. J., Chen, J., Huang, W., & Qian, P. Y. (1999). Red tides during spring 1998 in Hong Kong: is El Niño responsible?. Marine Ecology Progress Series, 187, 289-294.

Appendix 1:

Oyster Shell Valuation:

Oyster Shell Valuation in per tonne (USD$)	Use	Source
$442	Raw Material/Restoration	The Delaware Estuary Organization. (2021). Bouboulis, S. ‘personal email’, 2021
$3,977	Animal Feed	https://www.alibaba.com/oyster-shell-meal-animal-feed-suppliers.html
$840	Liming Agent	https://www.groworganic.com/products/oyster-shell-flour-50-lb
$550		
$840	pH Buffer	https://www.lazada.sg/products/6kg-oyster-shells-filter-media-and-ph-buffer-for-koi-fish-pond-and-fish-tanks-i721004899.html
$550		

$2,120	Shell Aggregate	https://www.specialistaggregates.com/
$132	Shell for restoration	https://www.nccoast.org/project/oyster-shell-recycling-program/

Appendix 2:

Analsyis of various oyster shell recycling programmes.

Oyster Shell Recycling Programme	Cost of Operations per year (USD$)	Scope of OSR programme	Shell volume recycled per year (tonnes)	Operating Model	Funding Mechanism	Source:
The Nature Conservancy 'Shuck don't Chuck' (Australia)	$83,436	15 partners	55	Non-profit	Private funding	National Australia Bank, (2019). TNC: Shuck Don't Chuck case study.
Oyster Recovery Partnership (USA)	N/A	350 partners	816	Non-profit	Private funding and Tax Credit	oysterrecovery.org.
The Coastal Conservation Association (New Hampshire)	N/A	22 partners	360.7	Non-profit	Private funding	https://ccanh.org/
The Massachusetts Oyster Project (Massachusetts)	N/A	0	0	Non-profit	Volunteer	http://massoyster.org/

Wellfleet (Massachusetts)	N/A	23 partners	250	Non-profit	Volunteer	https://wellfleetspat.org/about-spat/oyster-shell-recycling-2/
Nantucket Shellfish Association (Massachusetts)	N/A	31 partners	12.8	Non-profit	Volunteer	https://www.nantucket-ma.gov/1425/Shell-Recycling-Program
Billion Oyster Project (New York)	$144,000	75 partners	60.4	Non-profit	Private funding	https://www.billionoysterproject.org/financials
The Chesapeake Bay Foundation (Virginia)	$1,578,318	Regional	45.3	Non-profit	Private funding	https://www.cbf.org/document-library/financial-documents/2020-audited-financial-statement.pdf

The North Carolina Division of Marine Fisheries (North Carolina)	$17,746.40	State-wide	930.1	Government	Federal funding, Tax credit and Legislation	North Carolina, Division of Marine Fisheries (NCDMF). (2009-14). Shellfish Rehabilitation Programs Annual Report. North Carolina: Department of Environmental and Natural Resources.
South Carolina Oyster Restoration & Enhancement (SCORE) (South Carolina)	N/A	State - wide	1750	Government	Federal funding, Tax Credit and Legislation	http://score.dnr.sc.gov/
Choctawhatchee Basin Alliance (CBA)(Florida)	$18,000	12 Partners	N/A	Non-profit	Private funding	http://basinalliance.org
Santa Rosa Count, FL, Offer Your Shell To Enhance Restoration (O.Y.S.T.E.R) Shell recycling Program	N/A	2 partners	3.22*	Government	Federal funding and Legislation	https://www.santarosa.fl.gov/758/Oyster-Shell-Recycling-Program
Galveston Bay Foundation's (Texas)	$64,223	12 partners	10	Non-profit	Private funding	https://galvbay.org
Coalition to Restore Coastal Louisiana (CRCL)	$240,000	31 partners	700	Non-profit	Private funding	https://www.crcl.org

Appendix 3:

Ecosystem services valuations.

Service	Process	Impact	Hong Kong Impact per year (176Ha)	Reference	Economic Valuation Method	Evaluation Tool	Price (USD) per tonne	Reference	Value per year ($USD)
Fisheries	Primary production	119,999 kg per year	110,999 kg	AFCD, 2020	Market Prices	Oyster Fisheries Value per tonne	$12,605.00	AFCD, 2020	$1,386,550.00
Increase Biodiversity	Secondary production	2.6 kg per 10m2 per year	4,576,000 kg	Harding & Mann, 2000	Market Prices + Value Transfer	Fisheries Value per tonne	$2,998.00	AFCD, 2020	$13,718,848.00
Water Quality	Nitrogen removal	235.86 kg per Ha per Year	41,511 kg	Rose et al, 2015	Market Prices + Value Transfer	Nitrogen Credit Market per tonne	$290.00	Rose et al, 2015	$120,350.00
Coastal Defense	Shoreline stabilization	5m2 for 1m shoreline	352,000m	Grabowski et al, 2012	Avoided-Cost	Seawall Cost per m	$112.00	Chow et al, 2017	$39,424,000.00
Carbon Removal	Carbon sequestration	830 kg per Ha per Year	146,080 kg	Hickey, 2008	Market Prices + Value Transfer	Carbon Policies per tonne	$27.10	World Bank Group, 2020	$3,956.00
Raw Material	Calcium carbonate (CaCO3)	3,671,000 kg per Year	3,671,000 kg	AFCD, 2020	Market Prices	Shell valuation per tonne	$1,931.00	Multiple	$7,088,701.00

								Total:	$61,742,405.00
								*Total without Coastal Defense	$22,318,405

Appendix 4:

Cost-benefit evaluation of establishing an Oyster Shell Recycling Programme in Hong Kong.

Reef Life Span (Years)	Mean Cost of OSR (USD$)	Mean Benefit (USD$)	Min Benefit (USD)	Max Benefit (USD)	Max Cost of OSR (USD)	Max Benefit without Coastal Defense (USD)
0	$306,532	$31,564,478	$1,386,550	$61,742,405	$1,578,318	$22,318,405
1	$294,742	$30,350,460	$1,333,221	$59,367,697	$1,517,613	$21,460,005
2	$283,406	$29,183,134	$1,281,943	$57,084,324	$1,459,244	$20,634,620
3	$272,506	$28,060,706	$1,232,638	$54,888,773	$1,403,119	$19,840,981
4	$262,025	$26,981,448	$1,185,229	$52,777,667	$1,349,153	$19,077,866
5	$251,947	$25,943,700	$1,139,643	$50,747,756	$1,297,262	$18,344,102
6	$242,257	$24,945,865	$1,095,811	$48,795,920	$1,247,368	$17,638,560
7	$232,939	$23,986,409	$1,053,664	$46,919,153	$1,199,392	$16,960,154
8	$223,980	$23,063,855	$1,013,139	$45,114,571	$1,153,262	$16,307,840
9	$215,365	$22,176,784	$974,172	$43,379,395	$1,108,905	$15,680,615

10	$207,082	$21,323,830	$936,703	$41,710,957	$1,066,255	$15,077,515
11	$199,117	$20,503,683	$900,676	$40,106,689	$1,025,245	$14,497,610
12	$191,459	$19,715,080	$866,035	$38,564,124	$985,813	$13,940,010
13	$184,095	$18,956,808	$832,726	$37,080,888	$947,897	$13,403,856
14	$177,015	$18,227,700	$800,698	$35,654,700	$911,439	$12,888,323
15	$170,206	$17,526,634	$769,902	$34,283,366	$876,384	$12,392,618
16	$163,660	$16,852,533	$740,290	$32,964,775	$842,677	$11,915,979
17	$157,365	$16,204,359	$711,818	$31,696,899	$810,266	$11,457,672
18	$151,313	$15,581,114	$684,440	$30,477,787	$779,102	$11,016,992
19	$145,493	$14,981,840	$658,115	$29,305,565	$749,137	$10,593,262
20	$139,897	$14,405,616	$632,803	$28,178,428	$720,324	$10,185,829
21	$134,517	$13,851,554	$608,465	$27,094,642	$692,619	$9,794,066
22	$129,343	$13,318,802	$585,062	$26,052,540	$665,980	$9,417,371
23	$124,368	$12,806,540	$562,560	$25,050,520	$640,365	$9,055,165
24	$119,585	$12,313,981	$540,923	$24,087,038	$615,736	$8,706,889
25	$114,985	$11,840,366	$520,118	$23,160,614	$592,054	$8,372,009

Total:	$5,095,199	$524,667,277	$23,047,345	$1,026,287,192	$26,234,928	$370,978,312
NPV		$519,572,078				
BCR		102.9728725				
BCR Min Ben / Max Cost		0.878498504				
BCP Max Ben - Coastal Defence / Mean Cost		72.80938625				

Appendix 5:

Density calculations for statistical analysis.

Substrate	Surface Area (cm2)	Spat Count	density	per m2
OS1	193	3	0.015544	155.4404
OS2	154	3	0.019481	194.8052
OS3	150	3	0.02	200
OS4	131.25	4	0.030476	304.7619
OS5	91.5	2	0.021858	218.5792

OS6	86.5	4	0.046243	462.4277
OS7	73.25	2	0.027304	273.0375
OS8	111.5	5	0.044843	448.4305
OS9	124.25	3	0.024145	241.4487
OS10	42.75	7	0.163743	1637.427
OS11	91	3	0.032967	329.6703
OS12	79.75	3	0.037618	376.1755
OS13	79.5	4	0.050314	503.1447
OS14	108.5	1	0.009217	92.1659
OS15	97	1	0.010309	103.0928
OS16	125.5	3	0.023904	239.0438
OS17	179.5	5	0.027855	278.5515
OS18	137.5	2	0.014545	145.4545
OS19	54	3	0.055556	555.5556
OS20	91.75	3	0.032698	326.9755
OS21	115	5	0.043478	434.7826

OS22	111.25	1	0.008989	89.88764
OS23	127	2	0.015748	157.4803
OS24	130.75	4	0.030593	305.9273
OS25	139	0	0	0
OS26	114	2	0.017544	175.4386
OS27	91.5	0	0	0
OS28	104.25	8	0.076739	767.3861
OS29	153	2	0.013072	130.719
OS30	134.75	3	0.022263	222.6345
OS31	132	6	0.045455	454.5455
OS32	122.25	4	0.03272	327.1984
OS33	118.5	2	0.016878	168.7764
OS34	166.25	3	0.018045	180.4511
OS35	158.25	4	0.025276	252.7646
OS36	130.75	3	0.022945	229.4455
OS37	138	4	0.028986	289.8551
OS38	99.25	6	0.060453	604.534

OS39	126	4	0.031746	317.4603		
OS40	112.5	6	0.053333	533.3333	Mean	SE
OS41	111.75	0	0	0	310.4587	42.35182782
TT1	380.25	4	0.010519	105.194		
TT2	380.25	5	0.013149	131.4924		
TT3	380.25	4	0.010519	105.194		
TT4	380.25	3	0.00789	78.89546		
TT5	380.25	2	0.00526	52.59698		
TT6	380.25	13	0.034188	341.8803		
TT7	380.25	8	0.021039	210.3879		
TT8	380.25	18	0.047337	473.3728		
TT9	380.25	22	0.057857	578.5667		
TT10	380.25	5	0.013149	131.4924		
TT11	380.25	3	0.00789	78.89546		
TT12	380.25	1	0.00263	26.29849	192.8556	51.21747341
B1	574.36	0	0	0		
B2	574.36	0	0	0		

B3	574.36	0	0	0		
B4	574.36	2	0.003482	34.82137		
B5	574.36	1	0.001741	17.41068		
B6	574.36	0	0	0		
B7	574.36	1	0.001741	17.41068		
B8	574.36	2	0.003482	34.82137	13.05801	5.456361607

Recruit density

	Density	Substrate
1	155.4404	Shell
2	194.8052	Shell
3	200	Shell
4	304.7619	Shell
5	218.5792	Shell
6	462.4277	Shell
7	273.0375	Shell
8	448.4305	Shell

9	241.4487	Shell
10	1637.427	Shell
11	329.6703	Shell
12	376.1755	Shell
13	503.1447	Shell
14	92.1659	Shell
15	103.0928	Shell
16	239.0438	Shell
17	278.5515	Shell
18	145.4545	Shell
19	555.5556	Shell
20	326.9755	Shell
21	434.7826	Shell
22	89.88764	Shell
23	157.4803	Shell
24	305.9273	Shell
25	0	Shell

26	175.4386	Shell
27	0	Shell
28	767.3861	Shell
29	130.719	Shell
30	222.6345	Shell
31	454.5455	Shell
32	327.1984	Shell
33	168.7764	Shell
34	180.4511	Shell
35	252.7646	Shell
36	229.4455	Shell
37	289.8551	Shell
38	604.534	Shell
39	317.4603	Shell
40	533.3333	Shell
41	0	Shell
42	105.194	Tile

43	131.4924	Tile
44	105.194	Tile
45	78.89546	Tile
46	52.59698	Tile
47	341.8803	Tile
48	210.3879	Tile
49	473.3728	Tile
50	578.5667	Tile
51	131.4924	Tile
52	78.89546	Tile
53	26.29849	Tile
54	0	Concrete
55	0	Concrete
56	0	Concrete
57	34.82137	Concrete
58	17.41068	Concrete
59	0	Concrete

60	17.41068	Concrete
61	34.82137	Concrete