ARTIFICIAL CORAL REEFS, COASTAL PROTECTION AND CLIMATE CHANGE

FINDING OUT HOW ARTIFICIAL REEFS COULD SAVE OUR CORAL REEFS

Pictures by Victor S. Freij

Written by Victor S. Freij 12/06/2023

ARTIFICIAL CORAL REEFS, COASTAL PROTECTION AND CLIMATE CHANGE

Finding out how artificial reefs could save our coral reefs

PERSONAL INFORMATION

AUTHOR: VICTOR S. FREIJ

STUDENT NUMBER: 3024052

STUDY: APPLIED BIOLOGY

EMAIL: 3024052@AERES.NL

UNIVERSITY INFORMATION

ADRESS: AERES UNIVERSITY OF APPLIED SCIENCES ALMERE

HONORARY SUPERVISOR: DR. IR. E.D. EKKEL

ADRESS: ARBORETUM WEST 98, 1325 WB ALMERE, NETHERLANDS

SUBMISSION INFORMATION

ADRESS: 12 JUNE 2023

PERIOD: JANUARY 2020 – JUNE 2023

LOCATION: ALMERE

PREFACE

This literature study is made as an assignment for the completion of my study at Aeres Applied University. But that doesn’t mean that it would’ve never been written if I didn’t follow this study. When I was but a child, I was always fascinated by nature and especially the oceans of the world with an emphasis on coral reefs. I really wanted to be a marine biologist when I grew up, so I started to research what it would take to become a marine biologist. And about one and a half-decade later I sit here writing what is supposed to be the culmination of my efforts to reach my dream, how awesome is that? I sure did get side-tracked in my teenage years, as teenagers tend to do. But I got back on track, and with a few (major) bumps along the way, I was eventually able to write this thesis. I hope it brings more understanding about the importance of coral reefs and I hope that maybe one day I can use the information I gathered here to create the basis of my own restoration program.

Victor Freij, 2023 Bathmen

TABLE OF CONTENT

DUTCH ABSTRACT

Door de stijging van de temperatuur op aarde worden zowel lokale als mondiale klimaatsystemen verstoord of veranderd. Deze studie gaat over een van de ecosystemen die het meest worden beïnvloed door klimaatverandering, namelijk de tropische koraalriffen op aarde. Een manier om deze wereldwijde afname van koraalriffen tegen te gaan is het aanvullen van natuurlijke gebieden met kunstmatige riffen. Het creëren van kunstmatige riffen (ARC) zou een mogelijke oplossing kunnen zijn om de achteruitgang van koraalriffen te stoppen en ze veerkrachtiger te maken. Er is geen duidelijke lijn over welke ARC-methode werkt. Deze studie probeert te achterhalen welke methoden er beschikbaar zijn voor ARC en probeert ze met elkaar te vergelijken. Daarbij wordt ook aangegeven waar je op moet letten. Dit omvat de selectie van de locatie, waar het zoutgehalte 34-37‰ moet zijn, de temperatuur 21,0-27,0 °C en de waterdiepte 36 ± 5,6 meter, vanwege de beperkingen van fotosynthese en duikdiepten. Andere beïnvloedende factoren zijn de kwaliteit van het substraat, de beschikbaarheid van voedingsstoffen, de nabijheid van mensen, de invloed van oceaanstromingen en de locatie binnen een breedtegraad van 35° noord of zuid. Er zijn verschillende materialen beschikbaar voor ARC, zoals verschillende soorten beton, staalconstructies en scheepsrompen. Er kan gebruik worden gemaakt van een reeks koraalvermeerderingsmethoden, waaronder in situ en ex situ kweek, microfragmentatie en het vangen, verbeteren en verspreiden van larven.

Vier methoden voor het creëren van kunstmatig rif worden besproken 1) Introductie van harde substraten zonder koraaltransplantatie, wat een duurzame structuur biedt voor kolonisatie door zeeleven, vaak met behulp van langzaam corroderende materialen zoals stalen scheepsrompen. 2) Koraaltapijten, een innovatieve benadering waarbij gebruik wordt gemaakt van vooraf geassembleerde "zoden" van riffragmenten en bindmaterialen om nieuwe kolonies te vormen. 3) Het omkeren van rifdegradatie, waarbij de nadruk ligt op het herstellen van beschadigde rifsecties. 4) De holistische benadering, waarbij elementen uit de andere methodologieën worden gecombineerd tot een allesomvattende oplossing voor verschillende mariene milieus. Deze benadering omvat moderne technologie voor het verzamelen en beheren van gegevens, betrokkenheid van de gemeenschap voor duurzaamheid en maakt gebruik van technieken zoals microfragmentatie en koraalbroed om de diversiteit te vergroten.

Er zijn verschillende manieren om kunstmatige riffen te creëren, ontwikkelen, financieren en onderhouden. Er is geen standaardaanpak voor het creëren van koraalriffen. Een aanpak die holistisch van aard is en rekening houdt met financiële, ecologische en sociaaleconomische aspecten lijkt het meest effectief voor het creëren van kunstmatige riffen. Daarnaast worden er verschillende suggesties gedaan: 1) Het moet een wereldwijde prioriteit worden om fondsen vrij te maken voor de bouw van kunstmatige koraalriffen in water tussen 21 en 27 graden Celsius. Het diversifiëren van de financiering wordt daarom als cruciaal beschouwd voor de slagingskans van kunstmatige rifprojecten. 2) Er moet worden geïnvesteerd in onderzoek en onderwijs om inzicht te krijgen in de verschillende omgevingsfactoren die nodig zijn voor het succesvol creëren van kunstmatige riffen. 3) Er moeten inspanningen worden geleverd om het onderzoek naar de ecologische langetermijneffecten van verschillende materialen die bij de bouw van kunstmatige riffen worden gebruikt, voort te zetten en te verbeteren. 4) Er moeten inspanningen worden geleverd om de huidige koraalriffen te behouden door het bestrijden van antropogene effecten zoals klimaatverandering en het verlichten van menselijke druk zoals overbevissing en vervuiling. 5) Aanvullend onderzoek naar het verloop van de temperatuurstijging van de oceaan in de toekomst is wenselijk. 6) Er moet extra toezicht worden gehouden op succesvolle herstelinspanningen.

ENGLISH ABSTRACT

Due to the rise of global temperatures both local and global climate systems are disrupted or altered. This study is about one of the ecosystems that are most affected by climate change, the world's tropical coral reefs. One way to combat this global decline in coral reefs is the supplementation of natural areas with artificial reefs. Artificial reef creation (ARC) could be a possible solution to stop the degradation of coral reefs and make them more resilient. There is no clear line on what ARC method works. This study tries to find what methods are available for ARC and tries to compare them to each other. In doing so it also states what to watch out for. This includes site selection where the site should have a salinity of 34-37‰, temperatures between 21.0 – 27.0 °C, and be at water depths within 36 ± 5.6 meters due to limits of photosynthesis and limitations in diving depths. Other influencing factors include substrate quality, nutrient availability, human proximity, the influence of ocean currents, and location within a latitude of 35° north or south. There are various materials available for ARC, such as different types of concrete, steel structures, and ship hulls. A range of coral multiplication methods, including in situ and ex situ farming, microfragmentation, and larval capture, enhancement and distribution, could be utilized.

Four methods for artificial reef creation are discussed 1) Introduction of hard substrates without coral transplanting, which provides a durable structure for marine life colonization, often using slowly corroding materials like steel ship hulls. 2)Coral carpets, an innovative approach using pre-assembled "sods" of reef fragments and binding materials to form new colonies. 3) The reversal of reef degradation, focusing on restoring damaged reef sections. 4) The holistic approach, combining elements from the other methodologies to provide a comprehensive solution for various marine environments. This approach incorporates modern technology for data collection and management, community involvement for sustainability, and uses techniques like microfragmentation and coral spawn slicks to boost diversity.

There is a variety of ways to create, develop, fund and maintain artificial reefs. There is no one size fits all approach to coral reef creation. An approach that is holistic in nature and considers financial, ecological, and socio-economic aspects appears to be the most effective for the creation of artificial reefs. Aside from this several suggestions are given: 1) It should become a global priority to free up funds to build artificial coral reefs in water between 21 and 27 degrees Celsius. The diversification of funding is therefore considered crucial to the success rate of artificial reef projects. 2) Efforts should be made to invest in research and education to understand the diverse environmental factors necessary for successful artificial reef creation. 3) Efforts should be made to continue and enhance research efforts on the long-term ecological impacts of various materials used in artificial reef construction. 4) Efforts should be made to conserve current coral reefs by combating anthropogenic effects such as climate change and alleviating human pressures like overfishing and pollution. 5) Additional research on the course of ocean temperature rise in the future is desirable. 6) Additional monitoring of successful restoration efforts should be conducted.

1 INTRODUCTION

At the end of the 20th century, it became clear that the average temperature of the world is increasing due to the anthropogenic addition of greenhouse gasses to the terrestrial atmosphere (Werndl, 2016). *Due to the rise of global temperatures both local and global climate systems are disrupted or altered. This results in warmer and drier summers in Europe, colder extreme winters in the USA, increased flooding risks in south-east Asia, deadlier forest fires in Australia, desertification of large parts of the world and more intense hurricanes across the globe* (IPPC, 2021). *If humanity as a whole doesn't reduce the amount of greenhouse gasses in the atmosphere these effects will not only worsen but will also increase in ferocity and frequency, ending the existence of entire ecosystems and resulting in millions of lives ruined or even lost* (IPPC, 2021).

This is the doomsday scenario one usually reads about in articles discussing the effects of climate change. The phenomenon of anthropogenic climate change is an established fact and common knowledge (Lindsey & Dahlman, 2021; Butler & Montzka, 2021; IPPC, 2021). Therefore this literature study will not go very deep into this subject and will instead talk about one of the ecosystems that are most affected by climate change, the world's tropical coral reefs (Hoey, et al., 2016).

1.1 THE IMPORTANCE OF CORAL REEFS

Coral reefs are one of the most vital ecosystems the world has to offer. Similar to the tropical rainforest on land, coral reefs are a biodiversity hotspot containing approximately two-thirds of all marine species (Plaisance, Caley, Brainard, & Knowlton, 2011). According to the most recent estimates, there are 8.8 million species on the globe, of which 2.2 million are marine species (Niggol Seo, 2021). While only 0,1% of the ocean surface is covered by coral reefs, they are still responsible for the survival of many marine species (Hoegh-Guldberg, Pendleton, & Kaup, 2019). The general consensus is that between 550.000 and 1.330.000 marine species are in some way dependent on coral reefs in their life cycle (Fisher, et al., 2015). Coral reefs are therefore essential for the survivability of the entire marine ecosystem.

Many of the species that are dependent on coral reefs are essential for the food stability and thus survival of many coastal communities. It is estimated that around 500 million people (EPA, 2022) are dependent on the exploitation of coral reefs for their daily nutrient intake. Other species have economic importance and are therefore responsible for the quality of life of many more people. Examples of these species are crustaceans like commercial lobsters and prawns, meaty fish species like tuna and mackerel as well as other edible fish varieties (Niggol Seo, 2021; Huston, 1985).

Other human dependencies on coral reefs include coastal protection and recreation (Ferrario, et al., 2014). Especially with the increase in stormy weather events, coral reefs may determine which community survives and which gets washed away in the waves. Ferrario et al. (2014) mentions that an average of 97% of wave action can be reduced by a typical reef. Around 100 million people depend on these reefs for their protection against wave action. If this protection would degrade or cease to exist, it would need to be replaced in de form of storm barriers and other expensive solutions, amounting to approximately $9.0 billion in costs according to Cesar, Burke, & Pit-Soede in 2003. Since then costs should have increased significantly, especially because of the current turmoil and the continuing inflation and resource shortages. Combined these treats to both the economy and habitability of coastal areas are a major reason to protect existing reefs and establish new ones.

The effects on humanity aren't the only reason why we should protect and preserve coral reefs. They perform a vital role as a nursery location for young fish and other marine animals. If these nurseries disappear it would mean that there would be a significant drop in the population of reef-dependent fish, which would have a cascading effect that could eventually change the entire marine ecosystem (Hoegh-Guldberg, Polocznaska, Skirving, & Dove, 2017). Who knows what these changes may be and what other problems they may cause? Logically it would not be sensible to let such a vital ecosystem perish, protection and expansion of this ecosystem's coverage are therefore essential.

1.2 WHAT ARE CORAL REEFS AND HOW DO THEY GROW

Now it is clear that coral reefs perform a vital ecosystem role, it is important to state how these ecosystems work and form so that we know why they are in danger. Reefs can be made up of many materials and made by a wide variety of ecosystem engineers, but the most common type of warm water coral reef is the one built by the animal order of *Scleractinia* (Sheppard, Davy, Pilling, & Graham, 2018; Ruppert, Barnes, & Fox, 2004). This animal order usually consists of polyp-like creatures that build up a skeleton around themselves consisting of calcium carbonate, small amounts of magnesium and fractions of other elements (Ruppert, Barnes, & Fox, 2004). This skeleton and their body plan is built up with a six-sided symmetry, hence the name of their class *Hexacoralia*. Most of the corals within this animal class exist in a colonial manner where many individuals coincide within the same structure. This six-sidedness provides structural strength and the colonial nature allows these animals to produce internal structures, not unlike the ones seen in bee hives or the aerospace industry.

Almost all corals that are part of the *Scleractinia* order are symbiotic creatures. They get their energy from the symbiotic dinoflagellates that reside in their tissue. These dinoflagellates are photosynthetic and provide the polyps with nutrients and energy, while the polyp themselves protect these creatures. The specific dinoflagellates that reside in corals are part of the taxonomic group of zooxanthellae. The primal energy exchange between the host coral and its zooxanthellae is done via the transfer of simple chemicals in the form of sugars, glycerol, and amino acids, in return the coral provides the zooxanthellae with carbon dioxide, phosphates, nitrogen compounds and a stable environment (Muscatine & Porter, 1977).

1.2.1 CORAL REPRODUCTION

In order to understand how the aforementioned hexagonal structures form it is good to know how the reproduction cycle of corals within the order of *Scleractinia* works. Corals within this order have two ways of reproduction: Asexual and sexual reproduction. Asexual reproduction is usually used within a colony to produce more polyps and thus increase the size of the colony. In rare cases of extreme stress, a polyp can choose to abandon its colony in a phenomenon that is called polyp bail-out (Chuang & Mitarai, 2020). Ultimately this could also be a form of reproduction of more colonies and thus be another form of asexual reproduction of an entire colony, although this topic is controversial and not very well understood. Another asexual reproduction form is tissue separation, in which a part of a polyp is cut off and performs a metamorphosis back to a full-size polyp, then it settles on bare oceanic substrate and grows into a full-sized new colony, this is usually only plausible with the larger polyp type species (Ruppert, Barnes, & Fox, 2004). The final asexual reproduction method is the fragmentation of a coral colony. In this process, a part of a colony consisting of multiple polyps is cut off by either mechanical stress due to wave action, blunt impact or human interference. This coral fragment can then continue to grow and form its own coral colony. This form of multiplication is widely used in the aquarium hobby to reproduce identical clones of high-value corals and is starting to be used in coral reef restoration projects (Bayraktarov, et al., 2019).

A coral's sexual reproduction is dependent on the type of parent coral. The vast majority of corals are hermaphroditic, meaning they are capable of both producing sperm and eggs. The fertilization of these gametes happens in mass spawning events like the one shown in Figure 1. Corals take part in this mass fertilization event when certain conditions are met. These conditions are usually revolving around the moon and tide cycles and the light changes that come forth because of this (Sweeney, Boch, Johnsen, & Morse, 2011).

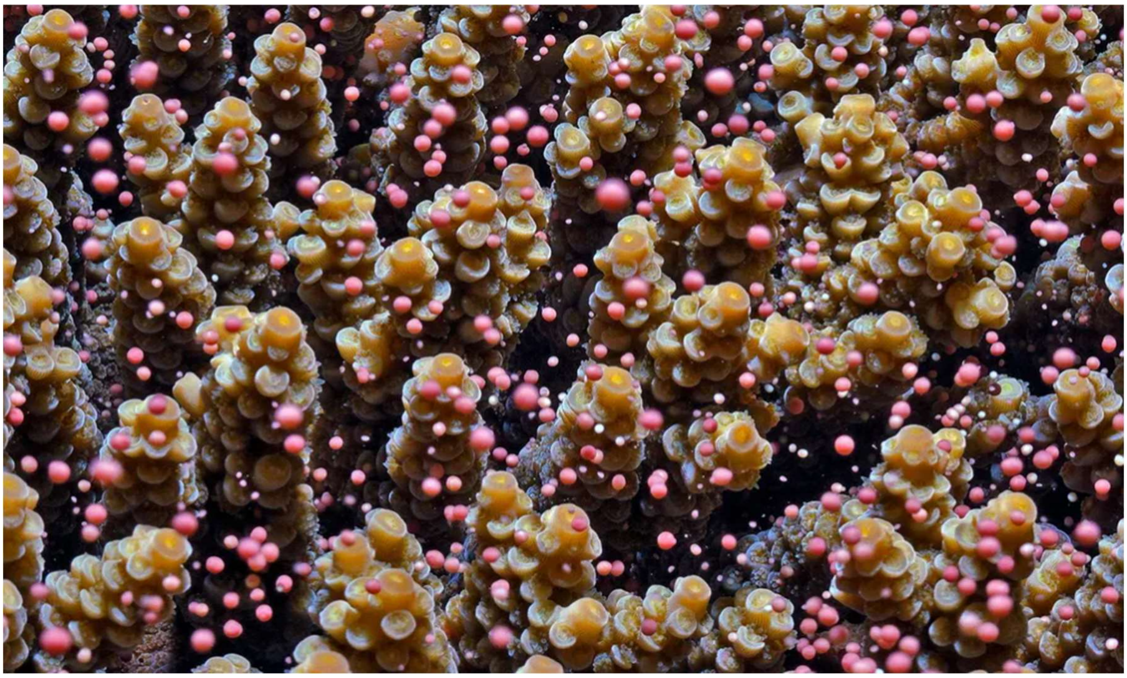

Figure 1 Coral spawning (Shlesinger)

After an egg is fertilized it grows into a free-swimming larva called a *planula*. Only Recently successful recreation of this fertilization process has been done in the labs of Wageningen university (Kleis, 2022). This *planula* is swept away by the ocean current and when it finds a suitable substrate to attach to it latches on to it. Suitable surfaces are mostly hard substrates like rocks, underwater cliffs or dead coral skeletons that are overgrown with coralline algae and bacterial biofilms. These surfaces are detected by complex triggers of dopamine, glutamic acid and epinephrine concentrations (Tran & Hadfield, 2013; Moeller, Nietzer, & Schupp, 2019) Without a hard surface to attach to, the larvae would be swept away in the violent ocean currents. Therefore the presence of a hard and solid settlement surface is vital for the formation of a coral reef.

After a planula has settled it begins its metamorphosis into a primary polyp and begins to build its first corallite. It does this by secreting calcium carbonite and forming the stone-type aragonite at its base. It does this in a radial and hexagonal shape resulting in an aragonite cup where the polyp is protected from predators and the elements. After this, the polyp starts cloning itself and in turn, these clones will make their own skeletal wall resulting in the formation of a small colony. After the first few clones are well established, the polyps lift themselves from their baseplate and form a new base plate on which they continue growing, this results in vertical growth (Sheppard et Al. 2018; Ruppert, Barnes, & Fox, 2004) and in turn, results in de formation of an intricate structure that can have many forms.

1.2.2 CORAL FORMATIONS

Figure 2 Illustrative examples of branching corals

The growth rate of a coral colony is highly dependent on its growth form. There are a variety of growth forms including branching, encrusting, tabling, semi-tabling, massive and plating. The branching type corals are the fastest growers consisting of mostly *Acropora* species and *Pocillopora*. These species can grow anywhere from 10 to 20 cm in length a year. The branching corals leave a lot of open space between their branches resulting in hiding spaces for smaller reef inhabitants (Huston, 1985; Plaisance, Caley, Brainard, & Knowlton, 2011). The branches are however vulnerable to damages caused by impact or storms (Jones, Fisher, & Bessell-Browne, 2019). The thin (1-3 cm in diameter) branches can be easily snapped and are therefore not ideal for coral reef formation. The branching corals are therefore considered secondary reef-building species. An example of a branching coral is illustrated in Figure 2.

A very important reef-building species is the encrusting coral growth type. This coral doesn't grow vertically, but instead covers dead parts of the reef or bare rock surfaces and completely encrusts them with a layer of coral. A diverse range of species uses this type of growth form. Together with encrusting coralline algae, these types of corals are the 'glue' that fixates the reef into one solid chunk and thus they are essential factors in the success and longevity of a coral reef.

The growth form that creates the foundation of the coral reef is the massive coral formation. These coral formations create large bulbous deposits that grow outward in all directions, as seen in Figure 3. In time, this type of formation can form spheres several meters in diameter (Sheppard, Davy, Pilling, & Graham, 2018). When the corals forming these formations die, the coralline algae and bacterial growth that eventually covers their bodies allow for the settlement of different types of corals and in turn different growth forms. A typical growth form that colonizes the skeletal remnants of such formations is the tabling variety, as seen in Figure 3 Example of a massive coral growth form Figure 4. Part of the massive coral colony can still be alive when other coral forms are settling on its exposed skeleton. In the course of hundreds of years, these collaborative structures ultimately form the coral reefs that dot the world's oceans.

Figure 3 Example of a massive coral growth form (Silbiger)

Figure 4 tabling coral colonizing a skeletal remnant (Hudson)

1.3 CLIMATE CHANGE AND CO_2, THE CAUSE OF THE DECLINE

Now it is established that coral reefs are extremely important and how they form, it is important to ascertain the threats to the survival of this ecosystem. One of the major threats to the world's tropical coral reefs is climate change. Under normal circumstances, climate change is a natural phenomenon that is caused by the fluctuation of energy output by the sun, the shift in the position of the earth's axes compared to the sun and the concentration of greenhouse gases in the earth's atmosphere. The slowly increasing energy output of the sun causes the temperature to increase at a flat rate. Since this increase in energy output happens over the cause of millions if not billions of years, the effect of this change is barely impactful in the short term (Kweku, et al., 2017).

A phenomenon that's a little more impactful on the terrestrial climate is the earlier mentioned shift in earth's axes. This phenomenon happens about every few thousand years and causes major disruptions to local climates due to changes in locally received solar energy concentrations. It is thought that this event may have caused the desertification of the Sahara desert and might be the driving factor behind the African monsoon cycle (Houérou, 2008). This goes to show that in the long term, this phenomenon can have a significant impact. On a human timescale however, this change is trifling and will therefore no longer be discussed in this paper.

The greenhouse gases can have a more impactful, direct and short-term effect on our planet's climate. In a nutshell, these gases are opaque to infrared radiation. This means that they absorb part of the energy emitted by our sun, mostly in the infrared spectrum (Kweku, et al., 2017). This causes the molecules to vibrate and this is what causes the heating of the entire atmosphere. In the proper concentrations, these gases enable the existence of life on earth. As Kweku et al. (2017) so diligently state, without the right concentrations, we would have the same climate as mars or venus. This is of course not suitable for terrestrial life, so humanity should be thankful for these gases and their current concentration.

Greenhouse gases enable life on earth and one of the most prominent ones of these is water (H_2O). The one most prone to change however is carbon dioxide or more commonly known by its chemical formula CO_2. This gas forms when carbon-based substances are burned through oxidation or are a part of vulcanic exhaust fumes. Since this gas can be added to the atmosphere via these acute processes and therefore the concentration of this gas is most prone to change. In common theory, it is thought that CO_2 is the gas that is the driving factor behind climate change (IPPC, 2021). Other less prominent but still important greenhouse gases are methane, nitrous oxide and fluorinated gases (Butler & Montzka, 2021).

Under normal circumstances, greenhouse gases and their concentration can only increase as fast as volcanic activity can exhaust them or as fast as a carbon-rich environment can naturally burn. In the entire history of the earth, greenhouse gas levels have never increased so much that they have brought significant change within a human lifetime, until now.

1.3.1 ANTHROPOGENIC CLIMATE CHANGE

In the previous paragraph, it is established that global climate is regulated by certain chemical and astrophysical processes that enable a comfortable environment for terrestrial life. Normally the variables governing these processes change very gradually over the course of thousands of years. The effect of this consequently is very subtle and only noticeable in multiple lifetimes. The advantage of this gradual and generational change is that wildlife and ecosystems can adapt to these changing circumstances through the course of natural selection. The effect of this type of climate change is therefore rather small (Kweku, et al., 2017; IPPC, 2021).

The problem with anthropogenic climate change is that one of these variables is altered rapidly, namely the concentration of greenhouse gasses (GHG) in the atmosphere, with CO_2 taking the lead. Ever since the industrial revolution, the concentration of CO_2 in the atmosphere has been exponentially increasing because of the burning of fossil fuels (IPPC, 2021). Since this variable is the most impactful of all the variables, the climate is also the most affected by its change. It is predicted that with our current GHG emission, the global climate can change by as much as +5 °C by the year 2100 (IPPC, 2021). Hopefully, with current and future countermeasures, humanity is able to reduce these increases in global temperature to just below +2 °C. This increase in temperature will be the guideline used by this paper and all necessary measures to preserve coral reefs will therefore be based on this temperature rise of +2 °C.

1.3.2 THE EFFECTS OF ANTHROPOGENIC CLIMATE CHANGE AND ATMOSPHERIC CO_2 ADDITION ON CORAL REEFS

The aforementioned increase of +2 °C in global temperature would still have disastrous effects across the globe including the melting of polar ice caps resulting in a rise of mean sea level, extreme droughts resulting in desertification, extreme precipitation events like frequent flash floods and downpours resulting in increased erosion, to extreme temperature fluctuations resulting in massive coral bleaching events. There are many other effects that this paper will not discuss further; These effects can be found in the regional fact sheets published by the ICCP (IPPC WG1, 2022) In this study, only the effects of climate change on coral reef systems will be discussed.

Figure 5 a severely degraded reef

The effects mentioned earlier, are mentioned for the specific reasons that they all affect the health and stability of coral reefs. Global sea-level rise will submerge atolls and low-lying island groups that are vital for coral reefs. Tropical coral reefs only thrive in the top 165 meters of the water column with the bulk of the reefs concentrating on the first 36 ± 5.6 meters of water depth (Laverick, Tamir, Eyal, & Loya, 2020). With a 2 °C increase in global temperature, it is predicted that sea levels will rise by at least 37cm but more likely is a rise of 80 cm (IPPC, 2021). This will result in increased island inundation and erosion, the sediments from this erosion might burry parts of the reefs, destroying them for good (Jones, Fisher, & Bessell-Browne, 2019). Increased erosion is not only dangerous because of its direct effects, but it is also indirectly dangerous because of the nutrients from farmland that could wash into the coral ecosystem. Since reefs are oligotrophic systems they can be easily destabilized by an increase in nutrients and could become overgrown with algae rather quickly, resulting in the death of the coral and coral-dependent species. The aftermath of such an event can be seen in Figure 5.

Another risk factor is the increase in global temperatures. Up to 90% of all increases in global temperature are measured in the ocean (Cheng, et al., 2022) and thus the area that is most affected by climate change is the world's oceans. Cheng et al. (2022) have measured record-breaking amounts of total energy locked into the world's oceans in the last few years. Each consecutive year the ocean heat content has increased by as much as 14 Zeta Joule. That amounts to an approximate rise in temperature of up to 0,045 °C annually (Cheng, et al., 2022).

This rise in global ocean temperature combined with extreme weather events over the past 5 years has already caused major problems for most of the world's reefs. One of the major effects that are visible right now is the occurrence of mass bleaching events in the reefs near Central America, South-East Asia, Australia and island groups in the Great Pacific Ocean (Sully et al. 2019). This bleaching is caused by temperature shock during extreme heat waves. The bleaching of corals is the result of the coral polyps expelling their symbiotic and photosynthetic dinoflagellates, called zooxanthellae because of a buildup of by-products of photosynthetic processes (Brown, 1997; Gates, Baghdasarian, & Muscatine, 1992). Without their photosynthetic allies, the coral will quickly run out of energy reserves and will perish, leaving behind a bare skeleton. This bare skeleton is vulnerable and prone to breaking, especially with the growth forms of branching and tabling variety.

Figure 6 A picture of bleached coral (Monroe)

The increased temperature also bears with it another problem; Ocean acidification. Corals need a pH of at least 7,6 to build their aragonite skeleton with the calcification process, but they thrive at a pH of 8,3 (Bove, Whitehead, & Szmant, 2022). If the pH is too low, the corallite can't keep the aragonite fluid it uses for the calcification process stable and thus the solution can't be used to create new aragonite skeletal growth. A pH that is too low will ultimately result in the dissolving of the skeleton in the water resulting in the bleaching of the coral and eventual death. Ultimately it will even lead to the complete disappearance of the coral reef. For this to happen, however, the seawater pH must delve below 7,0 and become entirely acidic. If this happens we have bigger problems.

With the continuous and currently accelerating rate of global warming, coral bleaching is one of, if not, the biggest threat to the world's coral reefs. If nothing is done about this decline, it is highly likely that by 2050 we would've lost over 90% of all coral reefs in the world. Already 50% of the world's known reefs have been lost or have been in critical condition since 1950 (Hoegh-Guldberg, Polocznaska, Skirving, & Dove, 2017). This means that rapid and adequate actions are necessary for the preservation of the coral reef ecosystem.

1.4 A PLAUSIBLE SOLUTION

Luckily it isn't all doom and gloom and there is a solution on the horizon, it is called the artificial reef (Kim et al., 2022). It is one of the possible solutions to stop the degradation of coral reefs and makes them more resilient. The average survival rate of the corals within the studies researched by Bayraktarov, et al. (2019), suggests a survival rate of around 60.9% of such projects. This is a substantial increase compared to natural reefs and their successful recreation rate. Artificial reefs do this by creating artificial structures from solid materials. On this solid material, certain corals can then be transplanted which will ultimately form a stable reef (Bayraktarov, et al., 2019). Creating artificial reefs in locations that are impacted significantly less by the aforementioned threats of temperature increase and extreme weather events could be vital for the survival of this ecosystem (Hoey, et al., 2016). There are however significant costs and problems attached to this solution. One of the problems is that there is no common consensus on what is the best artificial reef creation (ARC) method (Lima, Zalmon, & Love, 2019).

This paper will try to find out what types of methods there are for creating an artificial reef, how effective the different methods are and how much they cost. The best successful reef creation methods will then be explained in a simple step-by-step guide. In this guide, the do's and don'ts will be expounded on, resulting in a comprehensible guide that can be used as a guideline for creating artificial coral reefs. This information will be summarised in a user matrix. This user matrix will contain information about project costs, the required amount of work, estimated effectiveness in enhancing local biodiversity, created coastal protection and possible economic opportunities created by the artificial reef. This matrix makes it possible to quickly choose an appropriate option for the creation or restoration of local coral reefs.

1.4.1 QUESTIONS

To create this matrix a few vital questions must be answered mainly: How can a thriving artificial reef be created and sustained? In order to answer this question, a few sub-questions must first be resolved.

1. What are suitable locations for an artificial reef?
2. What material is best suited to create an artificial reef?
3. Which coral multiplication method is suitable for creating an artificial reef?
4. What are the different building options for creating an artificial reef?
5. How could an artificial reef be funded?

1.4.2 TARGET AUDIENCE

This paper is intended for people who are interested in coral restoration and is specifically designed to be read by people who are working in policy-forming jobs at governments or other associations that are involved in decision-making and for people who want to establish an artificial reef. The matrix should be understandable even for people who are not well-versed in ecology and other relevant scientific knowledge. Thus, it should result in a well-informed decision regarding the protection, creation and continuation of coral reefs.

1.5 SETUP OF THIS DOCUMENT

With the aim of creating a comprehensible and enjoyable reading experience, a certain literary structure must be established in this paper. This allows the reader to quickly find the subject that they are looking for and should enhance the reader experience significantly. The structure is as follows; In chapter 2 the research method is expounded. In chapter 3 all five sub-questions will be answered, each in their specific section. Each section will consist of different paragraphs each answering one piece of the puzzle. At the end of chapter 3, the most important results will be summarized so that the following analysis is still comprehensible even without reading all of chapter 3. This analysis will consist of the earlier mentioned cost-benefit matrix (§1.4) as told in (§2.2). Once all the "puzzle pieces" are in place an answer to the specific sub-question will be stated in the conclusion within chapter 5. Any knowledge conflicts that may arise or inconsistencies that may occur will be discussed in Chapter 4 and possible locations to utilise each different method will be briefly mentioned there. Chapter 5 will then conclude with the best possible solution to the questions mentioned in §1.4.1. This should allow the reader to quickly find answers to their own questions without much effort while using the table of contents.

2 METHODS

To find the answer to the question: "How can a thriving artificial reef be created?" proper research must be conducted. This research needs to be theoretically reproducible by any capable human and thus a certain process must be used as a guideline to come to the same conclusion. In this chapter, the way research was done is solidified and expounded.

2.1 HOW WAS THE RESEARCH DONE?

The research was done by a single person searching for specific terms in (online) libraries and search engines. For every sub-question, the same research restrictions will be applied. The search engines that will be used include:

- Google Scholar
- ResearchGate
- Plus ONE
- Green Eye
- Science Direct
- Wiley
- Springer

In order to find the most pertinent information, certain limitations were set to prevent the use of outdated data or the application of obsolete scientific consensus. The following research restrictions were used:

The information within the paper needed to be at most 30 years old, thus 1993 was set as a baseline for all research. Younger papers were favoured, anything published after 2013 was considered recent and thus was given priority over older papers if the information in the paper was concurred by multiple sources. Otherwise, the older consensus was adopted for the evaluation of information. During the gathering of information, only peer-reviewed papers were used as well as information made available by trusted governmental associations (TGA). Examples of these TGA's are NAOO, NASA, NIOS, WUR/WMR etc.

The scope of the study was the creation or addition of tropical coral reefs that utilized the calcification process to form an aragonite skeleton or cohesive structure. Any papers that mentioned other reef types like seagrass meadows, kelp forests or sponge-like species were excluded.

For the sake of reproducibility, certain pre-determined search terms were documented for every sub-question. For each sub-question, the intended method of finding the answer to the stated question was expounded in the paragraphs below. A summary with the intended search terms was added. The ultimately used search terms were written down and added in Appendix I.

2.1.1 QUESTION 1: WHAT ARE SUITABLE LOCATIONS FOR AN ARTIFICIAL REEF?

Logically, finding a suitable location for the formation of an artificial reef was crucial for the success rate of the intended project. This was the first sub-question that was answered. Key factors that allowed for the formation of a coral reef were determined. In chapter 1 the way a reef was naturally formed and where it was found was already explained. This information was expounded further, resulting in a more complete picture. The exact temperature and flow range of tropical reefs were stated, along with suitable substrate types, chemical ranges of water, and water depths. This information can however be explicated further resulting in a more complete picture. For instance, the exact temperature and flow range of tropical reefs needs to be stated, along with suitable substrate types, chemical ranges of water and water depths. Search terms that were used for this are: Temperature range of coral reefs, Flow range of coral reefs, *Hexacoralia* flow temperature range, practical diving depths and coral reef locations.

2.1.2 QUESTION 2: WHAT MATERIAL IS BEST SUITED TO CREATE AN ARTIFICIAL REEF?

Once a proper location was determined, the type of material to build with was the next consideration. Factors like local material availability and inertness of the material were deemed important for the longevity of an artificial reef. Material costs, strength, longevity, and ease of use were also deemed significant for a reef creation project. As stated in chapter 1, without an active and healthy biofilm, new coral polyps would not settle on the material. Therefore, the recruitment capability of the material was important and found. Questions like “What type of Inert marine grade materials are readily available?” and “Coral recruitment rate of material (X)” was answered to solve this sub-question. Thus search terms like coral recruitment, marine biofilm formation and artificial reef materials were used.

2.1.3 QUESTION 3: WHICH MULTIPLICATION METHODS ARE SUITABLE FOR CREATING AN ARTIFICIAL REEF?

Once the location and building material was selected, the introduction of species was the next consideration. This subquestion’s chapter established which species were suitable for artificial reef formation and how these species could be multiplied. Different propagation methods were discussed and summarized. Along with coral multiplication, the selection of suitable species was determined. Coral growth rates, species cohesion and ecosystem dependencies were therefore determined and summarized. Search terms for this were Coral propagation, mariculture of corals, coral growth rates, and coral species. Other factors that could be important for species suitability were also found. Search terms like the following were used: suitability of coral (species A) for coral farming, ongoing and established project names (barefoot manta, Florida reef conservation etc.), challenges of artificial reef formation and threads for corals.

2.1.4 QUESTION 4: WHAT ARE THE DIFFERENT BUILDING OPTIONS FOR CREATING AN ARTIFICIAL REEF?

After the location and materials were selected, the various types of building methods were explored. Many experimental building methods in development for this particular subject were found. The best method or combination of methods was then selected for distinction and further analyses. Used search terms were: Reef formation methods, Reef building, Coral propagation, coral farming, artificial reef creation and different project names.

2.1.5 QUESTION 5: HOW COULD AN ARTIFICIAL REEF BE FUNDED?

An artificial reef couldn't be created without a certain amount of work and effort. Such work needed to be paid for and required certain financial resources. Therefore, certain financing options were explored by using the following search terms: Coral reef farming expenditures, Coral pricing, Ecotourism benefits, Coral propagation cost, Coral farming costs and coral planting costs could be used.

2.2 ANALYSIS

To find the best solution to the previously mentioned questions a proper analysis of the collected information was required. Since the ultimate goal is to preserve the world's coral reefs the best method according to the matrix should be the one that is ultimately the most cost-effective per ha. High costs for creation and maintenance could make alternative options, like mechanical storm surge barriers, more appealing to policymakers in terms of coastal protection (Bayraktarov, et al., 2019; Vaughan, 2021). However, such solutions likely offer fewer ecological benefits, making them less desirable for coral reef preservation.

In this analysis, both ecological and financial aspects are considered. We process the acquired information in a cost-benefit analysis, allowing empirical verification of the final conclusions. This comparison assesses the financial cost of each artificial reef creation type against its ecological benefits. Each method is evaluated across five categories and ranked from 1 (most preferred) to 4 (least preferred). The categories include cost, labour amount, and ecological, economic, and environmental benefits, deemed crucial for restoration efforts (Quigley, Hein, & Suggett, 2022). The individual scores were then summed; lower totals indicate better-rated Artificial Reef Creation (ARC) methods.

Evaluation parameters for each subject were as follows. For costs, the number one would be the cheapest option followed by the second cheapest and ending the most expensive option in the last position of place four. For labour amount, it is similar, where the less labour is required the better the score is. The least amount of labour would result in the first position and the most amount of labour would result in the last position. For the benefits, it is the other way around. The better the benefits of the method the higher the scored place. This means that the best benefits will be in the first place, while the worst benefits will be in the last. All scores will be added up and the lower the score the better suited the method is deemed to be for coral reef creation.

In the evaluation process, each category of benefits is defined by specific metrics. Ecological benefits are assessed based on factors such as the enhancement of biodiversity, the method's contribution to ecosystem services, and the success rates of coral reef growth and survival. Economic benefits are determined by the potential of each method to boost tourism, create jobs, and positively impact local fishing industries. Lastly, environmental benefits are evaluated based on a method's ability to mitigate coastal erosion, sequester carbon, and improve water quality. These specific measures ensure a comprehensive understanding of the benefits associated with each artificial reef creation method.

3 RESULTS

Information about each sub-question will be stated in this chapter. Each sub-question will serve as a puzzle piece and thus, each paragraph will build on the next until the entire puzzle is made and the picture clear, so to speak. Each puzzle piece should exclude some criteria so that the eventual answer to the main question will be as sharp as possible Only the information that is gathered will be stated in this chapter. Requirements, Cost and ecological benefits can be found in the chapter in this chapter, as well as a financial analysis of the data. The discussion of the data is realized in Chapter 4. Chapter 5 will be a conclusion and recommendations.

3.1 SUITABLE LOCATIONS FOR ARTIFICIAL CORAL REEFS

Before creating an artificial coral reef, the single most important step must first be made: Choosing the location for creating an artificial reef. The suitability of the chosen location is vital for the success or failure of an artificial reef. If the reef is formed in a location that is too warm or too cold for instance, the success rate will be exactly zero. First and foremost it must be stated that tropical coral reefs have very specific parameters that must be met for their natural formation. These parameters include the salinity, temperature, depth, available substrate, stability of the area (both physically and chemically), availability of free-floating phytoplankton and other nutrients and last but not least light penetration and flow (Kleypas, McManus, & Menez, 1999). *The exact minimum and maximum values are gathered in the following text and will be discussed in Chapter 6.*

3.1.1 CHEMICAL AND PHYSICAL PARAMETERS

The chemical parameters of seawater for the intended location to develop an artificial coral reef must be within the right range for the reef to prosper. Important chemical and physical values for the biographic range of natural coral systems have been known since the late 90s and are known to be the temperature, salinity, pH, nitrate (NO_3) and phosphate (PO_4) availability (Sheppard, Davy, Pilling, & Graham, 2018; Oliver & Palumbi, 2011; Ferrier-Pagès, Gattuso, & Jaubert, 1999). Therefore these parameters will be further investigated in the following text, only the nutrients that are nitrate and phosphate will be discussed in paragraph 3.1.4.

A tropical coral reef can only form in salt water (EPA, 2022). This means that fresh or brackish waters are already excluded from our search for a proper location. Since there are so many species that can form a natural reef there isn't an exact agreement on the required salinity of the seawater because different species thrive in different environments. Most corals tend to thrive in the range of 34-37‰ and thus this should be the targeted salinity for choosing a location according to Cyronak, et al. (2022) and Sheppard, Davy, Pilling, & Graham (2018).

Factors that influence the local salinity are flow, freshwater input as well as evaporation rate. Hence locations that receive a relatively high amount of precipitation tend to have a lower salinity than their dry-area counterparts. Proximity to the coast can also influence the salinity because an area directly adjacent to the mouth of a river or stream could increase the influx of freshwater to the ocean. Therefore the formation of artificial reefs is ill-advised in locations close to the mouths of rivers and streams (Dias, et al., 2019). Other reasons why artificial reef creation near freshwater outlets are a bad idea will be mentioned in paragraphs 3.1.4.

Earlier on the ranges of the pH level have already been mentioned, they were mentioned to be between 7,6 and 8,7. But most thriving reefs have a stable average pH of 8,3 ±0,3 (Bove, Whitehead, & Szmant, 2022). In the study of Foo and Asner (2020), it is mentioned that temperature, depth and pH are correlated.

A factor that can influence the salinity, density and other water parameters directly is the temperature of the surrounding seawater (Cyronak, et al., 2022). There is clear evidence that any temperature above 30,5 °C will result in a mortality of 50% of the corals that are transplanted to a restoration project (Foo & Asner, 2020). The absolute coldest temperature a tropical reef is documented to survive and thrive in is 21,0 °C. Another study shows that the temperature range for a healthy coral reef lies between 21.7—29.6 °C (Guan, Honh, & Merico, 2015) Maximum temperatures have been shown to be at 31°C (Schoepf, Stat, Falter, & McCulloch, 2015)

3.1.2 DEPTH

Although reefs have been found at depths of 165 meters these types of reefs are less prone to changes in temperature and thus less vulnerable and consequently not influenced as much by climate change (Page, et al., 2019). According to Laverick, Tamir, Eyal, & Loya (2020) papers, light penetration can influence the maximum depth of a coral reef greatly. This is caused by the photo-dependence of all zooxanthellae and thus resulting in the corals themselves being limited by light availability (Roth, 2014). Without a sufficient amount of light, the photosynthesis within the symbiont cannot produce energy for the coral and therefore the coral starves. Light penetration of the area is therefore the most important factor that influences the maximum depth of the mesophotic coral reef. In Chapter 1 it was stated that the ideal depth for a tropical coral reef is between 0 and 36 ± 5.6 meters of water depth. This value can still be used as a general guideline if the former is taken into consideration. A useful tool for estimating if an area is suitable or not could be the Allen Coral Atlas (2023) or other bathymetry datasets.

Another important factor that needs to be taken into consideration concerning depth is practicality. If a reef is created in deeper waters (> 40 meters depth) the increasing depth can cause a multitude of challenges. The most prominent of these challenges is water pressure. The higher the water pressure the more the cost of operation and execution will rise, resulting in skyrocketing cost of the project. The increased depth will also have a negative effect on the effectiveness to reduce wave action and thus negatively impacts the ability to protect coastlines, which is a primal reason to create an artificial reef in the first place (Bayraktarov, et al., 2019). Therefore it is best to concentrate our efforts on shallow water reefs.

Additionally to this, coral transplantation and mariculture need to be done mostly by human hands and human-assisted machinery. Therefore it is also required that the depth of the ARC is within practical scuba diving range. Depths below 25 meters require extensive training to dive, hence it is best to keep the scope of our effort towards the shallow waters of the world. A practical and safe diving depth is anything between 0 and 18 meters. Reaching these depths requires minimal training (PADI, 2022).

3.1.3 SUITABLE SUBSTRATES

For a coral reef to form, most corallites must be able to attach themselves to a solid substrate that has certain biological stimuli present and is stable, as mentioned in Chapter 1 (Bayraktarov, et al., 2019; Kleypas, McManus, & Menez, 1999) There are a handful of species that can settle on sand-like sediment deposits and form a solid base from there (Sheppard, Davy, Pilling, & Graham, 2018). Although this is the case, some studies are working on developing methods for artificial reef creation on soft-bottom substrates like sand and gravel and seem to be succeeding. (Golomb, Shashar, & Rinkevich, Coral carpets- a novel ecological engineering tool aimed at constructing coral communities on soft sand bottoms, 2020) Besides this, the most likely suitable substrates seem to be any form of non-toxic stable hard bottom substrate, including but not limited to metal framing/wiring, concrete structures and stones/boulders (Ceccarelli, et al., 2020). A more in-depth review of the use of these substrates and materials can be found in paragraph 3.2.

3.1.4 NUTRIENT AVAILABILITY AND ECOSYSTEM STABILITY

Another important local factor for coral reef systems is the availability of food and nutrients (Sheppard, Davy, Pilling, & Graham, 2018). As stated in chapter one reef-forming corals mostly consist of the genus *Scleractinia* and almost all species are dependent on their symbiotic relationship with the dinoflagellates within their cells for 90% of their food intake. Without the proper nutrients, the symbiotic zooxanthellae cannot perform photosynthesis and thus the coral will not prosper and will eventually die (Roth, 2014). However, too many nutrients can lead to algal outbreaks that overgrow and outcompete corals when the nutrient levels are exceedingly high. According to Miller, et al., 1999 coral reefs can be especially vulnerable when they are still young and haven't attracted enough herbivorous fish to slow the explosive growth of algae. In the aforementioned study, it is stated that not nutrient availability but herbivory is what keeps algal growths in check. Consequently, the quick attraction of herbivorous fish is deemed vital for the successful creation of an artificial reef.

The two substances that are most important for the zooxanthellae to perform photosynthesis are nitrate (NO_3) and phosphate (PO_4), CO_2 is also a key substance for this process, but because of human activity, CO_2 isn't in short supply any time soon. Hence NO_3 and PO_4 are the most prominent nutrients to influence the success of the artificial reef. According to Guan, Honh, & Merico (2015), the maximum value that a reef can still thrive in concerning nutrients is 4.51 µmol L^{-1} for nitrate and 0.63 µmol L^{-1} for phosphate. When these nutrient values are below the aforementioned values, especially during the establishment period of the artificial reef, the coral is able to outcompete algae.

Thankfully the conditions in most of the world's tropical oceans are oligotrophic and thus below the aforementioned maximum values for coral reef ecosystems (EPA, 2022). Nevertheless, some locations are not suitable for reef creation because of the high nutrient outpour of rivers and streams that are polluted with agricultural remnants like manure runoff and other fertilizers. The availability of an abundance of nutrients in the mouths of these rivers would make it impossible for corals to outcompete macroalgae and other marine plant life. River mouths also deposit sandy substrates, which are detrimental to reef health and prohibit most forms of formation. Hence, seagrass fields and mangroves would be better suited for these areas as a natural barrier against wave action because these types of ecosystems are better suited for higher nutrient levels (Jones, Fisher, & Bessell-Browne, 2019).

3.1.5 REMOTENESS AND ANTHROPOGENIC EFFECTS

Besides the anthropogenic effects like climate change and ocean acidification, other human activities can also greatly influence the health of any coral reef, especially those that aren't well established yet. Human activities like agriculture, storm drainage systems, fishing and dredging are examples of activities that negatively impact coral reef systems (Niggol Seo, 2021). All the effects of these human activities eventually end up in the ocean. Because of their proximity to the coast, coral reefs are often the ecosystems that are most vulnerable to these activities and therefore receive the most negative impact (Hoegh-Guldberg, Pendleton, & Kaup, 2019). One could think that therefore restoration efforts should be conducted in low-population areas. Research from Baumann, Zhao, Stier, & Bruno (2021) shows that this is not the case and the opposite is true. Reefs that have developed near humans are adapted to human induces environmental change, hence they are more resilient to human disturbances. Therefore focusing restoration and conservation efforts near more populated areas could maximize conservation outcomes.

3.1.6 OCEAN BIOGRAPHY, FLOW AND LATITUDES

Factors that could influence the water temperature are mostly consisting of oceanic flow patterns and latitude and the corresponding increase in solar input because of low latitude (Kleypas, McManus, & Menez, 1999; Spalding, et al., 2007). According to the aforementioned study, a latitude between 35° and -35° is best for the formation of coral reefs. Prevailing ocean currents can influence these ranges for a marginal amount. In Ocean currents that are typically warmer, the suitable latitude ranges can increase in size, while in colder waters the range decreases. Colder ocean currents carry relatively more nutrients than their warmer counterparts and are therefore vital for nutrient deliveries to the nutrient pore waters in the tropics (Guan, Honh, & Merico, 2015).

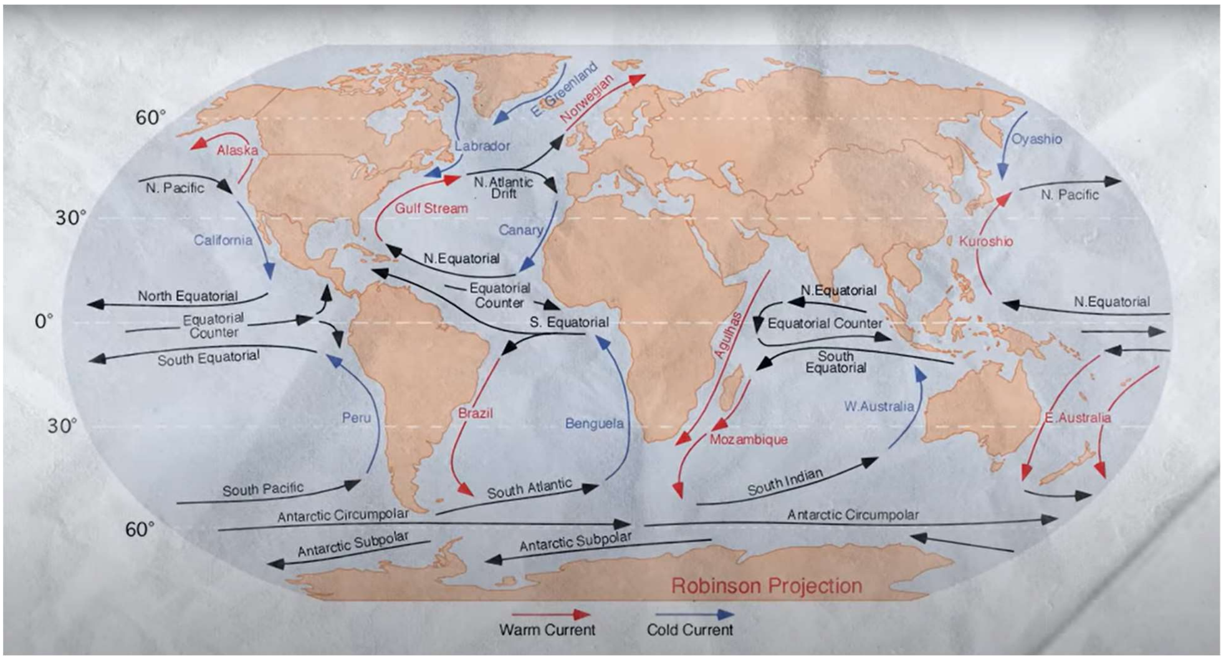

Figure 7 A schematic overview of prevailing ocean currents, with the red arrows being the warmer currents and the blue arrows being the colder ocean currents. The black arrows show regions where two ocean currents meet, mix and exchange heat and resources (Image Source: Atlas Pro).

3.1.7 LIGHT AVAILABILITY AND PENETRATION

Light availability and light penetration can be measured or stated in a variety of ways. PAR is the most used variant and hence will be the variant that this paper uses to state the amount of light. PAR is measured in the number of photons with a wavelength between the photosynthetic range of light (400nm – 700nm) that can reach a certain area within a certain time frame. Usually, it is stated as X-amount µmol photons m^{-2} s^{-1} Meaning around 6,02214076 × 10^{17} photons in the wavelengths between 400nm – 700nm hit an area of $1cm^2$ every second. For every 8 photons, one CO_2 molecule is fixated via the complex process of photosynthesis. (hatch, 1987) Now the measurement system is explained, the light values that were found by different studies can be stated. According to research by Guan, Honh, & Merico from 2015, the average minimum light intensity in healthy coral reefs is 450 µmol photons m^{-2} s^{-1}. Average available light intensity doesn't say everything about the ecological community that could thrive at that location however other factors like flow and light penetration into the water column are also important (Laverick, Tamir, Eyal, & Loya, 2020). Therefore depth and light availability can't be seen separately from one another.

3.1.8 TOTAL REEF AREA

Now that all factors that can influence the occurrence of a natural reef have been discussed, the total area that could foster a coral reef could be stated. The total global area of coral reef habitat coverage could be as high as 330,5 × 10^3 km^2 according to the model used in Guan, Honh, & Merico's study (2015). The same study estimates that around 209,5 × 10^3 km^2 of this potential reef area actually contains natural reefs, meaning that a relatively large amount of 1/3 of suitable locations for reef development has not cultivated a natural reef. This could be because some factors for the creation of a natural reef are missing. The introduction of a missing factor, like a hard substrate or a missing coral population could create a reef where first there wasn't one.

3.1.9 OVERVIEW OF PARAMETERS

Now that all the main information is expounded upon it is time to summarise. An artificial reef should be created in optimal conditions. Optimal sites should have a salinity of 34-37‰, temperatures of 21.7—29.6 °C, and be at water depths within 36 ± 5.6 meters due to limits of photosynthesis and limitations in diving depths. Other factors that influence site selection include substrate quality, nutrient availability, human proximity, ocean current influence, and the site's need to be within a latitude of 35° north or south.

3.2 SUITABLE MATERIALS FOR ARTIFICIAL CORAL REEFS

When a location is found that is suitable for artificial reef development, the proper material should be selected for successful artificial reef creation. In paragraph 3.2 the different available and future materials will be stated.

3.2.1 REQUIRED PROPERTIES

Materials that are used in marine environments need to be resilient to harsh conditions (Bayraktarov, et al., 2019). Saltwater has corrosive properties and can render especially metals useless in mere years. Therefore the material that is used should at least have marine-resistant properties (Lima, Zalmon, & Love, 2019). Another important factor that has to be taken into consideration is water solubility, any material that has this property could leach its contents into the ocean and could harm the marine environment that it is trying to protect. Since massive amounts of material are needed to create expansive artificial reefs, the material should be cheap and abundant. And finally, the material must be biocompatible. If corals can't grow on the medium then the purpose is surpassed.

Besides the abovementioned absolutely necessary requirements, there are also a few preferences when it comes to material. A suitable material would preferably be locally available or locally produced to keep shipping costs low. Aside from this, a bonus could be that it also uses waste material from industrial processes. These factors will also influence the cost-benefit analysis in paragraph 3.6.

3.2.2 MATERIALS

A material that might be suitable for artificial reef creation is Mineralized Cellulose Materials (MCM). This material is made by injecting CO2 into a mix of the industrial waste products of cement manufacturing and the paper industry. The alkaline wastewater that remains after cement production is combined with the cellulose pulp that remains after paper production. As a bonus, MCM has the benefit of fixating CO_2 during its manufacturing process. This means that the material can store CO_2, thus resulting in a carbon sink. In the study of Reyes, et al. (2023) MCM has been proven to be a suitable material for artificial reef creation. Corals could easily attach to the material and were able to grow on the material for seven months.

Another material that shows promising results is new artificial reef concrete (NARC). This material is created with sulfoaluminate cement and marine materials like seawater and marine sand. This mixture is proven to be more durable and stronger than conventional Portland cement concrete in a marine environment. It is also far more workable than Portland cement-based concrete. According to Chen, Ji, Zhuang, & Lin (2015), this makes the material a feasible material for creating artificial reefs

Similar to NARC, Green artificial reef concrete (GARC) is also a human-made substance that shows marine-resistant properties and a wide range of capabilities (Huang, Wang, Liu, Hu, & Ni, 2016). GARC is made with the industrial waste material of steel processes and contrary to NARC and MCM doesn't contain portlandite, a fancy term for hardened cement. The study suggests that the lack of portlandite decreases the number of barnacles that can attach to the surface while still being suitable for algae and other marine life to attach to it.

A final material that could be used is old heavy metal objects and vehicles like ships, train carts, busses and other intact metal scrap (Vaughan, 2021). Shipwrecks have been known to attract an abundance of marine life while they lay in the ocean. The benefit of using these objects is that they are less likely to be moved by storm events or other extreme forms of wave action. This ensures a stable foundation for the formation of a reef. Aside from metal hulls, old concrete structures, like bridges and foundation plates, could also be used as a basis for ARs.

3.3 CORAL MULTIPLICATION IN SPECIES SELECTION

Now that the requirements for the location and the different building types have been discussed, it is time to search for coral species that are suitable for coral multiplication and propagation and find out what types of coral farming are available. Aside from species, propagation methods will also be discussed in this paragraph. There are a lot of similar propagation methods that have very small differences between them. Therefore only a summary of the different methods has been given within the text. All methods mentioned within the following text have been field tested and have proven to be effective.

3.3.1 CORAL MULTIPLICATION

All building methods shown and analysed in this paper rely on a form of coral multiplication. These methods could be anything from coral gardening in both onshore or offshore facilities, micro fragging and sexual multiplication. These methods will be briefly explained in this section of this chapter.

One of the methods that are prevalently and successfully used for coral multiplication is offshore coral gardening. This method consists of harvesting small (1-5cm in size) coral fragments and attaching them to a form of hard substrate. Then letting these coral fragments grow for a specified amount of time in favourable conditions. The duration of this growing period depends largely on the coral species and growth form. Usually, a growth period of 1 – 2 years can be enough to create coral colonies of significant size (Hernández-Delgado, Mercado-Molina, & Suleimán-Ramos, 2018) An example of different types of growing methods can be seen in Figure 8.

Figure 8 Examples of additional low-tech coral farming methods used in Puerto Rico. From top left: (A) PVC plastic grid; (B) "cathedral" line nursery; (C) tree unit; (D) modified benthic underwater coral array (m-BUCA); (E) concrete cookies; and (F) tree unit. (Hernández-Delgado, Mercado-Molina, & Suleimán-Ramos, 2018)

Onshore (or *ex-situ*) coral gardening is a more modern method that is commonly used to create more individual coral colonies. This method involves different types of onshore water basins or grow beds where filtered seawater combined with supplement additions create ideal conditions for coral growth. This method allows for faster growth speeds and healthier corals, while also reducing SCUBA diving costs associated with *in situ* coral farming (Schmidt-Roach, Duarte, Hauser, & Aranda, 2020). This method can also work in tandem with *in situ* coral farming, allowing for sexual reproduction and micro-fragging to be used in *ex-situ* sites and asexual reproduction to be used in the *in situ* sites. (Barton, Willis, & Hutson, Coral propagation: a review of techniques for ornamentaltrade and reef restoration, 2015). An example of a basic onshore coral farm can be seen in Figure 9 Basic *ex situ* coral farm

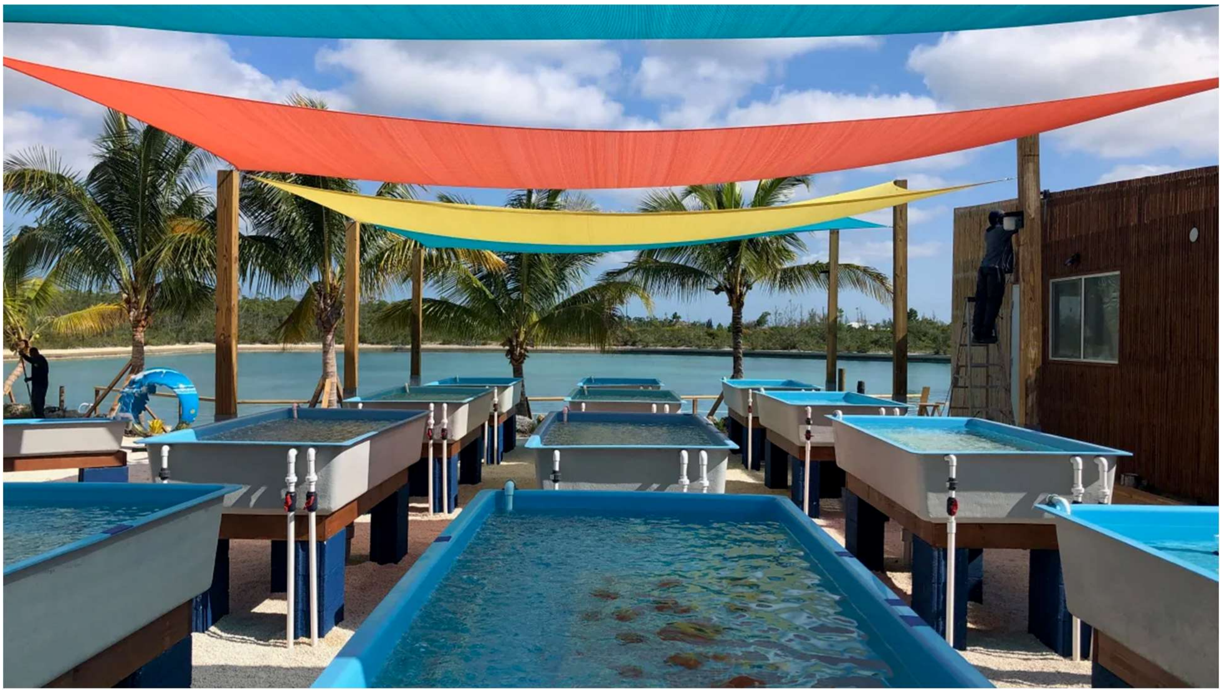

Figure 9 Basic *ex situ* coral farm that can supply a large number of corals

3.3.2 SUITABLE CORAL SPECIES

Species that are suitable for coral farming should have a variety of traits. According to recent studies (Schmidt-Roach, Duarte, Hauser, & Aranda, 2020), useful properties for corals to have are suitability for propagation, high temperature resistance, general resistance to chemical fluctuations in water parameters, resistance to and ability to reduce wave action and last but not least, a high growth rate of the coral (Hernández-Delgado, Mercado-Molina, & Suleimán-Ramos, 2018). According to research from Oliver & Palumbi (2011), some corals and their symbionts can be naturally more resistant to certain temperatures. These species could be used to create a more temperature resistant reef system. Another way this goal could be achieved is by the hybridization of coral species. These hybrids have been shown to have increased resistance and resilience to extreme weather events and other climate change effects (Chan, Peplow, Menéndez, Hoffmann, & van Oppen, 2018).

Other factors that have to be taken into consideration when choosing coral species for artificial reef creation are both the growth form and the ecosystem niche that the coral provides and fulfils (Sheppard, Davy, Pilling, & Graham, 2018; Bostrom-Einarsson, et al., 2020; Quigley, Hein, & Suggett, 2022). In other words, the trophic interactions within the created ecosystem must also be taken into consideration. Not only when it comes to corals but also when it comes to species like sea urchins and seastars that either benefit or harm the corals and the subsequent species that depend on them (Ladd & Shantz, 2020). The aforementioned study also states that, Herbivory, corallivory, coral heterotrophy and consumer-derived nutrient cycling are important factors that dictate this trophic interaction. When monitoring for ecosystem development these species should therefore be taken into consideration when ascertaining the success rate of the project.

In line with this subject is the topic of biodiversity. When following the 10 golden rules of restoration stated by Quigley, Hein, & Suggett (2022), rules 3 and 6 come into play. These rules state that maximisation of coral biodiversity should be strived for and that coral species should be selected to maximize functional diversity. This biodiversity and functional diversity should enhance the resilience and resistance of the ACR. Consequently, any introduction of invasive species—corals or otherwise harmful organisms—should be strictly avoided. The effects of such an introduction should not be underestimated. This includes not only corals but also the larvae of coralivorous or otherwise harmful organisms (Quigley, Hein, & Suggett, 2022). It is best to keep the 10 golden rules of restoration proposed by the aforementioned study in mind when choosing suitable species for the ARC project.

In summary, the overall criteria seem to be: Propagation rate, growth rate, survivability, growth form, resilience to chemical change, ecological function and resistance to wave action. These are the pillars on which the species that are selected should be judged upon. Using these criteria different species have been found resulting in the species listed in Table 1. For each species, a short explanation has been given as to why the species in question are suitable/practical for multiplication.

Table 1 A summarized overview of suitable coral species for coral farming and ARC. SPS means small polyp coral (3<mm polyp size) and LPS means Large Stony Coral (3>mm polyp size), pictures provided by Coralpedia (2023) and Reefbuilders (2023) under creative commons, the information provided by (Vaughan, 2021; IUCN, 2023)

Species name	Species traits	Growth form	Pro's	Cons
Acropora cervicornis 	Once abundant but now threatened coral species that is found mostly in the Caribbean Sea. The branches provide shelter for small fish (5-15 cm). Is deemed to be a secondary reef-building species	Branch-like with wide open branches grown at right angles from each branch. Grows … per year	Fast grower (multiple cm per year), propagates easily with fragmentation.	The relatively high mortality rate of both adult colonies and sexually produced offspring.
Acropora palmata 	Once abundant but now threatened coral species that is found mostly in the Caribbean Sea. Is deemed to be a secondary reef-building species	Branch-like with growth form resembling moose antlers.	Fast grower (multiple cm per year), propagates easily with fragmentation.	The relatively high mortality rate of both adult colonies and sexually produced offspring.
Acropora prolifera 	Once abundant but now threatened coral species that is found mostly in the Caribbean Sea. The branches provide shelter for small fish (3-8 cm). Is deemed to be a secondary reef-building species	Dense branches that grow in a staghorn-like way.	Fast grower (multiple cm per year), propagates easily with fragmentation.	The relatively high mortality rate of both adult colonies and sexually produced offspring.

Acropora yongei 	Common and abundant coral species that is found across Southeast Asia. The branches provide shelter for small fish and invertebrates (1-15 cm). Is deemed to be a secondary reef-building species	Dense branches that grow in a staghorn-like way.	Fast grower, propagates easily with fragmentation. Is also far less susceptible to mortality issues than its Caribbean counterpart.	Can overgrow entire areas, creating a monoculture.
Agaricia spp. 	Once abundant but now vulnerable coral species that is found mostly in the Caribbean Sea and can also thrive in lagoons and other brackish environments. It functions as a reef cementation species. It is considered a primary reef-building species	Encrusting when young and later on plate-forming with upright protrusions from these plates. depending on the species.	Propagates relatively easily with fragmentation. Is suitable for microfragging	Slow grower (several mm per year)
Diploria labyrinthiformis  **(Haarsma, 2023)**	Threatened coral species that is found mostly in the Caribbean Sea. The coral functions mostly as a reef-building coral. It is considered a primary reef-building species	Brain coral that grows in massive growth form resembling a human brain. Spherical in shape	Propagates relatively easily with fragmentation. Is suitable for microfragging	Slow grower (several mm per year)
Montastraea (or Orbicella) annularis 	Once Abundant but now threatened coral species that is found mostly in the Caribbean Sea. Provides a foundation for other corals. Is considered a primary reef-building species	Massive growth form that consists of densely packed nodules that can form 'bommies' that function as their own small isolated reef.	Propagates relatively easily with fragmentation. Is suitable for microfragging	Slow grower (several mm per year)
Orbicella faveolate 	A massive coral that can form large groups of individual colonies. It can provide shelter to a variety of species and has its own microsystem. It grows mostly on the fringe of a reef and is considered a primary reef-building species.	Massive growth form that consists of large dome-like outcrops with a mushroom-like edge.	Propagates relatively easily with fragmentation. Is suitable for microfragging	Slow grower (several mm per year)

Pocillopora Damicornis 	Common and abundant coral species that is found across the world. The branches provide shelter for small fish and invertebrates (1-5 cm). Is deemed to be a secondary reef-building species	SPS, Stub-like branches with small protrusions. Grows are relatively dense.	Fast grower, high survivability rate, Easily propagated. Resilliant to both temperature and chemical fluctuations	Less resistant to wave action than massive growth forms but otherwise extremely hardy without any major cons.
Porites astreoides 	Common SPS coral with different growth types depending on water turbulence. Its encrusting capabilities allow for the cementation of loose reef structures. is considered a primary reef-building species.	Either encrusting (high flow) or massive (Low flow) growth form	Propagates relatively easily with fragmentation. Is suitable for microfragging	Slow grower (several mm per year)
Porites porites 	Common coral with finger-like growth form that is found around the world. Fish and invertebrates can seek shelter within the branches. This hardy coral is considered a secondary reef-building species.	Common SPS coral with finger-like growth form	Average grower (1-2 cm per year), high survivability rate, Easily propagated. Resilliant to both temperature and chemical fluctuations	Less resistant to wave action than massive growth forms but otherwise extremely hardy without any major cons.
Stylophora pistillata 	Common and abundant coral species that is found across the world but is still considered near threatened. The branches provide shelter for small fish and invertebrates (1-5 cm). Is deemed to be a secondary reef-building species	Common SPS coral with finger-like growth form	Fast grower, high survivability rate, Easily propagated. Resilliant to both temperature and chemical fluctuations	Less resistant to wave action than massive growth forms but otherwise extremely hardy without any major cons.

3.4 DIFFERENT BUILDING METHODS FOR ARTIFICIAL CORAL REEFS

In this paragraph five different types of reef restoration and creation will be explained. There is a rainforest worth of theoretical methods available in the public record and beyond. Because the evaluation of every single ARC method available isn't possible, requirements for eligibility for analysis had to be made. Theoretical methods that have not been tested in the field extensively were excluded from the evaluation because their effectiveness couldn't be verified yet. Therefore the requirement was created that a study should have at least some application of the ARC method applied in the field to be eligible for analysis. Another factor that was taken into consideration when the selection of the different ARC methods was made, was the rate of improvement of the biodiversity of the local ecosystem and the resulting reef resilience of said ARC method. The four ARC methods that have been highlighted in this paragraph have all shown promising and reliable results in the field.

3.4.1 INTRODUCTION OF HARD SUBSTRATE WITHOUT CORAL TRANSPLANTING

As mentioned before, one of the major limitations for coral reef formation is the absence of a suitable substrate for corals to grow on (Sheppard, Davy, Pilling, & Graham, 2018). Therefore coral reefs tend to form only in areas where bare bedrock is located at the surface. In many tropical areas, particularly in the Red Sea and the Caribbean, the shallow regions are predominantly covered in sand, creating extensive low-value sandflat habitats that offer limited ecological productivity and inadequate coastal wave protection (Ferrario, et al., 2014). The introduction of a hard substrate in the form mentioned earlier in 3.1.3 is therefore vital for the creation of a coral reef.

This method aims to introduce this hard substrate into the environment by various methods. The most common method used is the sinking of the steel hull of maritime ships. The ship is first stripped of any valuable or harmful materials. Once this process is completed the ship hull can then be towed to a suitable location and can be submerged on location (Vaughan, 2021). This sinking process typically involves the detonation of small explosives added beneath the water line. This allows for water to rush into the hull and will allow it to sink to the bottom of the ocean. Once the hull, now shipwreck, is settled on the ocean floor the corrosion from the saline sea water can corrode the upper layer of the wreck. This corrosion can attract benthic sealife that is able to attach itself to the rusted layer (Hudatwi, et al., 2021). The ship that is used should be made of gauge steel because this type of steel corrodes slowly. Slow corrosion allows for the integrity of the hull to be held for several decades and sometimes even centuries. This process ensures that the corals and other life forms can create a stable structure that can support itself without the help of the metal frame.

An additional form of steel structure introduction is the placing of coral stars or MARS (Mars Assisted Reef Restoration System). These structures involve a hexagon-shaped steel structure fabricated from steel rebar. These structures can then be hardened either with limestone-based concrete or they can be electrified allowing for a chemical reaction to take place that creates a limestone layer (Hilbertz, 1979). This limestone layer can then be colonized by corals and other reef-building organisms. The limestone functions as an ideal substrate for coral growth as it simulates the natural geologic formations corals usually grow on.

Another similar form of hard substrate addition involves the deployment of concrete structures using various techniques. One commonly employed method is the sinking of concrete modules or blocks specifically designed for reef creation. These structures are typically made from marine-grade concrete, which is resistant to the corrosive effects of seawater and durable enough to provide a stable foundation for reef formation. The concrete modules are transported to the desired location and carefully positioned on the seabed. These structures can consist of either new material or old material in the form of large debris.

To promote colonization by marine organisms, the concrete structures can be designed with textured surfaces or incorporate specialized features that mimic natural reef formations. These surface irregularities provide attachment points for corals, sponges, and other benthic organisms, facilitating their growth and enhancing the biodiversity of the newly formed reef (Hudatwi, et al., 2021). Over time, the concrete structures become encrusted with marine life, creating a complex ecosystem that supports the development of a thriving coral reef.

The advantage of using concrete is its longevity and stability in marine environments. Unlike organic materials that degrade over time, concrete structures can withstand harsh conditions and remain intact for several decades or even centuries. This extended lifespan ensures the long-term viability of the created reef, allowing it to serve as a sustainable habitat for coral colonies and associated marine species (Ferrario, et al., 2014; Roelvink, Storlazzi, van Dongeren, & Pearson, 2021).

3.4.2 CORAL CARPETS

This method encompasses an innovative approach to the restoration of degraded coral reef ecosystems through the utilization of "coral sods," which are assemblages consisting of coral fragments and binding materials (Golomb, Shashar, & Rinkevich, 2020). The use of coral sods offers several advantages compared to other methods, including higher survival rates and faster growth compared to conventional transplantation methods. By providing a ready-made substrate, coral sods facilitate the establishment of new coral colonies and contribute to the overall restoration of degraded coral reef ecosystems.

The coral sods are fabricated by combining robust natural materials with an iron rebar metal frame. Examples of these natural materials are coconut fibre, banana fibre and hemp rope. The fibrous material is used to attach the coral fragments to the frame, resulting in a preformed reef patch. Once the coral sods are prepared, they are suspended in the water column using buoys or other flotation devices, as exemplified in Figure 10. Once the coral carpets are created they can be transferred to a location with favourable conditions for 3-8 months. This method is also used in the aquarium trade and ensures that the corals are grown in favourable conditions, which results in increased growth rates (Barton, Willis, & Hutson, 2015).

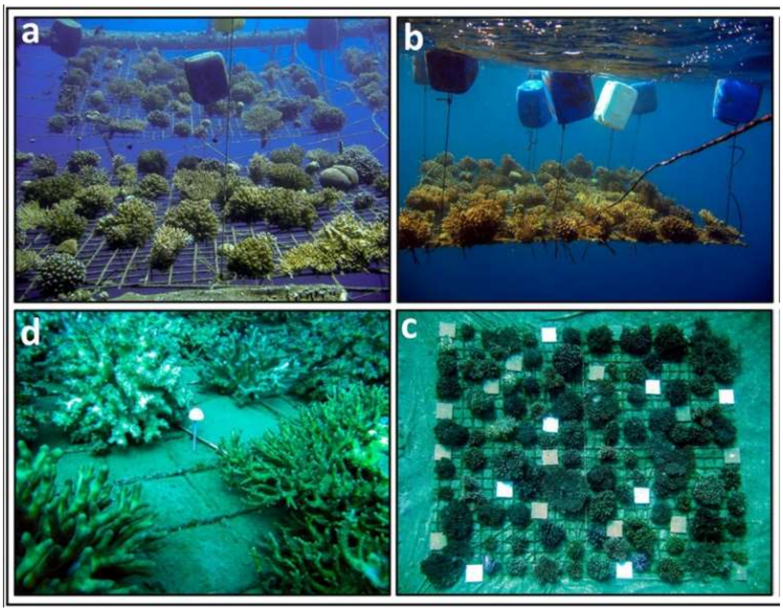

Figure 10 Coral carpets created during the study of (Golomb, Shashar, & Rinkevich, 2020)

The coral fragments utilized in this approach can be obtained from either a coral nursery or sourced naturally. Once the coral sod is matured, the coral carpet can be transferred to the area where the artificial reef is going to be created. To ensure secure attachment to the soft substrate, metal pins or concrete blocks can be employed to firmly anchor the coral sods. Once fixed, the coral carpets are left to grow and develop.

The outcomes of the study conducted by Golomb, Shashar, & Rinkevich (2020) demonstrated high survival rates among transplanted corals, accompanied by an increase in ecological volume. Within a year, the aerial coverage of the branching units rose from an initial 50% to 67.3%, while the mixed units achieved coverage of 61.5%. The coral sods proved successful in attracting coral larvae, which exhibited superior performance compared to those originating from native colonies during subsequent reproductive seasons.

3.4.3 REEF DEGRADATION REVERSAL

Contrary to the other methods mentioned in this paper that try to create a reef where there is none, this method aims to restore deteriorated reef sections. These sections may have suffered damage due to human activities such as dynamite fishing and commercial coral harvesting. Additionally, bleaching events combined with extreme weather events can contribute to reef degradation and could be a cause to intervene. Given a sufficient timeframe without anthropogenic disturbances, these reef systems have the potential to naturally restore themselves over several decades. This process occurs through a series of successive processes that culminate in the transformation of rubble fields into consolidated reefs and thriving coral communities (Ceccarelli, et al., 2020). However, most reefs are located in close proximity to human populations. This results in the creation of anthropogenic pressures that deteriorate these reef sections so severely that a negative feedback spiral has been set in motion. If left unaddressed, this cycle will ultimately lead to the demise of the reef and the loss of its habitat function.

The method described in this section aims to counteract the negative feedback loop and facilitates an accelerated rate of restoration (Ceccarelli, et al., 2020). The method does this by intervening in different critical processes so that further reef deterioration is halted and the natural restorative processes of the reef can start again. One of the main processes in the negative cycle is the creation of coral rubble that smothers the healthy parts of the reef. During extreme weather events with increased wave action, this rubble can damage healthy corals, perpetuating the cycle of coral rubble formation and reef erosion (Ross, Fisher, & Bessell-Browne, 2019).

The technique to halt this process involves the fixation of this loose coral rubble with the use of metal wire frames, cement mixtures or bio glues. Once the coral rubble is fixated it is less likely to move due to wave action. This allows for the corals and other reef-building fauna to reinforce the rubble further. A stable substrate means that other coral recruits are more likely to successfully settle creating a positive feedback loop, thus restoring the natural restoration cycle. The restoration of this natural process improves the resilience of the coral reef, allowing for a greater chance of survival during extreme weather events. An infographic has been created by Ceccarelli, et al. (2020) that expounds upon the further processes that influence the cycle, see Figure 11.

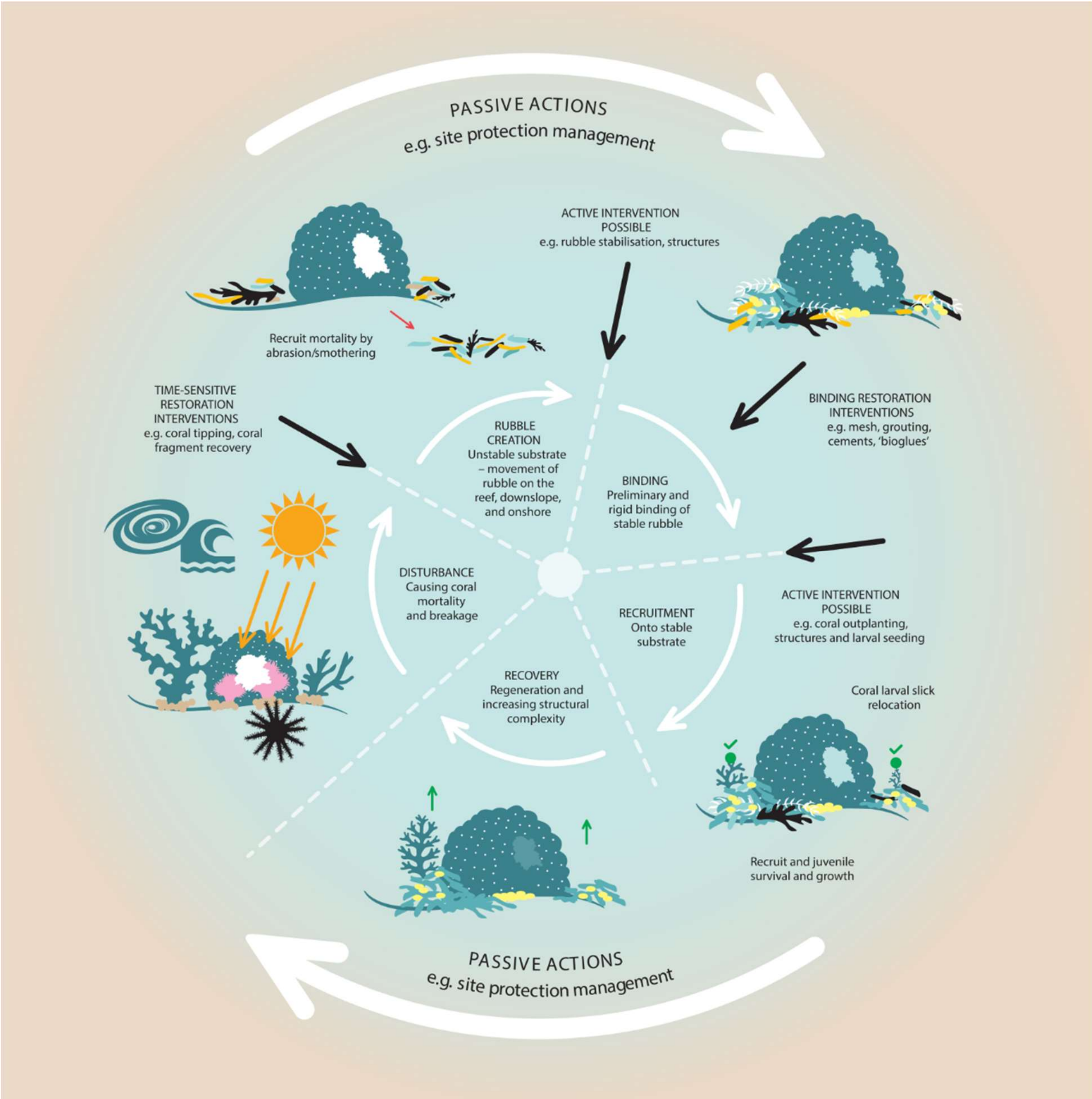

Figure 11 A Schematic representation of the coral reef rubble cycle made by (Ceccarelli, et al., 2020)

The structures introduced by the fixation process allow for the attachment of coral fragments. This allows for further improvement of the process. This is because the addition of cultured corals can amplify the natural restoration process. The amplification is caused by the increase in the recruitment rate of new corals. This approach should accelerate the recovery process for the reef system (Moeller, Nietzer, & Schupp, 2019).

3.4.4 THE HOLISTIC APPROACH

This method tries to encompass all known methods of artificial reef creation and combine them in a single approach. This holistic approach ensures a versatile use case that can be used in all types of marine environments. In a nutshell, this method involves the introduction of hard substrate structures in low-quality conditions combined with rubble fixation and the addition of farmed corals, microfragmentation and the introduction of wild-harvested coral offspring (Ceccarelli, et al., 2020; Bayraktarov, et al., 2019; Doropoulos, et al., 2019). In the following texts, this holistic approach to artificial reef creation will further be explained

As mentioned earlier, this method uses the introduction of a hard substrate or the stabilization of (coral) rubble for creating a hard substrate. The hard substrate is then used as a foundation for the creation of the artificial coral reef. The hard substrate could consist of the earlier mentioned methods of the introduction of concrete or rock structures, the creation of a new shipwreck by sinking a prepared ship hull or the fabrication of a steel rebar structure called a coral star. Whichever way the reef structure is formed, ultimately these hard substrate allows for the attachment of coral fragments. These coral fragments can then grow into full-sized colonies and in turn, can attract more natural coral recruits, allowing for the development of a genetically diverse artificial reef.

Figure 12 The MARS - method demonstrated within this image is a prime example of a holistic approach to coral restoration (MARRS, 2023)

One way to produce these coral fragments is by the process of microfragmentation, also known as microfragging. This is a technique used to increase coral cover and promote the growth of corals in degraded reef ecosystems (Vaughan, 2021). It involves the fragmentation of larger coral colonies into small fragments, typically less than 5 cm^2 in size (Mostrales, Rollon, & Licuanan, 2022). These microfragments are then closely transplanted onto a substrate, such as ceramic tiles or concrete modules, in a high-density arrangement, usually with a spacing of 1 to 2 cm between fragments, see Figure 13. The goal of microfragmentation is to take advantage of the high productivity and potential fusion of these smaller coral fragments (Vaughan, 2021). By closely spacing the microfragments, the growth and fusion of adjacent fragments are encouraged, allowing for the rapid formation of new coral colonies.

Microfragmentation offers several advantages over conventional transplantation methods. Firstly, it allows for the mass production of corals from potentially fewer parent colonies, maximizing the use of available coral material. Additionally, the proximity of microfragments accelerates the coverage of large substrate areas, making it more efficient in terms of time and effort compared to traditional transplantation approaches. Moreover, microfragmentation can be applied to various substrates, including three-dimensional structures like artificial habitats or specially designed ceramic and cement plugs, further enhancing its versatility and potential applications (Mostrales, Rollon, & Licuanan, 2022).

Microfragging is particularly useful for increasing the cover of massive corals and other growth forms that are often overlooked in traditional transplantation approaches, which mainly focus on fast-growing branching corals like Acropora species. Massive corals are the cornerstones of the reef. Without these giant structures, the reef would be too unstable and will turn back into a rubble cascade of broken branches. For the introduction of branching coral, the conventional transplantation methods seem more appropriate. Hence a combination of these two methods seems to be the most optimal way to create the artificial reef within this approach (Hernández-Delgado, Mercado-Molina, & Suleimán-Ramos, 2018; Vaughan, 2021).

Figure 13 An example of microfragmentation at one of the coral growbeds at Mote Marine Laboratory, Florida

A booster could be given to the artificial reef by injecting it with a coral spawn slick. When corals reproduce, they release their gametes into the surrounding water. These gametes float to the surface and form a thin, oily film known as a spawn slick. This substance then floats away by hitching a ride on oceanic currents. These oceanic currents in turn carry the fertilized coral eggs and developed *planula* across vast distances. Around 99% of the offspring are eaten or otherwise perish during this trip (Schmidt-Roach, Duarte, Hauser, & Aranda, 2020). Only a few individuals can find a suitable location to settle in and evolve into mature specimens. If the spawn slick could be harvested and deployed within a new artificial reef it could greatly increase both the species and genetic diversity of the newly formed reef.

The successful collection of this spawn is described in a method developed by Doropoulos et al. (2019). In the aforementioned study, the collection, storage, and survival of spawn slicks are addressed. The method describes the harvesting of wild coral slicks, followed by their deployment in newly formed reef structures to enhance the ecosystem. Additionally, satellite-based models have been created to detect these slicks efficiently (Yamano, Sakuma, & Harii, 2020). This technology facilitates the rapid identification and capture of slicks, allowing for their distribution to artificial reefs. This could significantly bolster the resilience of the created artificial reef.

Figure 14 A step-by-step image where the harvesting of coral spawn slick is illustrated. (A) shows the localization of the spawn slick; (B) Shows the containment of a spawn slick; (C) Collection onto the tugboat; (D) Overview of the back deck of the tugboat with several 4500-litre tanks made of steel and plastic (Doropoulos, et al., 2019).

To improve this holistic approach even further, intensive monitoring and adaptive management of the constructed reef should be conducted. This enables continuous learning, improvements and corrective actions to be made during the course of the reef's existence (Vaughan, 2021). With the aid of modern technology like remote sensing and advanced AI software, real-time data collection and analysis of the reef's health and progress can be gathered efficiently (Lamont, et al., 2022). The data collected not only informs adjustments to the reef structure and management practices but also contributes to a greater understanding of reef ecosystems and humanity's impacts upon them.

If monitoring is done along with the involvement of local communities and stakeholders in the planning and implementation process, then a local culture could be developed around sustainability that could foster a sense of ownership and responsibility, thus contributing to the reef's long-term continuity. Thus local involvement could be an essential addition to the entire reef-building method. If all these practices are considered when creating the artificial reef, then a genetically diverse, resilient and ecologically beneficial reef would be created. This could then augment and preserve the valuable marine ecosystem that is a coral reef.

3.5 ECONOMICS OF CORAL REEF KEEPING

The costs of restoration projects and attempts are most often widely overlooked (Abrina & Bennet, 2021) *this breaks rule 10, according to the restoration rules stated by Quigley, Hein, & Suggett (2022). This rule suggests that restoration efforts should eventually produce economic gain. Otherwise, large-scale investors will stay away and without large-scale investors there will not be any restoration on large scales because of lack of funding. Therefore this section will explore the financial considerations that come into play with artificial coral reef projects. While the overall goal of artificial reefs is the restoration of marine biodiversity and coastal protection, the implementation of these projects also requires substantial financial investment* (Bayraktarov, et al., 2019)*. This section seeks to analyze the costs associated with coral reef restoration projects.*

3.5.1 OVERVIEW OF THE COST ASSOCIATED WITH ARTIFICIAL CORAL REEFS

Factors that could influence the cost are the amount of manual labour, the duration of the project, material cost and techniques used. According to the study of Bayraktarov, et al. (2019), which is an analysis of a multitude of other studies that report on the financial costs of reef keeping, the median cost of a coral restoration process is roughly 404,147 US$/ha, with the project's spatial extent averaging 0.01 ha. The costs associated with artificial coral reef projects vary substantially depending on the restoration technique employed. For instance, the substrate addition-artificial reef method ranks as the most expensive, with a median cost of 3,300,000 US$/ha. In contrast, the collection and nursery phase of the coral gardening approach proves to be the most cost-effective, with a median cost of 28,000 US$/ha. Nevertheless, cost estimates across different techniques can vary enormously, ranging from as low as 6,000 US$/ha up to 143,000,000 US$/ha.

3.5.2 COSTS PER METHODS

because of the different techniques employed by each ARC method, the cost of the different methods varies widely. To get an idea of the cost of each artificial reef creation method mentioned in this study a summarization has been made in Table 2. The table is made by adapting the results of Bayraktarov, et al. (2019) and the inclusion or exclusion of different techniques employed by each method. The crosses imply which costs are added to the total cost of the method per ha. The median costs were used instead of the mean costs because of the large variation in cost.

Table 2: Overview of the costs of different restoration techniques. Adapted from (Bayraktarov, et al., 2019)

Restoration technique	Method 1	Method 2	Method 3	Method 4
Direct transplantation		x	x	x
Larval enhancement			x	x
Coral gardening		x	x	x
Substrate addition with artificial structures	x	x		x
Substrate stabilization			x	x
TOTAL COST PER METHOD	$914.755	$1.043.687	$601.373	$1.516.128

3.5.3 FUNDING SOURCES AND ECONOMIC CHALLENGES

There is a variety of ways to fund artificial reef projects. One of these methods is the involvement of large-scale businesses (Lamont, et al., 2022). These large-scale businesses and industries can upscale global reef restoration efforts. Key challenges, such as translating local successes into global outcomes and securing long-term funding, can be addressed by these entities due to their financial stability. They can navigate hurdles like language barriers and manage long-distance collaborations, often difficult for smaller projects. These businesses can engage diverse partners across industries and geographies, enabling context-specific restoration efforts. Moreover, they have the potential to galvanize public engagement and awareness. However, care must be taken to prevent 'greenwashing', ensuring genuine intent behind their environmental sustainability claims (Lamont, et al., 2022). Properly managed, large businesses can be central in driving global reef restoration, melding financial stability, international partnerships, and community engagement.

Another promising source of funding for artificial reef projects is ecotourism and resort hotel investments. The global tourism industry, particularly in regions with coral reefs, can play a significant role in supporting the creation and maintenance of these reefs (Bayraktarov, et al., 2019). Ecotourism, defined as "responsible travel to natural areas that conserves the environment and improves the well-being of local people" (TIES, 2023) has the potential to provide a substantial financial boost to reef restoration efforts. Hotels and resorts in these areas, as they directly benefit from healthy and vibrant reef ecosystems attracting tourists, also have a vested interest in maintaining and restoring them.

Resorts may allocate part of their income to reef restoration efforts, making it a mutually beneficial relationship for both the environment and the tourism industry (Scott, Gössling, & Hall, 2012). This strategy also supports local economies and provides incentives for ongoing maintenance and conservation of the reefs. Such collaborations should, however, aim to prioritize ecological balance over commercial interests, avoiding potential overuse or misuse of the reefs due to tourism activities.

Another funding method is the funding by governmental funding or donation. This would result in a situation like in Australia where national parks are created within the waterfront like the world-famous great barrier reef. Such a protected ecological zone could draw in tourists and should allow for an increase in sustainability

3.5.4 BENEFITS OF AN ARTIFICIAL REEF

One of the primary economic benefits of artificial reefs is the stimulation of local tourism industries. Artificial reefs attract divers, snorkelers, and eco-tourists, contributing to increased spending on accommodation, food, and related services (Scott, Gössling, & Hall, 2012) and coastal protection (Ferrario, et al. 2014; Bayraktarov, et al. 2019; Kim, et al. 2022). Hotels and resorts that contribute to reef creation can also benefit indirectly through increased tourist attractiveness. Visitors are drawn not only to the reefs themselves but also to the wider ecosystem services they support, thus creating a positive feedback loop for the local economy. This tourism boost often leads to job creation and revenue growth in local communities, which allows for coastal areas to increase their income from tourists.

Besides this the increase in coastal protection allows vulnerable coastal communities to survive the harsher storms and extreme weather events that are caused by climate change. This ensures that communities are less likely to be destroyed by these

Furthermore, artificial reefs serve as thriving hotspots of marine biodiversity, bolstering fish populations, and thereby augmenting local fisheries (Bayraktarov, et al., 2019). This, in turn, can support and enhance the socio-economic resilience of local communities, whose livelihoods often depend on these marine resources (Niggol Seo, 2021). By providing ample, sustainable fish stocks, artificial reefs can indirectly contribute to alleviating poverty, as they can help sustain and grow fishing-related businesses, including local seafood restaurants, market vendors, and associated service sectors.

Moreover, the reefs can act as buffers against the impacts of overfishing on natural reefs, providing alternative locations for fish to breed and mature. The improved fisheries also have the potential to open new employment opportunities, such as in ecotourism or conservation roles, contributing to a diversified local economy. Additionally, the reefs can serve as sites for marine research, further contributing to local and global understanding of marine ecosystems, their importance, and how to preserve them effectively. Thus, the implications of artificial reefs extend far beyond environmental benefits, intertwining ecological sustainability with social and economic prosperity (Bayraktarov, et al., 2019; Abrina & Bennet, 2021)

3.5.5 THE COST OF NOT DOING ANYTHING AND CLIMATE CHANGE IMPLICATIONS

Climate change poses substantial challenges to the cost-effectiveness of artificial reef deployment. With rising sea levels, increased storm activity, and other climatic disruptions, the initial investment and maintenance costs of these structures may see considerable escalation. For instance, the anticipated sea-level rise may necessitate the creation of higher or adjustable artificial structures to remain within the optimal light zone for coral growth, resulting in augmented costs (Vaughan, 2021). Likewise, intensified storm activity and increased ocean temperatures can lead to higher rates of coral bleaching and structural damage, necessitating additional investment in monitoring, repair, and coral rehabilitation (Hoey, et al., 2016). Further, ocean acidification—a critical impact of climate change—decreases the pH of the sea (Hoegh-Guldberg, Polocznaska, Skirving, & Dove, 2017), impairing the corals' ability to form their calcium carbonate skeletons, which might demand the implementation of costlier, more resilient materials or technologies to sustain artificial reefs.

Nonetheless, these financial considerations must be weighed against the potential cost of inaction. Failing to invest in artificial reefs could exacerbate the decline of natural reefs and associated ecosystem services, risking considerable socio-economic and environmental repercussions. The demise of reefs would lead to loss of coastal protection, causing increased coastal erosion and property damage, potentially leading to large-scale human displacement from coastal areas (Ferrario, et al., 2014). Moreover, the diminished fish stocks due to reef degradation would impact local fisheries, disrupting livelihoods and food security, particularly in regions heavily reliant on these resources (Bostrom-Einarsson, et al., 2020)

Therefore, while climate change may escalate the costs associated with the construction and maintenance of artificial reefs, these costs must be compared against the high economic, social, and environmental toll of not safeguarding these invaluable ecosystems in an era of rapidly intensifying climate change.

3.6 COST-BENEFIT ANALYSIS

Now that all the information for the creation of a coral reef has been summarized it is time to find out which method is best for artificial reef creation. This section will compare the four artificial creation methods and their effectiveness both on a financial level and on an ecological value level. The results will be summarized in this section.

3.6.1 SUMMARY

Before diving into the analysis, let's recap what an optimal site for artificial reef creation should possess. The site should have a salinity of 34-37‰, temperatures between 21.7 and 29.6 °C, and be at water depths within 36 ± 5.6 meters due to limits of photosynthesis and limitations in diving depths. Other influencing factors include substrate quality, nutrient availability, human proximity, the influence of ocean currents, and location within a latitude of 35° north or south. There are various materials available for ARC, such as different types of concrete, steel structures, and ship hulls. A range of coral multiplication methods, including in situ and ex situ farming, microfragmentation, and larval capture, enhancement and distribution, could be utilized. This paper considers four methods for coral reef creation: Hard substrate introduction only, Coral Carpets, Reef Degradation Reversal, and the Holistic Approach.

3.6.2 ANALYSIS

The cost-benefit analysis has been conceived by comparing a variety of data sets and knowledge points adapted from a variety of studies (Abrina & Bennet, 2021; Bayraktarov, et al., 2019; Bostrom-Einarsson, et al., 2020; Ceccarelli, et al., 2020; Lamont, et al., 2022; Vaughan, 2021). Using the information in these studies combined with the information previously gather has allowed for the creation of Table 3. In the table, Method 1 is Hard substrate introduction only, Method 2 is Coral carpets, Method 3 is reef degradation reversal and Method 4 is the holistic approach. The scores in Table 3 range from 1 (best) to 4 (worst). The sum of the scores determines the overall ranking of the methods. The lower the score, the better the method.

This table shows that the introduction of hard substrate and reef degradation score well in projected costs and are therefore the cheapest options. Meanwhile, the holistic approach might be the most expensive but also gets the most promising results. Mainly because of the adaptability of the holistic approach it score in benefits is extremely high. The coral carpets method also scores high and comes in second place. The farming of the coral on ready-to-transport structures practised by this method ensures quick deployment and high survival rates, keeping costs lower than the holistic approach while still being outcompeted by methods 1 and 3 in costs.

Table 3: Overview of the costs-benefits analysis of different artificial reef creation techniques. Adapted from (Abrina & Bennet, 2021; Bayraktarov, et al., 2019; Bostrom-Einarsson, et al., 2020; Ceccarelli, et al., 2020; Lamont, et al., 2022; Vaughan, 2021). The scores range from 1 – 4, in which 4 is the worst and 1 is the best compared to the others. The sum of the scores then determines which one of the methods is the best. The lower the score the better. Method 1 is Hard substrate introduction only, Method 2 is Coral carpets, Method 3 is reef degradation reversal and Method 4 is the holistic approach.

Evaluation factor	Method 1	Method 2	Method 3	Method 4
Projected cost	2	3	1	4
Expected labour hours	1	2	4	3
Ecological benefit	4	2	3	1
Economic benefit	4	2	3	1
Environmental benefit	4	3	2	1
Score	**15**	**12**	**13**	**10**

4 DISCUSSION

The objective of this study was to investigate what types of methods there are for creating an artificial reef, how effective the different methods are and the most suitable location. The most successful reef-creation methods are explained using a literature review. Guidelines are given for creating artificial coral reefs. Additional information about project costs, the required amount of work and estimated effectiveness in enhancing local biodiversity was given. In this chapter, the conducted study will be discussed. The scope of this study, the results and their interpretation will be discussed first along with the implications for the field. Afterwards, the study method will be discussed along with the limitations of the study methods used. Finally, a critical note will be given on the implications for the field.

4.1 RESULTS

In this section of the chapter, the results will be discussed by having a paragraph for each sub-question. This method should allow for each section to be read separately without reading the entire discussion. This should ease the finding of the information searched by the reader.

4.1.1 SUB-QUESTION 1: WHAT ARE SUITABLE LOCATIONS FOR ARTIFICIAL REEF DEVELOPMENT?

In the first sub-question asked within this study the selection of a proper site has been researched. The results of this research show that an artificial reef should be created in optimal conditions. There are a multitude of studies that have discussed the ranges of these parameters. Reported in this study was a salinity between 34-37‰ and a temperature of 21.7—29.6 °C. These values are close to temperatures reported in other studies as reported by Cyronak, et al. (2022), Foo & Asner (2020) and Guan, Honh, & Merico (2015) who have found an average of 21.3—30.1 °C. Logically it could be argued that the optimal range for artificial reef creation is within this range.

There is however a caveat to these values as they do not take into account the effects climate change will have on these ranges. Earlier on, in Chapter 1, it was mentioned that global ocean temperatures rise by an average of 0,045 °C per year (Cheng, et al., 2022). If we do a quick napkin calculation this would mean that in the year 2100 ocean temperatures would have increased by 3,51 °C. For a future-proof artificial reef, this doomsday scenario has to be taken into account with a bit of margin. Taking the temperature rise of 3,51 °C into account, currently developed coral reefs should be placed in water no warmer than 27,0 °C (because 27,0 + 3,51 = 30,51 °C). Therefore it could be argued that the annual average temperature range of the area must be between 21,0 °C and 27,0 °C when searching for an optimal location for reef development.

In the study of Foo and Asner (2020), it is mentioned that temperature, depth and pH are correlated. Salinity in turn is connected to temperature, pH and precipitation as mentioned by Guan, Honh, & Merico 2015. Since climate change could increase or decrease precipitation and ocean acidification lowers the pH value, it could be argued that the range of 34-37‰ is not optimal for the future-proofing of new coral reef systems. Since this study used a dataset from around the world and compared the results with a similar study it could be stated that this is a common fact. The general consensus still seems to be that the salinity should range around 35‰ ±2,5‰ (Cyronak, et al., 2022; Kleypas, McManus, & Menez, 1999). However, Guan, Honh, & Merico's research from 2015 suggests a brother salinity range of 28,7‰ and 40,4‰ and thus a wider range of salinities could also be accepted, but could be less preferable because of the unpredicdable effects of climate change.

Since the pH is correlated to the aforementioned factors, the pH range of 7,6 and 8,7 was mentioned as an optimal range within this study. When reflecting on the aforementioned pH values it is vital to also consider climate change. One of the main effects is not only an increase in ocean temperature, but also an increase in ocean acidity because of elevated CO_2 levels. Since most coral reefs thrive within a stable pH level of 8,3 ±0,3 (Bove, Whitehead, & Szmant, 2022), areas with already lower pH values than average should be avoided for artificial reef development.

Other factors that have been shown to influence site selection within this study include depth, substrate quality, nutrient availability, human proximity, ocean current and latitude. Aside from depth which is correlated to light availability and light penetration and nutrient availability, the other values seem to be less influential to site selection than temperature, salinity and pH value. Therefore the ranges mentioned within this study of the values of substrate quality, human proximity, ocean current and latitude could be taken as guidelines rather than hard limits as is the case with temperature, light availability and correlated depth, nutrient availability salinity and pH value.

4.1.2 SUB-QUESTION 2: WHAT ARE SUITABLE MATERIALS FOR ARTIFICIAL REEF CREATION?

The materials that were mentioned within this study only skim the surface of (new) materials that are suitable for artificial reef creation. Since the time to conduct this study was limited it should be mentioned that some subjects have received more research than others. This subject was one of the subjects that has excellent other research written about it, hence the choice was made to only briefly go over this subject. The materials found include steel structures, new types of concrete and stripped ship hulls. The main killing point for materials seems to be toxicity and structural integrity. For a more in-depth view of material choice and material placement the book Active Coral Restoration: Techniques for a Changing Planet written by field expert Dr. David Vaughan (2021) could be read.

4.1.3 SUB-QUESTION 3: WHICH MULTIPLICATION METHODS ARE SUITABLE FOR ARTIFICIAL REEF CREATION?

In this study, a variety of coral species for propagation and propagation methods of these corals were mentioned. There are of course many more propagation methods that are not mentioned within this study. As mentioned before the time to conduct this study was not limitless. Concessions had to be made about what subject to delve into deeply and what subject would be worth a study of its own. This subject is definitely one of the subjects that are worth several studies and was therefore chosen to be a summarization of results and should be used as an indication of what to do and choose so that the following building methods could be better understood.

Suitable species for quick and stable settlement are deemed vital for the longevity of a coral reef. Having said that it is also crucial to note that while Table 1 includes multiple species, countless others exist. The primary selection criteria should be the species' native status to the project's target area. It is deemed logical that multiple species should be used to enhance the resilience of the created reef. This will contribute to the structural complexity, which in turn provides various niches for a wealth of marine organisms, this diversity in turn enhances the reef's resilience (Vaughan, 2021; Quigley, Hein, & Suggett, 2022).. Monocultures in agriculture, forestry and mariculture are known to have stability issues, the importance of biodiversity should not be underestimated (Quigley, Hein, & Suggett, 2022).

A side note on one of the multiplication methods called microfragmentation is that it is not without challenges. Mortality and dislodgement of microfragments can be significant concerns that need to be addressed for the method to be more widely applicable. Proper site selection, careful design of the intervention effort, and consideration of local environmental conditions are crucial for successful implementation. Ongoing research is also needed to evaluate the performance of microfragments from different coral genera, including those with different growth forms and life histories, and to compare the cost-effectiveness of microfragmentation with other coral restoration methods such as coral gardening and larval enhancement. Overall, microfragmentation holds promise as a versatile and potentially cost-effective approach to increase coral cover and restore degraded coral reef ecosystems. With further research and refinement, it has the potential to contribute significantly to the conservation and restoration of coral reefs worldwide.

4.1.4 SUB-QUESTION 4: WHAT ARE THE DIFFERENT ARC METHODS FOR CREATING AN ARTIFICIAL REEF?

This question was one of the key questions researched in this study. Therefore it has received a lot of attention in both research and selection and could be considered the main focus of this study together with site selection. The ARC methods mentioned within this study have been selected because they are relatively distinct from one another. There are countless variations on each method and so a generalization of the results had to be made to keep it remotely comprehensible for the average reader. The four methods shown in the results are the introduction of a hard substrate, coral carpets, reef degradation reversal and the holistic approach. Each method has its benefits and downsides which will be discussed below.

The introduction of a hard substrate without the attachment of corals is by far the cheapest option (when waste materials are used) and is relatively easy to implement. There is however one problem with the introduction of hard substrate without any addition of coral fragments or other forms of coral recruitment enhancers. The maturation process of these structures takes years or even decades (Vaughan, 2021; Tran & Hadfield, 2013) and the method itself is a relatively passive approach to artificial reef creation. Once coral colonists finally settle on these artificial structures it can take several decades before the reef is mature enough that it can support a similar ecosystem functionality as a natural accruing reef. It is therefore not suitable as the sole solution to the degrading reefs situation but could be useful for smaller budgets

The second ARC method discussed is the formation of coral carpets. The study by Golomb, Shashar, & Rinkevich (2020) reveals that the aforementioned method represents a viable option for establishing coral reefs in sandy environments lacking suitable hard substrates. However, due to the novelty of this approach, long-term effects have not been thoroughly investigated, thus precluding definitive assessments regarding the longevity of this method.

The third distinct method researched within this paper was the restoration of degraded parts of locations where a prosperous reef was previously located. The method uses cheap steel rebar or other widely available materials and is, therefore, the cheapest to implement. This versatility along with the success rate of these projects and proven longevity means that this method is applicable in a lot of locations. It does however diverge slightly from the goal of this paper which is to create a coral reef where the was none to begin with. It is however still mentioned within this study because de restoration of coral reefs is equally important – if not more important – to the preservation of the world's coral reefs.

The last method that was shown in the results is the holistic approach, a method that not only takes into consideration project costs and ecological benefits but also takes into account socioeconomic benefits and the local community. Because of the versatility of this method, it could be used in all types of situations. It is however also highly dependent on experts which are often expensive this can be seen in the projected cost for these types of restorations. The effects of the proposed harvesting and subsequent distribution of coral spawn slicks have yet to be studied (Doropoulos, et al., 2019) and this practice could therefore not be advised yet. Overall the methods mentioned in this study show great promise and could certainly be used in the field for promising results.

4.1.5 SUB-QUESTION 5: HOW COULD AN ARTIFICIAL REEF PROJECT BE FUNDED?

The funding of coral projects has been proven to be an elusive subject. A lot of studies don't mention their cost and expenses. As found by Bayraktarov, et al. (2019) only 17.3% of these studies report on project costs, and even fewer, around 14.3%, provide a detailed breakdown of restoration components included in these costs. This discrepancy implies the real total project cost could be higher, considering that merely 38% of the studies reported both capital and operating costs. The cost reported per method where adapted from another study conducted by Bayraktarov, et al. (2019) by refitting their data to fit the methods described in this paper better. Different methods for cost evaluation could have been used but this method was chosen for clarity's sake.

4.1.6 COST-BENEFIT ANALYSIS

The cost-benefit analysis conducted in this paper, although effective in comparing various ARC methods, is more basic in nature compared to those presented in other studies (Abrina & Bennet, 2021; Bayraktarov, et al. 2019; Bostrom-Einarsson, et al. 2020). However, this was intentional as the primary objective of this study was not to determine the absolute best methods but to explore and contrast the different ARC methods available.

When this study was initiated in early 2020, many of the papers that have since informed our research were not yet published, highlighting the rapid development and continuous evolution of this field. The knowledge gap in 2020 was more significant than it is now in 2023. This serves to emphasize the dynamism of the field of coral reef restoration and creation, showing that it is an industry in constant improvement, driven by continuous and intensive research.

4.2 METHOD EVALUATION AND SCOPE AND LIMITATIONS OF THE STUDY

Through a literature review, the different ways to create artificial coral reefs were shown along with a minor analysis on which method is best. The current study combines information from many separate studies. Because the information was gathered from different, international studies, the interpretation of some terms can differ. Depending on the study, there may be a different interpretation of when a coral reef is restored or sustainable, thus leading to differences that are merged. During the literature review, care was taken as much as possible to ensure that the assumptions about sustainability and coral reef restoration were in line with Dutch reference values.

The studies used within this study were mainly conducted all over the world but concentrated on locations where coral reefs are already present. Because of this, the results of this study are designed to be applicable within the tropical regions of the world where coral reefs are most prevalent. Nevertheless, this is a general exploration and the local environment may differ from site to site. The local situation and its assumptions should always be taken into account when applying research results.

Within this research, the focus was on the locations and methods for creating an artificial reef. The location is essential to the chances of success in establishing an effective artificial reef (Vaughan, 2021). Because widening the study, in this case, would detract from the quality, the choice was made to include the other sub-questions about the building material and *in situ* and *ex situ* coral multiplication to a minimal extent. For a comprehensive guide to coral farming, the studies of Barton, Willis, & Hutson (2015) and the book Active Coral Restoration: Techniques for a Changing Planet written by David Vaughan (2021) can be read. In some cases, a more extensive analysis of these factors could have led to a better interpretation of the other literature results.

The research findings from different researchers were not always uniform. It became clear that there is a major influence of environmental factors on the results. For this reason, only results were incorporated on which there was agreement among the majority of researchers. The studies were also sometimes found as citations within other studies. The amount of used searched terms is therefore rather limited. Aside from these changes, there were no changes and the method was used as mentioned in §2.1 without any discrepancies.

4.3 IMPLICATIONS OF THE RESULTS OF THIS STUDY

The results of this study are of particular value to practitioners with less experience. The results are intended for people interested in coral restoration and are specifically designed to be read by people working in policy-making positions in governments or other organisations involved in decision-making and for people who want to construct an artificial reef. The cost-benefit matrix is set up so that personal preferences could be made. For instance, if budgetary constraints are more important to the project than results then a higher place could be assigned to this specific value. It is made understandable even to people who are not well-versed in ecology and other relevant scientific knowledge. The matrix leads to a well-informed decision on the protection, creation and continuation of coral reefs.

5 CONCLUSIONS AND RECOMMENDATIONS

The concluding chapter of this study synthesizes findings to answer the primary research question: How can a thriving artificial reef be created and sustained? This chapter reviews suitable locations for reef establishment, optimal materials for construction, effective multiplication methods, varied building options, and feasible funding models. Following the comprehensive analysis of gathered data, it proceeds to provide definitive answers to the earlier posed questions. By doing so, it aims to offer a clear framework for what to consider when creating and maintaining a successful artificial reef.

5.1.1 QUESTION 1: WHAT ARE SUITABLE LOCATIONS FOR AN ARTIFICIAL REEF?

In light of the information gathered it's evident that the development of an artificial coral reef requires careful consideration of various environmental parameters. These parameters include temperature, salinity, pH, nutrient availability, depth, light penetration, substrate quality, and human influences. A suitable location for artificial reef development should possess a salinity range of 34-37‰, while areas with a high influx of freshwater are not advised. A temperature range between 21.0—27.0 °C is deemed healthy for coral reefs with adverse effects shown for temperatures exceeding 30.5 °C.

When considering depth, ideal locations should be within 0 to 36 ± 5.6 meters of water depth due to light penetration requirements for photosynthesis. Practical considerations also come into play with scuba diving depths ideally within 0 and 18 meters, ensuring ease of installation and maintenance of the artificial reef. In terms of substrate, most corallites need a solid, stable substrate for attachment, with some being able to form on sand-like sediment deposits.

Nutrient availability, particularly nitrate (NO_3) and phosphate (PO_4), also plays a crucial role, with excess nutrient levels resulting in algal outbreaks that may outcompete corals. Proximity to human populations, rather than remote areas, can enhance coral reef resilience due to adaptation to human-induced environmental changes. Ocean currents and latitudes play a role in the variability of water temperature with the most suitable coral formation latitudes between 35° and -35°. Finally, light availability, measured as Photosynthetically Active Radiation (PAR), should be around 450 µmol photons m^{-2} s^{-1} for a healthy coral reef. According to estimates, roughly a third of suitable locations for reef development globally do not contain natural reefs, implying potential sites for artificial reef realization.

The successful creation of an artificial coral reef requires a comprehensive understanding of the aforementioned diverse environmental factors, careful selection of appropriate locations, and careful intervention to ensure that these ecosystems flourish. This only underlines the importance of scientific research in guiding conservation efforts and human intervention in preserving these vital ecosystems.

5.1.2 QUESTION 2: WHAT MATERIAL IS BEST SUITED TO CREATE AN ARTIFICIAL REEF?

Material selection for artificial reef development significantly influences the success and environmental sustainability of the reef. The chosen material must be resilient to marine conditions, non-soluble, cost-effective, and biocompatible. Promising materials include Mineralized Cellulose Materials (MCM), new artificial reef concrete (NARC), Green artificial reef concrete (GARC), and repurposed heavy metal objects. Each offers unique benefits: MCM serves as a carbon sink, NARC offers improved durability and workability, GARC shows marine-resistant properties and provides a good substrate for marine life, while repurposed metal objects provide a stable and immobile foundation. Despite these benefits, further research is needed to ensure the long-term ecological safety of these materials. Therefore, the choice of materials in artificial reef construction must consider both immediate benefits and long-term impacts on marine ecosystems.

5.1.3 QUESTION 3: WHICH MULTIPLICATION METHODS ARE SUITABLE FOR CREATING AN ARTIFICIAL REEF?

Suitable species for quick and stable settlement are deemed vital for the longevity of a coral reef. It is deemed logical that multiple species should be used to enhance the resilience of the created reef. Monocultures in agriculture, forestry and mariculture are known to have stability issues. Biodiversity is an important factor in any stable ecosystem, hence different suitable species must be used for the best chance of survival. Species that could be used should be relatively easy to propagate to have enough of them to colonize the bare structure that will be built. Besides this, different growth forms are also vital for reef creation; If only branching corals are used the reef is more prone to erode during extreme weather events.

5.1.4 QUESTION 4: WHAT ARE THE DIFFERENT BUILDING OPTIONS FOR CREATING AN ARTIFICIAL REEF?

The four methods of artificial reef creation found are the introduction of hard substrate without coral transplanting, coral carpets, reef degradation reversal and the holistic approach. The four approaches offer a diverse array of techniques, each with unique benefits and limitations. These benefits can range from cost effectiveness to easy of implementation.

The introduction of hard substrates without coral transplanting provides a durable, long-lasting structure for marine life colonization, utilizing materials such as steel ship hulls and concrete structures which possess a slow corrosion rate, thereby ensuring a stable structure for long-term ecological development (Vaughan, 2021; Hudatwi, et al., 2021) but is slow in colonization rate and thus not suitable for all types of restoration projects.

Coral carpets represent an innovative approach, leveraging pre-assembled "sods" of coral fragments and binding materials to expedite the growth and survival of new coral colonies, which shows promise in restoring degraded reefs more quickly and effectively then the aforementioned method (Golomb, Shashar, & Rinkevich, 2020). The novely of this approach however still requires further research to establish its long-term efficacy and environmental impact

The reversal of reef degradation focuses on restoring damaged reef sections. This method requires considerable time for the natural succession processes to occur but promises the revival of the original ecosystem, provided anthropogenic disturbances are managed (Ceccarelli, et al., 2020).

Finally, the holistic approach combines elements from several methodologies to provide a comprehensive and versatile approach suitable for various marine environments (Ceccarelli, et al., 2020; Bayraktarov, et al., 2019; Doropoulos, et al., 2019). This method employs multiple techniques, including microfragmentation to foster rapid coral colony formation (Vaughan, 2021), and the utilization of coral spawn slicks to enhance species and genetic diversity (Schmidt-Roach, Duarte, Hauser, & Aranda, 2020). In addition to these biological aspects, it leverages modern technology for real-time data collection and adaptive management, which drives continuous improvement and responsiveness to changing conditions (Lamont, et al., 2022). Community involvement is also integrated into this approach, fostering local stakeholder buy-in and contributing to the long-term sustainability of these artificial reefs. Through its multi-pronged strategy, the holistic approach offers a comprehensive and adaptive method for the creation and maintenance of artificial reefs.

Moreover, the project duration also varies according to the technique employed. Substrate stabilization projects typically last the longest at two years, while projects using artificial reefs enhanced by electrical fields have the shortest duration at 0.3 years. In terms of spatial extent, the techniques of larval enhancement and substrate addition cover the most significant areas (Bayraktarov, et al., 2019). If fast action is necessary these time restrictions need to be taken into consideration as well.

Ultimately, the choice of method depends on specific local conditions, resources available, and restoration objectives. However, a combination of these methods might offer the most resilient and effective solutions for various challenges faced in coral reef restoration. The best building method is one that is specific to the area in which the artificial reef will be created (Ceccarelli, et al., 2020)

5.1.5 QUESTION 5: HOW COULD AN ARTIFICIAL REEF BE FUNDED?

Funding artificial reef projects is essential for their successful implementation and long-term viability. There is a variety of funding methods, including the involvement of large-scale businesses, reef adoption, ecotourism, local hotel investment and government funding. Collaboration with local communities and prioritizing ecological and economic balance are vital for sustainability. The costs associated with coral reef restoration projects can vary significantly depending on factors such as the restoration technique, labor, duration, and materials used. This variation in costs could lead to spiralling expenses and ultimately result in project shutdown due to lack of funds. Therefore the funding should be tackled from multiple angles and would preferably be as diverse as possible. Understanding these financial considerations is crucial for effective planning and the implementation of coral restoration and creation projects.

5.2 ANSWER TO THE MAIN QUESTION AND SUMMARISED RECOMMENDATIONS

There is a variety of ways to create, develop, fund and maintain artificial reefs. There is no one size fits all approach to coral reef creation. An approach that is holistic in nature and considers financial, ecological, and socio-economic aspects appears to be the most effective for the creation of artificial reefs. Using this method will ensure that the longevity of the created coral reef is maintained and should ensure that future generations might still enjoy the beauty and wonder of coral reefs as well as their economic benefits.

Furthermore, it's vital to remember that the creation of artificial reefs must be done in conjunction with, and not as a replacement for, the conservation and restoration of natural coral reefs. The best way to ensure the survival of coral reefs is to alleviate the pressures they face, such as climate change, anthropogenic effects and pollution. Thus, artificial reefs should be seen as one of many tools in our arsenal to support, augment and preserve our marine ecosystems.

In the current situation, where the presence of natural coral reefs declines, it is important to invest in developing artificial coral reefs. To continue the development of artificial reefs, the following recommendations have been drawn up:

- It should become a global priority to free up funds to build artificial coral reefs in water between 21 and 27 degrees Celsius. The diversification of funding is therefore considered crucial to the success rate of artificial reef projects
- Efforts should be made to invest in research and education to understand the diverse environmental factors necessary for successful artificial reef creation.
- Efforts should be made to continue and enhance research efforts on the long-term ecological impacts of various materials used in artificial reef construction.
- Efforts should be made to conserve current coral reefs by combating anthropogenic effects such as climate change and alleviating human pressures like overfishing and pollution.
- Additional research on the course of ocean temperature rise in the future is desirable.
- Additional monitoring of successful restoration efforts should be conducted.

6 REFERENCES

Abrina, T. S., & Bennet, J. (2021). A benefit-cost comparison of varying scales and methods of coral reef restoration in the Philippines. *Science of The Total Environment*(Volume 799), 149325. doi:10.1016/j.scitotenv.2021.149325.

Allen Coral Atlas. (2023, Februari 13). *Allen Coral Atlas*. Retrieved from AllanCoralAtlas.org: https://allencoralatlas.org/atlas/#11.40/-2.9629/108.3144

Barton, J. A., Willis, B. L., & Hutson, K. S. (2015). Coral propagation: a review of techniques for ornamental trade and reef restoration. *Reviews in aquaculture*, 238-256. doi: https://doi.org/10.1111/raq.12135

Barton, J. A., Willis, B. L., & Hutson, K. S. (2015). Coral propagation: a review of techniques for ornamentaltrade and reef restoration. *Reviews in Aquaculture*, 1-19.

Baumann, J. H., Zhao, L. Z., Stier, A. C., & Bruno, J. F. (2021). Remoteness does not enhance coral reef resilience. *Global Change Biology*, 417-428.

Bayraktarov, E., Stewart-Sinclair, P. J., Brisbane, S., Boström-Einarsson, L., Saunders, M. I., Lovelock, C. E., . . . Wilson, K. A. (2019). Motivations, success, and cost of coral reef restoration. *Restoration Ecology*, 981-991.

Bostrom-Einarsson, L., Babcock, R. C., Bayraktarov, E., Ceccarelli, D., Cook, N., Ferse, S. C., . . . McLeod, I. (2020). Coral restoration – A systematic review of Coral restoration – A systematic review of future directions. *PloS One*. doi:10.1371/journal.pone.0226631

Bove, C. B., Whitehead, R. F., & Szmant, A. M. (2022). Responses of coral gastrovascular cavity pH during light and dark incubations to reduced seawater pH suggest species-specific responses to the effects of ocean acidification on calcification. *Coral reefs 39*, 1675-1691.

Brown, B. E. (1997). Coral bleaching: causes and consequences. *Coral Reefs*, 129-138.

Butler, J. H., & Montzka, S. A. (2021, 11 23). *THE NOAA ANNUAL GREENHOUSE GAS INDEX (AGGI).* Retrieved from Global Monitoring Laboratory: https://gml.noaa.gov/aggi/aggi.html

Ceccarelli, D. M., McLeod, I. M., Boström-Einarsson , L., Bryan, S. E., Chartrand, K. M., Emslie, M. J., . . . Bay, L. K. (2020). Substrate stabilisation and small structures in coral restoration: State of knowledge, and considerations for management and implementation. *PLoS ONE 15(10): e0240846*, 1-27.

Cesar, H., Burke, L., & Pit-Soede, L. (2003). *The economics of worldwide coral reef degradation.* Zeist: Cesar Environmental Economics Consulting.

Chan, W. Y., Peplow, L. M., Menéndez, P., Hoffmann, A. A., & van Oppen, M. J. (2018, May). Interspecific Hybridization May Provide Novel Opportunities for Coral Reef Restoration. *FRONTIERS IN MARINE SCIENCE*(Volume 5). doi:https://doi.org/10.3389/fmars.2018.00160

Chen, C., Ji, t., Zhuang, Y., & Lin, X. (2015). Workability, mechanical properties and affinity of artificial reef concrete. *Construction and Building materials*, 227-236.

Cheng, L., Abraham, J., Trenberth, K. E., Fasullo, J., Boyer, T., Mann, M. E., . . . Reagan, J. (2022). Another Record: Ocean Warming Continues through 2021 despite La Niña Conditions. *Advances in Atmospheric Sciences*, 373-385.

Chuang, P.-s., & Mitarai, S. (2020). Signaling pathways in the coral polyp bail-out response. *Coral reefs*, 1535–1548.

Coralpedia. (n.d.). Coralpedia. *Coralpedia: Your guide to Caribbean coral and sponges*. Warwick, Great Britain. Retrieved May 23, 2023, from https://coralpedia.bio.warwick.ac.uk/

Cyronak, T., Takeshita, Y., Courtney, T. A., DeCarlo, E. H., Eyre, B. D., Kline, D. I., . . . Andersson, A. J. (2022). Diel temperature and pH variability scale with depth across diverse coral reef habitats. *Limnology and Oceanography Letters Volume 5, Issue 2*, 193-203.

Dias, M., Madeira, C., Jogee, N., Ferreira, N., Gouveia, R., Cabral, H., . . . Vinagra, C. (2019). Oxidative stress on scleractinian coral fragments following exposure to high temperature and low salinity. *Ecological Indicators Volume 107*, 105586.

Doropoulos, C., Vons, F., Elzinga, J., ter Hofstede, R., Salee, K., van Koningsveld, M., & Babcock, R. C. (2019). Testing Industrial-Scale Coral Restoration Techniques: Harvesting and Culturing Wild Coral-Spawn Slicks. *Frontiers in Marine Science*, 1-14. doi:10.3389/fmars.2019.00658

EPA. (2022, Februari 15). *Basic Information about Coral Reefs*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/coral-reefs/basic-information-about-coral-reefs

Ferrario, F., Beck, M. W., Storlazzi, C. D., Micheli, F., Shepard, C. C., & Airoldi, L. (2014, May 13). *The effectiveness of coral reefs for coastal hazard risk reduction and adaptation.* Retrieved from nature.com: https://doi.org/10.1038/ncomms4794

Ferrier-Pagès, C., Gattuso, J., & Jaubert, J. (1999). Effect of small variations in salinity on the rates of photosynthesis and respiration of the zooxanthellate coral Stylophora pistillata. *Marine Ecology Progress Series Vol.181*, 309-314.

Fisher, R., O'Leary, R. A., Low-Choy, S., Mengersen, K., Knowlton, N., Brainard, R. E., & Caley, M. J. (2015). Species Richness on Coral Reefs and the Pursuit of Convergent Global Estimates. *Current Biology*, 500-505.

Foo, S. A., & Asner, G. P. (2020). Sea surface temperature in coral reef restoration outcomes. *Environmental Research Letters, Volume 15, Number 7*.

Gates, R. D., Baghdasarian, G., & Muscatine, L. (1992). Temperature Stress Causes Host Cell Detachment in Symbiotic Cnidarians:Implications for Coral Bleaching. *The biological Bulletin Volume 182*, 324-332.

Golomb, D., Shashar, N., & Rinkevich, B. (2020). Coral carpets- a novel ecological engineering tool aimed at constructing coral communities on soft sand bottoms. *Ecological Engineering volume 145*, 105743. doi:https://doi.org/10.1016/j.ecoleng.2020.105743

Guan, Y., Honh, S., & Merico, A. (2015, June 1). *Suitable Environmental Ranges for Potential Coral Reef Habitats in the Tropical Ocean.* Retrieved from Plos One: https://doi.org/10.1371/journal.pone.0128831

Haarsma, M. (2023, May 23). *Grooved Brain Coral Diploria labyrinthiformis.* Retrieved from dutch caribbean species register: https://www.dutchcaribbeanspecies.org/linnaeus_ng/app/views/species/nsr_taxon.php?id=180256&cat=CTAB_MEDIA

hatch, M. D. (1987). photosynthesis: A unique elend of modified biochemistry, anatomy and ultrastructure. *Biochimica et Biophusica Acta (BBA) Reviews on Bioenergetics Volume 895 Issue 2*, 81-106.

Hernández-Delgado, E. A., Mercado-Molina, A. E., & Suleimán-Ramos, S. E. (2018). *Multi-Disciplinary Lessons Learned from Low-Tech Coral Farming and Reef Rehabilitation.* Intech.

Hilbertz, W. (1979, July). Electrodeposition of minerals in sea water: Experiments and applications. *IEEE Journal of Oceanic Engineering*, 94-113. doi:10.1109/JOE.1979.1145428.

Hoegh-Guldberg, O., Pendleton, L., & Kaup, A. (2019, June 3). *People and the changing nature of coral reefs.* Retrieved from ScienceDirect: https://doi.org/10.1016/j.rsma.2019.100699

Hoegh-Guldberg, O., Polocznaska, E. S., Skirving, W., & Dove, S. (2017, May 29). *Coral Reef Ecosystems under Climate Change and Ocean Acidification.* Retrieved from Frontiers in marine science: https://doi.org/10.3389/fmars.2017.00158

Hoey, A. S., Howells, E., Johansen, J. L., Hobbs, J.-P. A., Messmer, V., McCowan, D. M., . . . Pratchett, M. S. (2016, may 18). *Recent Advances in Understanding the Effects of Climate Change on Coral Reefs.* Retrieved from MDPI.com: https://doi.org/10.3390/d8020012

Houérou, H. N. (2008). *Bioclimatology and Biogeography of Africa.* international: Springer Science & Business Media.

Huang, X., Wang, Z., Liu, Y., Hu, W., & Ni, W. (2016). On the use of blast furnace slag and steel slag in the preparation of green artificial reef concrete. *Construction and Building materials*(112), 241-246. doi:https://doi.org/10.1016/j.conbuildmat.2016.02.088

Hudatwi, M., Syari, A., Utami, E., Nugraha, M. A., Akhrianti, I., & Pamungkas, A. (2021). Diversity of Benthic Organisms on Artificial Reef. *IOP Conf. Ser.: Earth Environ. Sci. 926 012033*, 926. doi:10.1088/1755-1315/926/1/012033

Hudson, T. (n.d.). A coral outcrop on the Great Barrier Reef, Australia. *A coral outcrop on the Great Barrier Reef, Australia.* Wikimedia Commons, Queensland.

Huston, M. A. (1985). Patterns of Species Diversity on Coral Reefs. *Annual Review of Ecology and Systematics Vol. 16*, 149-177.

IPPC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge university press.

IPPC WG1. (2022, februari 14). *Interactive atlas.* Retrieved from IPCC.ch: https://www.ipcc.ch/report/ar6/wg1/#InteractiveAtlas

IUCN. (2023, May 23). *Red list*. Retrieved from IUCN Red list: https://www.iucnredlist.org/species

Jones, R., Fisher, R., & Bessell-Browne, P. (2019, June 19). *Sediment deposition and coral smothering.* Retrieved from Plos One: https://doi.org/10.1371/journal.pone.0216248

Kim, Kim, T., Kwon, Y., Lee, J., Lee, E., & Kwon, S. (2022). Wave attenuation prediction of artificial coral reef using machine-learning integrated with hydraulic experiment. *Ocean Engineering*(Volume 248). doi:10.1016/j.oceaneng.2021.110324

Kleis, R. (2022, march 29). Koralenlarven kweken in het lab. *WAGENINGENWORLD 1*, pp. 16-17.

Kleypas, J. A., McManus, J. W., & Menez, L. A. (1999). Environmental Limits to Coral Reef Development: Where Do We Draw the line? *American Zoologie 39*, 146-159.

Kweku, D. W., Bismark, O., Maxwell, A., Ato Desmond, K., Danso, K. B., Oti-Mensah, A. E., . . . Adormaa, B. B. (2017). Greenhouse Effect: Greenhouse Gases and Their Impact on Global Warming. *Journal of Scientific Research & Reports*, 1-9.

Ladd, M. C., & Shantz, A. A. (2020). Trophic interactions in coral reef restoration: A review. *Food Webs*, e00149.

Lamont, T. A., Razak, T. B., Djohani, R., Janetski, N., Rapi, S., Mars, F., & Smith, D. J. (2022). Multi-dimensional approaches to scaling up coral reef restoration. *Marine Policy*, 105199. doi:10.1016/j.marpol.2022.105199

Lamont, T., Williams, B., Chapuis, L., Prasetya, M. E., Seraphim, M. J., Harding, H. R., . . . Simpson, S. D. (2022). The sound of recovery: Coral reef restoration success is detectable in the soundscape. *Journal of Applied Ecology*, 742-756.

Laverick, J. H., Tamir, R., Eyal, G., & Loya, Y. (2020, June 28). *A generalized light-driven model of community transitions along coral reef depth gradients.* Retrieved from Wiley: https://doi.org/10.1111/geb.13140

Lima, J. S., Zalmon, R. I., & Love, M. (2019). Overview and trends of ecological and socioeconomic research on artificial reefs. *Marine Environmental Research*, 81-96.

Lindsey, R., & Dahlman, L. (2021, march 15). *Climate Change: Global Temperature.* Retrieved from Climate.gov: https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

MARRS. (2023, May 23). *Section 2: Our solution*. Retrieved from buildingcoral.com: https://buildingcoral.com/our-solution

Miller, M. W., Hay, M. E., Miller, S. L., Malone, D., Sotka, E. E., & Szmant, A. M. (1999). Effects of nutrients versus herbivores on reef algae: A new method for manipulating. *Limnology and Oceanography 44 (8)*, 1847–1861.

Moeller, M., Nietzer, S., & Schupp, P. J. (2019, February 19). *Neuroactive compounds induce larval settlement in the scleractinian coral Leptastrea purpurea.* Retrieved from Scientific Reports: https://doi.org/10.1038/s41598-019-38794-2

Monroe, B. (n.d.). Coral Bleaching on the Great Barrier Reef in Australia. *Bleached coral on the Great Barrier Reef outside Cairns Australia during a mass bleaching event, thought to have been caused by heat stress due to warmer water temperatures as a result of global climate change.* Getty Images, Cairns, Queensland, Australia.

Mostrales, T. I., Rollon, R. N., & Licuanan, W. Y. (2022). Evaluation of the performance and cost-effectiveness of coral microfragments in covering artificial habitats. *Ecological Engineering*(Volume 184). doi:10.1016/j.ecoleng.2022.106770

Muscatine, L., & Porter, J. W. (1977). Reef Corals: Mutualistic Symbioses Adapted to Nutrient-Poor Environments. *BioScience, Volume 27, Issue 7*, 454-460.

Niggol Seo, S. (2021). *A Story of Coral Reefs, Nemo, and Fisheries: On Biodiversity Loss and Mass Extinction.* Chambridge: Palgrave Macmillan.

Oliver, T. A., & Palumbi, S. R. (2011). Do fluctuating temperature environments elevate coral thermal tolerance? *Coral Reefs (2011) 30*, 429-440.

PADI. (2022, December 28). Retrieved from www.PADI.com

Page, C. E., Leggat, W., Heron, S. F., Choukroun, S. M., Lloyd, J., & Ainsworth, T. D. (2019, June 19). *Seeking Resistance in Coral Reef Ecosystems: The Interplay of Biophysical Factors and Bleaching Resistance under a Changing Climate.* Retrieved from BioEssays Problems and Paradigms: https://doi.org/10.1002/bies.201800226

Plaisance, L., Caley, M. J., Brainard, R. E., & Knowlton, N. (2011, october 13). *The Diversity of Coral Reefs: What Are We Missing?* Retrieved from PLOS ONE: https://doi.org/10.1371/journal.pone.0025026

Quigley, K. M., Hein, M., & Suggett, D. J. (2022). Translating the 10 golden rules of reforestation for coral reef restoration. *Conservation Biology*(Volume 36). doi:10.1111/cobi.13890

Reyes, G., Vega-Coloma, M., Antonova, A., Ajdary, R., Jonveaux, S., Flanigan, C., . . . Rojas, O. J. (2023). Direct CO2 Capture by Alkali-Dissolved Cellulose and Sequestration in Building Materials and Artificial Reef Structures. *Advanced Materials*, n/a.

Roelvink, F. E., Storlazzi, C. D., van Dongeren, A. R., & Pearson, S. G. (2021). Coral Reef Restorations Can Be Optimized to Reduce Coastal Flooding Hazards. *Frontiers in marine Science*. doi:10.3389/fmars.2021.653945

Ross, J., Fisher, R., & Bessell-Browne, P. (2019). Sediment deposition and coral smothering. *PLoS ONE*. doi:10.1371/journal.pone.0216248

Roth, M. S. (2014). The engine of the reef: photobiology of the coral–algal symbiosis. *Fronties in Mircobiolgy*(5). doi:DOI=10.3389/fmicb.2014.00422

Ruppert, E. E., Barnes, R. D., & Fox, R. S. (2004). *Invertebrate zoology : a functional evolutionary approach.* Delhi: Cengage Learning.

Schmidt-Roach, S., Duarte, C. M., Hauser, C. A., & Aranda, M. (2020, january). Beyond Reef Restoration: Next-Generation Techniques for Coral Gardening, Landscaping, and Outreach. *Frontiers in Marine Science*(Volume 7: Article 672).

Schoepf, V., Stat, M., Falter, J. L., & McCulloch, M. T. (2015). Limits to the thermal tolerance of corals adapted to a highly fluctuating, naturally extreme temperature environment. *Scientific reports*(Volume). doi:10.1038/srep17639

Scott, D., Gössling, S., & Hall, C. M. (2012). *Tourism and Climate Change: Impacts, Adaptation and Mitigation. Routledge.* New York: Routledge.

Sheppard, C. R., Davy, S. K., Pilling, M. G., & Graham, N. A. (2018). *The Biology of Coral reefs.* Oxford: Oxford University Press.

Shlesinger, T. (n.d.). A coral spawns pinkish bundles of eggs and sperm, in the Red Sea, off the coast of Eilat. *A coral spawns pinkish bundles of eggs and sperm, in the Red Sea, off the coast of Eilat.* Reuters, New York.

Silbiger, N. (n.d.). Massive coral. *Macroborer presence on corals increases with nutrient input and promotes parrotfish bioerosion.* California State University, Northridge.

Spalding, M. D., Fox, H. E., Allen, G. R., Davidson, N., Ferdaña, Z. A., Finlayson, M., . . . Robertson, J. (2007). Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas. *Bioscience*, 573-583. doi:https://doi.org/10.1641/B570707

Sully, S., Burkepile, D. E., Donovan, M. K., Hodgsen, G., & van Woesik, R. (2019, februari 14). *A global analysis of coral bleaching over the past two decades.* Retrieved from nature.com: https://doi.org/10.1038/s41467-019-09238-2

Sweeney, A. M., Boch, C. A., Johnsen, S., & Morse, D. E. (2011). Twilight spectral dynamics and the coral reef invertebrate spawning response. *The Journal of Experimental Biology 214*, 770-777.

TIES. (2023, June 9). *What is Ecotoruism*. Retrieved from Ecotourism.org: https://ecotourism.org/what-is-ecotourism/

Tran, C., & Hadfield, M. G. (2013). Localization of sensory mechanisms utilized by coral planulae to detect settlement cues. *Invertebrate Biology*, 195-206.

Vaughan, D. E. (2021). *Active Coral Restoration : Techniques for a Changing Planet.* Fort Lauderdale: J. Ross Publishing Inc.

Werndl, C. (2016). On Defining Climate and Climate Change. *The British Journal for the Philosophy of Science*(Volume 67, number 2), 337-364.

Yamano, H., Sakuma, A., & Harii, S. (2020). Coral-spawn slicks: Reflectance spectra and detection using optical satellite data. *Remote Sensing of Environment*, 112058.

APPENDIX I: USED SEARCH TERMS

Coral reefs	*Hexacoralia* growth	Artificial reefs ecosystem
coral reef restoration	*Milleporina* growth	Reef biology
Coral growth	Stoney coral	Artificial reef materials
Coral Bleaching	Reef formation	Inert marine-grade materials
Scleractinia growth	Artificial reef	Marine biofilm creation
Coral recruiting	Micro fragging of coral	Coral mariculture
Genetic alteration of coral	Coral farming	Project barefoot
Reef highways	Reef buoys	Dredging impact on marine life
New artificial reef concrete	David Vaugahan	Coral species for propagation

Checklist Report Writing

1. Use of English
- ☐ Complies with grammar, spelling and style rules
- ☐ Has an active writing style
  →Active/Passive:
  "In this study, we investigated the effect of drug X on the serum levels of phosphorus under various conditions" with "In this study, the effect of drug X on the serum levels of phosphorus was investigated under various conditions."
- ☐ Is professional, formal and objective
  https://study.com/academy/lesson/writing-in-a-formal-objective-tone.html
- ☐ Is coherent (referral and linking words)
  https://www.english-at-home.com/grammar/linking-words/
- ☐ Has appropriate use of personal and possessive pronouns
- ☐ Is attuned to the chosen target group
- ☐ Has a uniform style

2. The organisation
- ☐ The report has a logical structure
- ☐ Each chapter has a logical paragraph structure

3. The report
- ☐ Has a uniform layout/format
- ☐ Has decimal chapter numbering and paragraph numbering with up to three digits
- ☐ Has titles and sub-titles with a fitting title
- ☐ Has an introductory passage in all chapters (except chapter 1)
- ☐ Has every new chapter starting on a new page
- ☐ Has pages that are numbered
  First in Roman then (from Introduction) normal page numbers
- ☐ Is free of plagiarism

4. Tables and figures
- ☐ Can be understood independently
- ☐ Supplement the text
- ☐ Have a fitting title (above the illustration)
- ☐ Are separately numbered (consecutive numbering)
- ☐ Have a reference to table/figure number in text

Report structure

5. The cover page
- ☐ Contains the title
- ☐ Contains the author(s)
- ☐ Contains the study programme or client, if relevant

6. The title page
- ☐ Contains the title
- ☐ Contains the author(s)
- ☐ Contains the place and date of publication
- ☐ Contains author affiliation

7. The preface
- ☐ Contains personal reason for writing the report
- ☐ Contains personal acknowledgements
- ☐ If applicable, describes the task division within the group

8. Table of contents:
- ☐ Contains all numbered parts (headings) of the report
- ☐ Contains summary, refrence list, and appendices
- ☐ Has a correct page reference

9. The summary
- ☐ Can be read and understood independently
- ☐ Is a concise version of the entire report
- ☐ Contains the conclusions and recommendations
- ☐ Includes suggestions for further research
- ☐ Does not contain any new information

10. The introduction
- ☐ Is chapter 1
- ☐ Describes the context and provides content relevant background information
- ☐ Contains the main research question
- ☐ Contains the sub-questions
- ☐ Includes the objective(s) of the report
- ☐ Includes the reader's guide

11. Materials and methods
- ☐ Describes the research method used
- ☐ Justifies the choice of the research method used
- ☐ Describes the research variables/units
- ☐ Describes the method of data analysis

12. Results
- ☐ Are presented in a structured manner
- ☐ Are analysed correctly

13. The discussion of results
- ☐ Includes the interpretation of the results
- ☐ Contains a comparison with relevant literature
- ☐ Valid argumentation is provided
- ☐ Evaluates the used research methods
- ☐ Contains a critical evaluation of own findings

14. The conclusions and recommendations
- ☐ Contains answer(s) to the main research question
- ☐ Are based on relevant facts
- ☐ Do not contain any new information

15. References
- ☐ References in the text are correct (conforms to APA standards)
- ☐ The reference list conforms to APA standards

16. The appendices
- ☐ Support the text
- ☐ Do not contain the author's own analyses
- ☐ Are referred to in text
- ☐ Are labelled with a capital letter, have a fitting title
- ☐ Are presented in a clear and readable manner