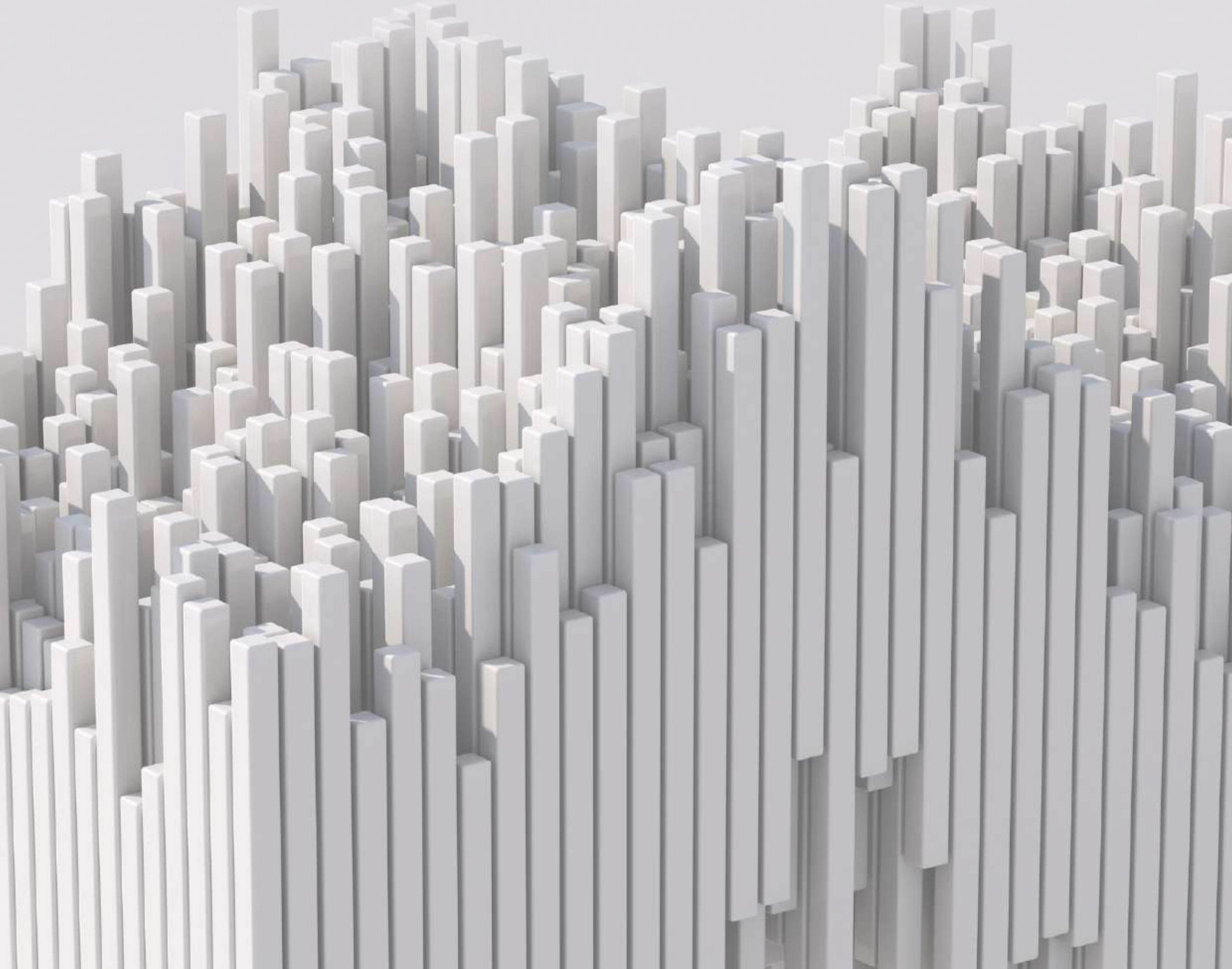
Infomatix

Investigating the carbon sequestration rates of artificial reefs



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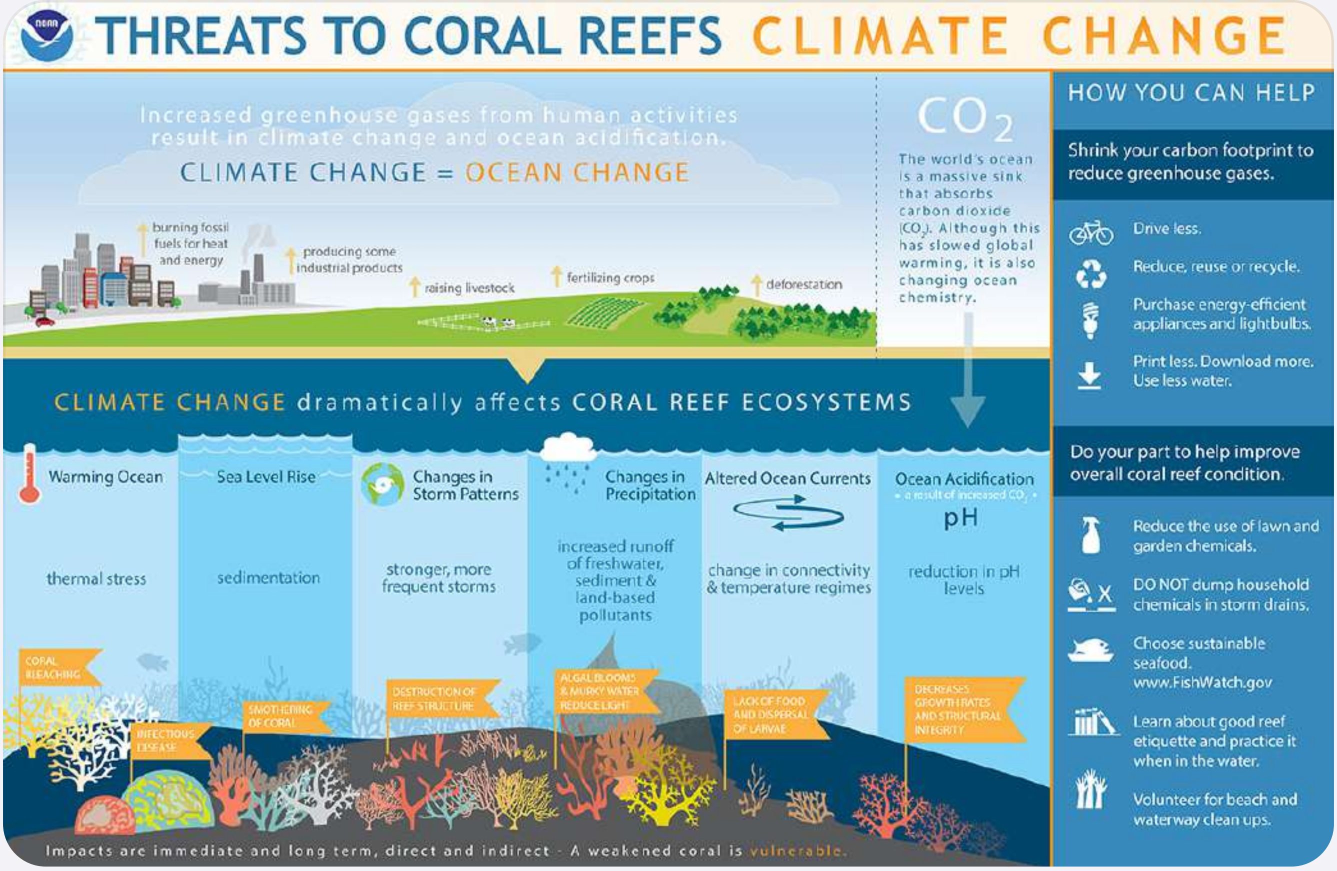
Abstract

This paper presents a comprehensive analysis of the carbon sequestration potential of artificial reefs, with a focus on the Oman artificial reef created by Haejoo company (www.haejoo.com). The study examines the diverse components of reef ecosystems, including seagrass, kelp, coral, seaweed, algae, and fish communities, to identify their individual rates of carbon capture. By quantifying the biomass, growth rates, and carbon uptake of these components, the research aims to gain a deeper understanding of the carbon sequestration capabilities of artificial reefs. Furthermore, the paper explores the positive impacts of Haejoo's artificial reefs, such as enhancing fish habitat, promoting coral colonization, supporting reef conservation and restoration, increasing fish populations and enhancing recreational utility. The findings from this study will contribute to a better understanding of the role of artificial reefs in mitigating climate change and provide valuable insights for reef conservation and restoration efforts.

Investigating the Carbon Sequestration Potential of Artificial Reefs and Their Contribution to the Global Ecosystem

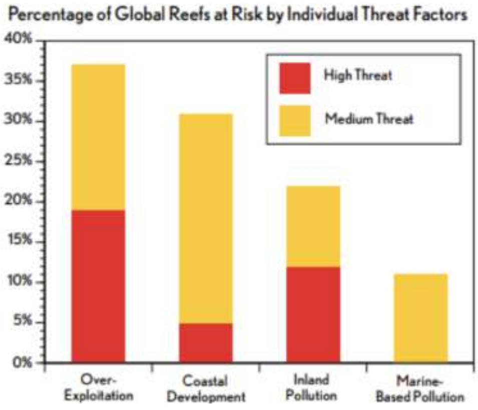
Coral and artificial reefs play vital roles in the global ecosystem, encompassing crucial functions such as environmental regulation and the provision of ecosystem services like carbon sequestration, coastal protection, and biodiversity conservation. However, our understanding of these ecosystems remains limited due to various constraints. Specifically, there is a lack of comprehensive knowledge regarding their ecological functions, specific roles, and long-term data on human impacts. To gain a comprehensive understanding of the contributions of coral and artificial reefs, including their role in carbon sequestration, it is essential to delve into specific details. Carbon sequestration, an essential ecosystem service, involves the capture and storage of atmospheric carbon dioxide in natural or artificial carbon sinks. Artificial reefs hold significant potential for contributing to carbon sequestration by promoting the growth of marine organisms that absorb and store carbon dioxide. However, quantifying the carbon sequestration potential of artificial reefs requires precise details such as information on species composition, growth rates, and biomass accumulation of marine organisms on these reefs. This research aims to address these knowledge gaps and provide valuable insights into the carbon sequestration potential of artificial reefs and their contribution to the global ecosystem.

The Impacts of Oceanic Temperature on Coral Reefs and Its Consequences for Global Environmental Health

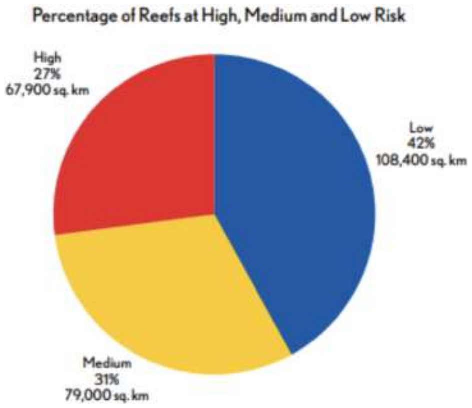


Infographic source: NOAA. How does climate change affect coral reefs? National Ocean Service website, https://oceanservice.noaa.gov/facts/coralreef-climate.html, accessed on 5/06/23.

Overexploitation and coastals development pose the greatest threat to reefs



Fifty-eight percent of the world's reefs are at risk



Source: Bryant, Dirk & Burke, Lauretta & McManus, John & Spalding, Mark. (1998). Reefs at Risk: A Map-Based Indicator of Threats to the World's Coral Reefs.

Coral reefs act as net sinks for carbon, primarily through the accretion of calcium carbonate. The rate of production of carbon can be accurately predicted based on the reef environment. The Great Barrier Reef is estimated to have a total production of approximately 50 million tonnes of carbon per year, with an average production rate of 2.4 kg CaCO3 m^{-2} yr^{-1}. Worldwide, it is estimated that coral reefs, including atolls, produce around 900 million tonnes of carbon per year. With the increasing rate of sea level rise, the production rate of carbon by coral reefs could almost double to approximately 1800 million tonnes within the next century[1].

Building upon the understanding of the vital role of coral and artificial reefs in the global ecosystem, it is imperative to investigate the impacts of oceanic temperature on these delicate ecosystems. Climate change poses a significant threat to coral reefs, with rising temperatures and other related factors causing widespread coral bleaching, disease outbreaks, and ecosystem disruptions. Understanding these impacts is crucial for assessing the consequences of changing oceanic conditions on coral reefs and their contribution to global environmental health.

Climate change is the greatest global threat to coral reef ecosystems[2]. The rise in temperature caused by the increase in greenhouse gases derived from human activities has led to more frequent mass coral bleaching events and infectious disease outbreaks. In addition, the ocean's absorption of carbon dioxide from the atmosphere has caused a decrease in the calcification rates of reef-building and reef-associated organisms. These changes in seawater chemistry, along with sea level rise, changes in tropical storm frequency and intensity, and altered ocean circulation patterns, have dramatically altered ecosystem function and impacted the goods and services that coral reef ecosystems provide to people around the globe. Effective global action is urgently needed to mitigate the impacts of climate change on coral reef ecosystems[3]. Climate change projections from the Blue Communities regional model, using linear regression, exponential regression, and polynomial regression, show that by the

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[1] Kinsey, D., & Hopley, D. (1991). The significance of coral reefs as global carbon sinks— Response to Greenhouse. Global and Planetary Change, 3(4), 363-377. https://doi.org/10.1016/0921-8181(91)90117-F

[2] NOAA. How does climate change affect coral reefs? National Ocean Service website, https://oceanservice.noaa.gov/facts/coralreef-climate.html, accessed on 5/06/23.

[3] NOAA. How does climate change affect coral reefs?. National Ocean Service website,accessed on 5/12/2023

decades 2041–2050 and 2051–2060, the environmental temperature will change beyond the coral capacity threshold. Of particular concern is the projected increase in seawater temperature caused by climate change and the El Niño phenomenon, leading to abnormal increases in the seawater environment beyond the coral resistance threshold and degradation of coral reefs[4]. Coral reefs are especially vulnerable to the impacts of climate change. It is projected that they could lose between 70% and 90% of their current coverage area with just 1.5°C of warming and over 99% with 2°C of warming[5]. By 2100, over half of the world's marine species may face extinction[6].

The impact of climate change on coral reefs is of significant concern, given the crucial role they play in supporting marine ecosystems. At least 11 percent of the world's coral reefs, which exhibit remarkable levels of reef fish biodiversity, face imminent threats from various human activities[7]. Understanding the positive effects of artificial reefs on climate change becomes even more imperative in light of these threats. By assessing the carbon sequestration potential and ecosystem services offered by artificial reefs, we can gain valuable insights into their ability to mitigate the adverse effects of climate change and protect the biodiversity-rich coral reef habitats.

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[4] Impact of Seawater Temperature on Coral Reefs in the Context of Climate Change. A Case Study of Cu Lao Cham – Hoi An Biosphere Reserve

[5] State of the Global Climate 2021, World Meteorological Organization, 2022

[6] Impacts of climate change on World Heritage coral reefs: update to the first global scientific assessment

[7] Bryant, Dirk & Burke, Lauretta & McManus, John & Spalding, Mark. (1998). Reefs at Risk: A Map-Based Indicator of Threats to the World's Coral Reefs

Reefs as a Carbon Sink

Reefs, including artificial reefs, have been recognized for their potential as carbon sinks, playing a crucial role in the sequestration of carbon dioxide. These diverse ecosystems have the capacity to capture and store significant amounts of atmospheric carbon dioxide. By providing an additional substrate and creating favorable conditions for various reef species, artificial reefs contribute to the growth of marine organisms that actively absorb carbon dioxide during photosynthesis. This process not only helps maintain the health and stability of the reef ecosystem but also contributes to global efforts in mitigating climate change by reducing greenhouse gas concentrations. Understanding and leveraging the carbon sequestration potential of artificial reefs can significantly benefit reef conservation and restoration efforts, showcasing their multifaceted advantages beyond their primary function as habitat providers. Ongoing research and monitoring initiatives are continually exploring the carbon capture capabilities of artificial reefs, further informing conservation strategies and supporting climate change mitigation endeavors.

Comprehensive efforts are currently underway to gather data on various components of the reef ecosystem and their carbon capture characteristics. Researchers are assessing seagrass beds, kelp forests, coral colonies, seaweed patches, and fish communities to quantify their biomass, growth rates, and carbon uptake. This valuable data will enhance our understanding of reef ecosystems as carbon sinks and inform conservation and restoration strategies. By integrating information on these diverse components, we can establish holistic reef management approaches that prioritize the preservation and enhancement of their carbon capture capabilities.

Our exhaustive research efforts have uncovered promising data to show that artificial reefs are capable of not only sequestering carbon at a rate similar to that of a natural reef, but to surpass that of a natural reef in a vastly reduced time frame. We are confident that the work being done at Haejoo and other similar reefs will further advance our understanding of an artificial reefs function and lead to a proliferation of reef development to combat the ever present effects of climate change.

Positive Impacts of Artificial Reefs on Marine Ecosystems

Artificial reefs have been recognized for their positive impacts on marine ecosystems, including

enhancing fish habitat, promoting coral colonization, and contributing to reef conservation and restoration efforts. This section highlights these significant positive effects and explores the role of artificial reefs in supporting marine biodiversity and ecosystem health.

Enhancing Fish Habitat

Artificial reefs have been found to exhibit similar fish community density, biomass, richness, and diversity as natural reefs, suggesting their effectiveness in enhancing habitat for reef-associated fish communities[8].In a study, it was found that the placement of small, structurally complex artificial reef modules significantly increased fish abundance and species richness compared to unmodified marina seawalls[9]. As per another study, it has been revealed that the growth rate for biological resources in the artificial reef working area is up to 72.81%, 24.45%, 77.00%, and 88.62% during the last 4 years if compared with those in the contrasting control area devoid of artificial reefs[10]. Additionally, research has demonstrated that artificial reefs can provide a better habitat for planktivorous fish compared to natural reefs. Surveys conducted at both natural and artificial reefs showed a higher likelihood of fish schools occurring upstream of artificial reefs, with increased volume and areal coverage at night and closer aggregation around the reef during the day[11].

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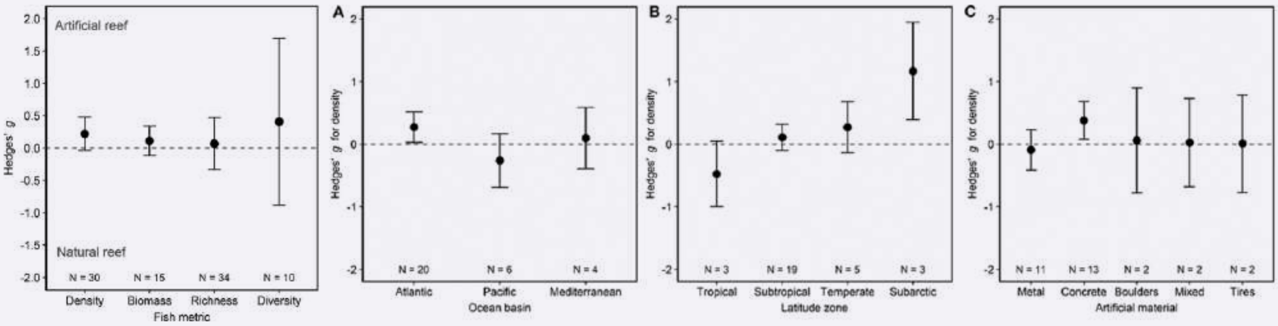
[8] Paxton, A. B., Shertzer, K. W., Bacheler, N. M., Kellison, G. T., Riley, K. L., & Taylor, J. C. (2020). Meta-Analysis Reveals Artificial Reefs Can Be Effective Tools for Fish Community Enhancement but Are Not One-Size-Fits-All. Frontiers in Marine Science, 7. https://doi.org/10.3389/fmars.2020.00282

[9] Allison Patranella, Kirk Kilfoyle, Sylvain Pioch, and Richard E. Spieler "Artificial Reefs as Juvenile Fish Habitat in a Marina," Journal of Coastal Research 33(6), 1341-1351, (1 November 2017). https://doi.org/10.2112/JCOASTRES-D-16-00145.1

[10] Shu, A., Zhang, Z., Wang, L., Sun, T., Yang, W., Zhu, J., Qin, J., & Zhu, F. (2022). Effects of typical artificial reefs on hydrodynamic characteristics and carbon sequestration potential in the offshore of Juehua Island, Bohai Sea. Frontiers in Environmental Science, 10. https://doi.org/10.3389/fenvs.2022.979930

[11] Holland MM, Becker A, Smith JA, Everett JD, Suthers IM (2021) Fine-scale spatial and diel dynamics of zooplanktivorous fish on temperate rocky and artificial reefs. Mar Ecol Prog Ser 674:221-239

These findings highlight the benefits of artificial reefs in creating favorable environments for reef-associated fish species and their potential role in conservation efforts. The construction of an artificial reef, located 120 meters off the shore, proved to be an effective measure for coastal protection and habitat creation. The prefabricated concrete structure not only acted as a barrier against storm-related sediment transport but also provided a habitat for various reef species, demonstrating its multifaceted benefits[12]

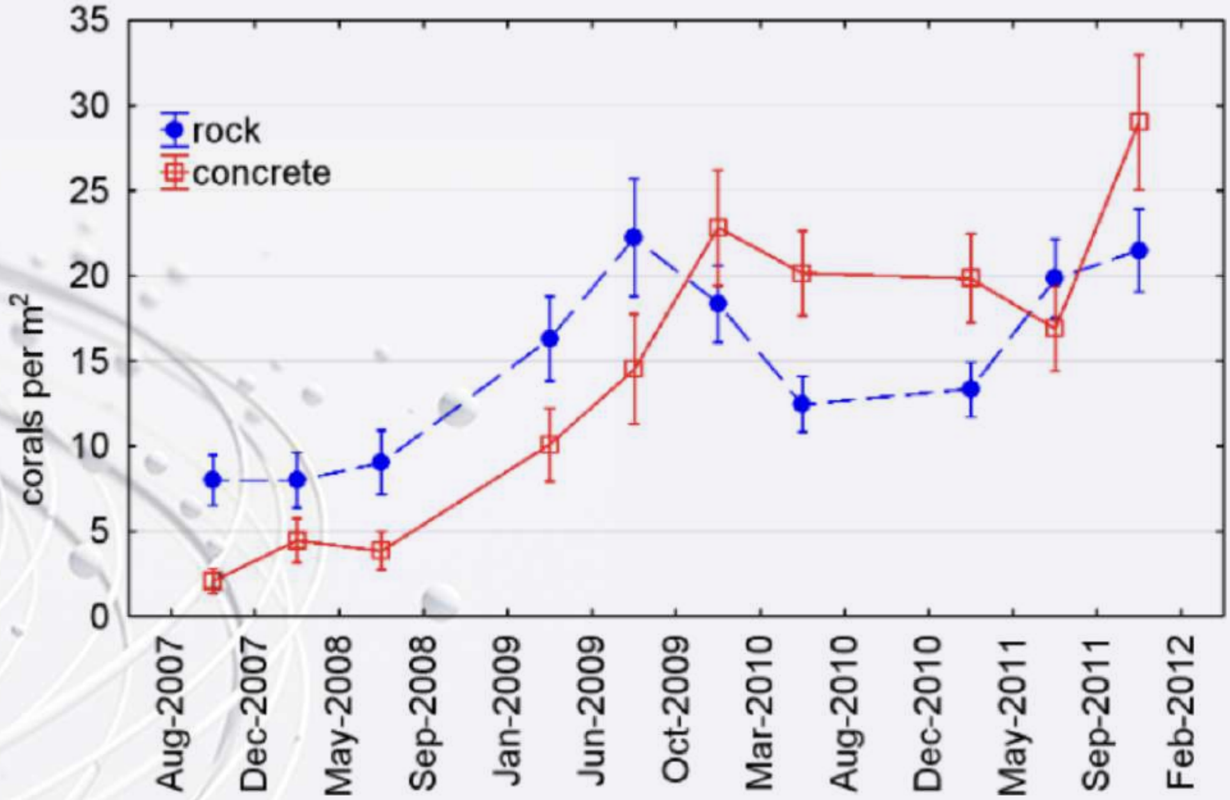


source: Paxton, A. B., Shertzer, K. W., Bacheler, N. M., Kellison, G. T., Riley, K. L., & Taylor, J. C. (2020). Meta-Analysis Reveals Artificial Reefs Can Be Effective Tools for Fish Community Enhancement but Are Not One-Size-Fits-All. Frontiers in Marine Science, 7, 534479. https://doi.org/10.3389/fmars.2020.00282

Promoting Coral Colonization

Mean ± SE coral density over time on the landward rock (LR) and concrete substrates of the artificial reef.

Seaward rock substrates were not included in this figure because there is no corresponding concrete substrate on the seaward side of the reef.



Source: Blakeway, D., Byers, M., Stoddart, J., & Rossendell, J. (2013). Coral Colonisation of an Artificial Reef in a Turbid Nearshore Environment, Dampier Harbour, Western Australia. PLOS ONE, 8(9), e75281. https://doi.org/10.1371/journal.pone.0075281

Artificial reefs play a crucial role in promoting coral recruitment and colonization. In Dampier Harbour, Western Australia, an artificial reef was constructed to offset the loss of a nearby coral community. Remarkably, despite the harsh environmental conditions, the reef successfully facilitated coral colonization, highlighting its effectiveness as a substrate for coral recruitment[13].

Reef Conservation and Restoration

Artificial reefs are widely utilized in marine ecosystems for conservation and restoration efforts. According to a study, it has been reported that Artificial reefs, serving as active restoration tools for tropical coral reefs, are most likely to accomplish their conservation goals by offering nursery habitat for rearing target reef species and providing additional hard substrate to facilitate the settlement and recruitment of corals and other marine organisms[14].

Enhancing Recreational Activities

Artificial reefs are increasingly popular among divers, with 35% of dives in Eilat, Israel, taking place at these man-made structures. They effectively divert divers from natural reefs and offer a suitable environment for training purposes[15].

In summary, the positive impacts of artificial reefs on marine ecosystems are evident in their ability to enhance fish habitat, promote coral colonization, support reef conservation and restoration efforts, and provide opportunities for enhanced recreational activities.

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[13] Blakeway, D., Byers, M., Stoddart, J., & Rossendell, J. (2013). Coral Colonisation of an Artificial Reef in a Turbid Nearshore Environment, Dampier Harbour, Western Australia. PLOS ONE, 8(9), e75281. https://doi.org/10.1371/journal.pone.0075281

[14] Higgins, E., Metaxas, A., & Scheibling, R. E. (2022). A systematic review of artificial reefs as platforms for coral reef research and conservation. PLoS ONE, 17(1). https://doi.org/10.1371/journal.pone.0261964

[15] Belhassen Y, Rousseau M, Tynyakov J, Shashar N. Evaluating the attractiveness and effectiveness of artificial coral reefs as a recreational ecosystem service. J Environ Manage. 2017 Dec 1;203(Pt 1):448-456. doi: 10.1016/j.jenvman.2017.08.020. Epub 2017 Aug 22. PMID: 28837911.

Positive impacts of Artificial reefs on climate change

Artificial reefs are recognized as a promising solution with notable positive implications for addressing climate change. These constructed underwater structures offer various advantages, including the mitigation of escalating ocean temperatures and ocean acidification effects. By serving as habitats for marine organisms, artificial reefs facilitate the preservation of biodiversity and bolster ecosystem resilience. Moreover, they contribute to carbon sequestration by stimulating the growth of marine vegetation and enhancing overall marine productivity. Thus, artificial reefs assume a pivotal role in combating climate change and promoting the vitality and sustainability of our oceans.

The Potential of Artificial Reefs to Sequester Carbon, a case study - Suwaiq Marine Farm Artificial Reef Complex, designed and built by Haejoo

Coral and artificial reefs are vital to the global ecosystem, providing essential services such as carbon sequestration, coastal protection, and biodiversity conservation. Despite their importance, our understanding of these ecosystems remains incomplete, with gaps in knowledge about their specific ecological roles and the human impacts on them. This lack of understanding extends to carbon sequestration, a crucial process whereby carbon dioxide is captured and stored, a service that artificial reefs can provide by promoting the growth of carbon-storing marine organisms.

Our ability to quantify the carbon sequestration potential of artificial reefs requires more detailed information, specifically about the species composition, growth rates, and biomass accumulation of these marine organisms. Fortunately, ongoing research is making strides towards a better understanding of these reefs, especially their contributions to carbon sequestration. Techniques like monitoring and modeling are being employed to understand better the carbon sequestration potential of artificial reefs, with metrics for quantifying carbon sequestration rates being developed.

While our knowledge of coral and artificial reefs and their contributions to carbon sequestration is still limited, current research efforts are striving to fill these gaps. There is still a lot to learn about these crucial elements of the global ecosystem, and this paper aims to explore the potential of artificial reefs for carbon sequestration further.

With this in mind, it is imperative we focus our resources on developing sites that exhibit all the characteristics of a thriving reef system, be they artificial or otherwise. The Haejoo artificial reef system in the Oman coast is one such system that has flourished in the 24 months since its deployment. We are seeing the potential carbon sequestration rates manifest in the coral and algae that has sprung where previously barron and the introduced marine species that now call this reef system home.

A closer look at the gulf’s biggest artificial reef in Oman

There's a rising interest in marine carbon sequestration methods, with artificial reefs being a particular focus. Artificial reefs are intentionally built benthic structures aimed at protecting, enhancing, or rehabilitating parts of marine ecosystems while balancing environmental and human socioeconomic needs. These structures mimic natural reefs to some extent and can offer a novel approach to carbon sequestration in the marine environment.

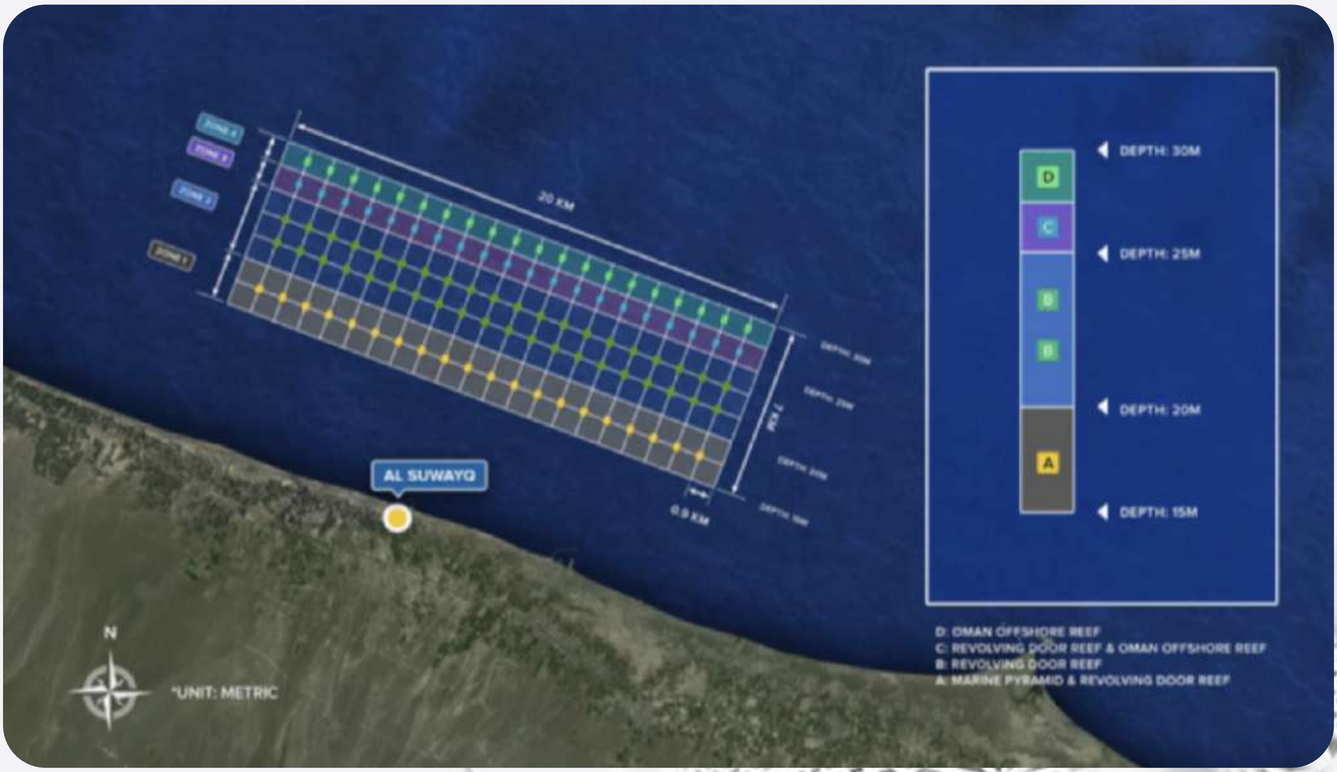
The Haejoo reef system is playing a vital role in ecological restoration off the Oman coast and is, purely by virtue of existing, amassing a more diverse ecosystem which contributes to greater carbon sequestration rates year on year.

Constructed from various materials, including concrete and steel, these reefs offer habitats that promote marine biodiversity. The organisms living in these habitats photosynthesize, absorbing carbon dioxide and storing it in their biomass, contributing to carbon sequestration.

Besides ecological restoration, artificial reefs serve other purposes such as coastal erosion protection, promotion of aquaculture and recreational activities. They also contribute to mitigating climate change effects on marine ecosystems, such as ocean acidification and coral bleaching, by reducing atmospheric carbon dioxide levels.

The shores of Al Suwaiq, Oman.

(FIG 1)



Suwaiq Marine Farm Artificial Reef Complex

Haejoo Group completed the Al Suwaiq Marine Farm project two years ago, beginning with a comprehensive site survey across the Al Batinah region. This initial phase was followed by the successful execution of a pilot marine farm program, and routine progressive monitoring continues to this day. Drawing from these experiences and the expertise acquired, Haejoo Group is confident that the proposed marine farm in Suwaiq will yield a significant increase in fisheries gain and aquatic resources within two years of its implementation.

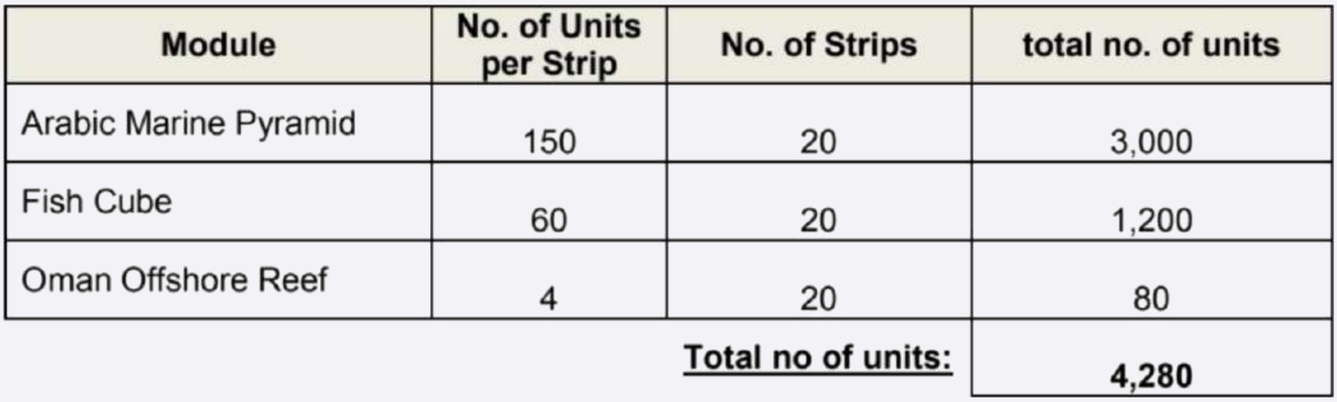
This project not only sets a precedent in the global fisheries sector but also highlights the Sultanate's innovative and scientific approach towards marine farming. It is worth noting that this initiative marks the construction of the first Marine Farm in the Gulf region, further underscoring its significance and the potential impact on regional marine resource management and sustainability.

We possess an extensive dataset concerning the influence that these reefs exert on fish populations. However, our current focus lies in comprehending the carbon sequestration potential of these installations.

Oman reef overview

Three site specific reef designs were placed at varying depths. Each reef design was created specifically to flourish in the conditions at their corresponding water depth. The table below outlines the key characteristics of each separate reef module, details on quantities deployed and information on placements.

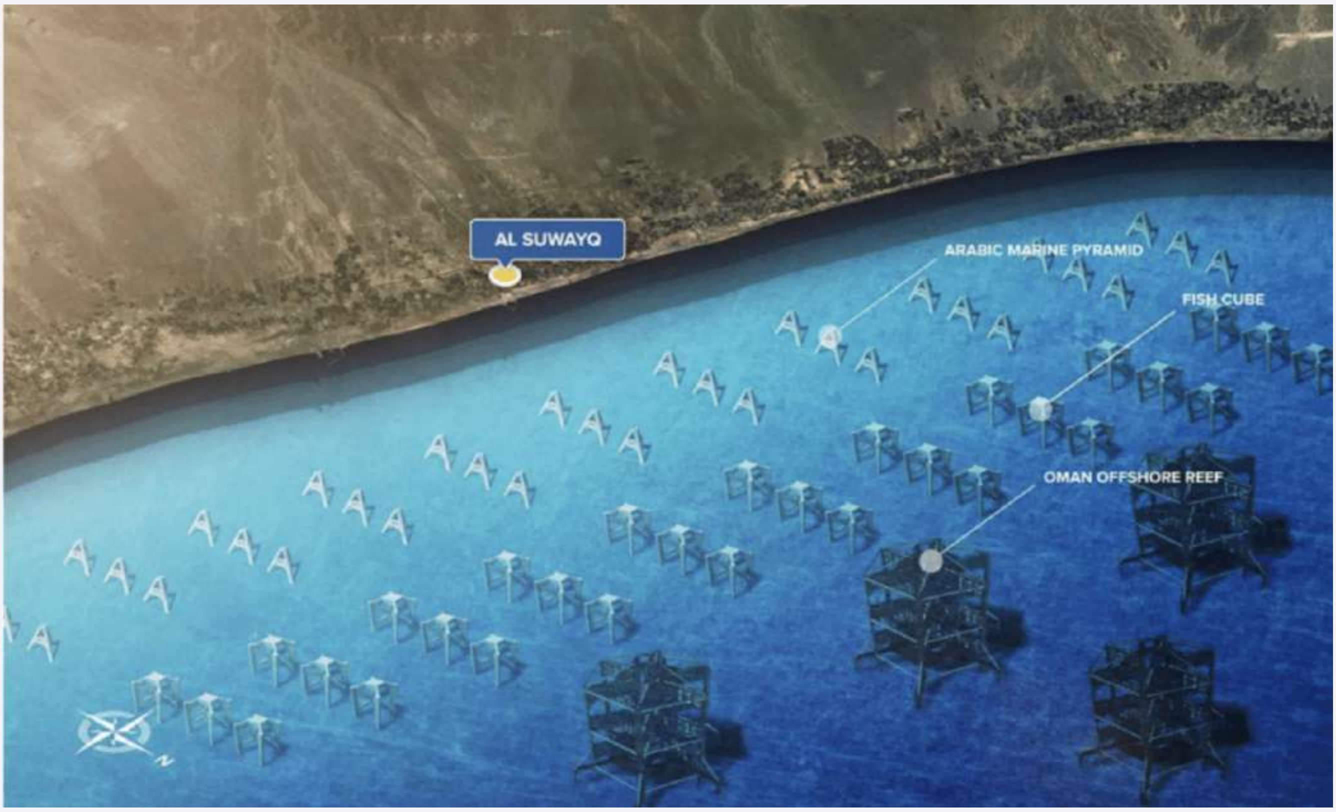
(FIG 2)



Module	No. of Units per Strip	No. of Strips	total no. of units
Arabic Marine Pyramid	150	20	3,000
Fish Cube	60	20	1,200
Oman Offshore Reef	4	20	80
		Total no of units:	**4,280**

Below is an image which gives visual context to the three separate reef designs placed off the shores of Al Suwaiq and their general positioning.

(FIG 3)



(FIG 4)

Arab Marine Pyramid (AMP)

Fish Cube (FC)

Oman Offshore Reef (OOR)

With reference to (FIG 1), the below images detail the position of each separate reef build according to their zone.

Timelines to maturity

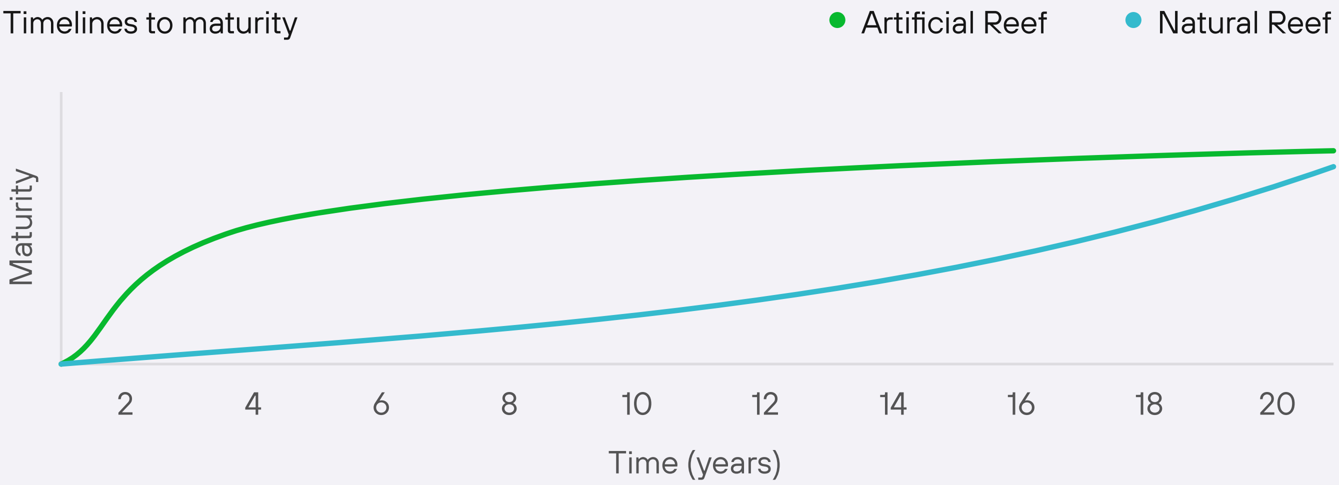


Figure 2. Deployment of Fish Cube module

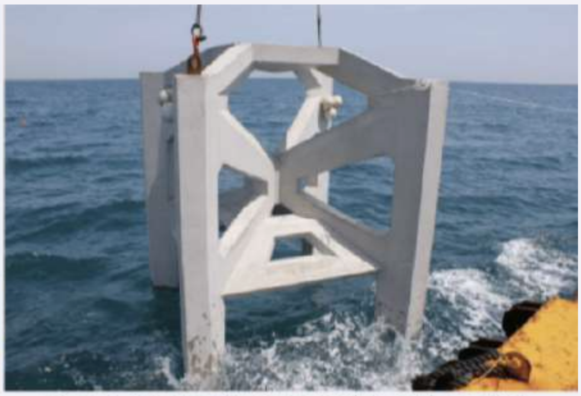


Figure 3. Lowering down the module on the seabed

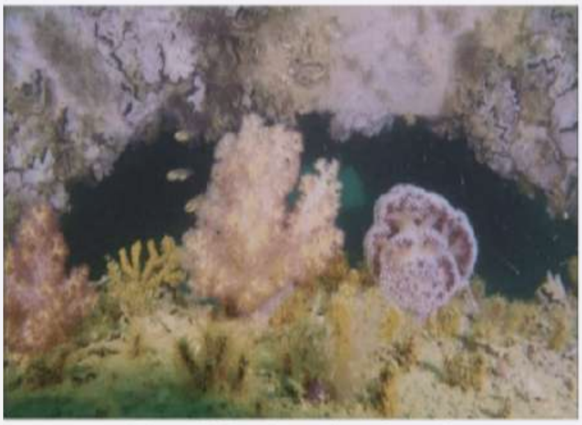


Figure 6. Coral growth at 6 month

Figure 7. Coral growth at 12 month

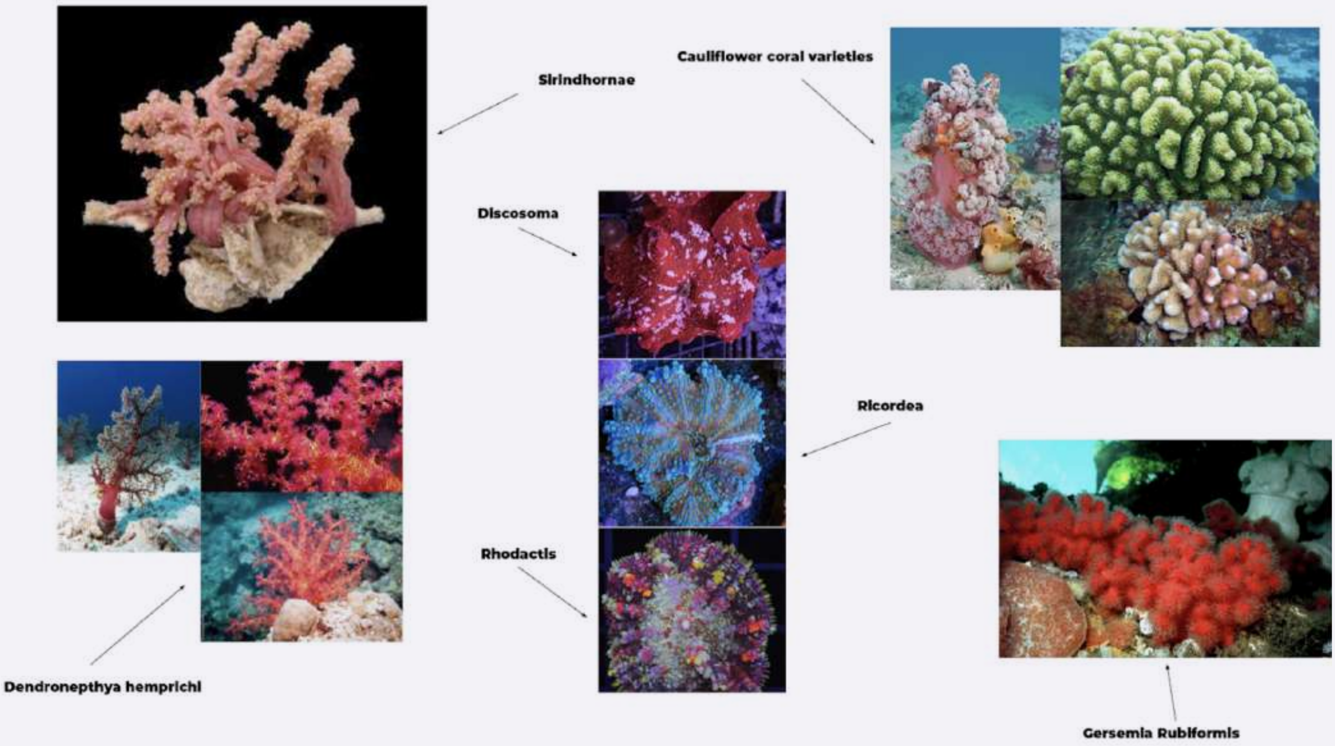
Figure 8. Coral growth at 18 month

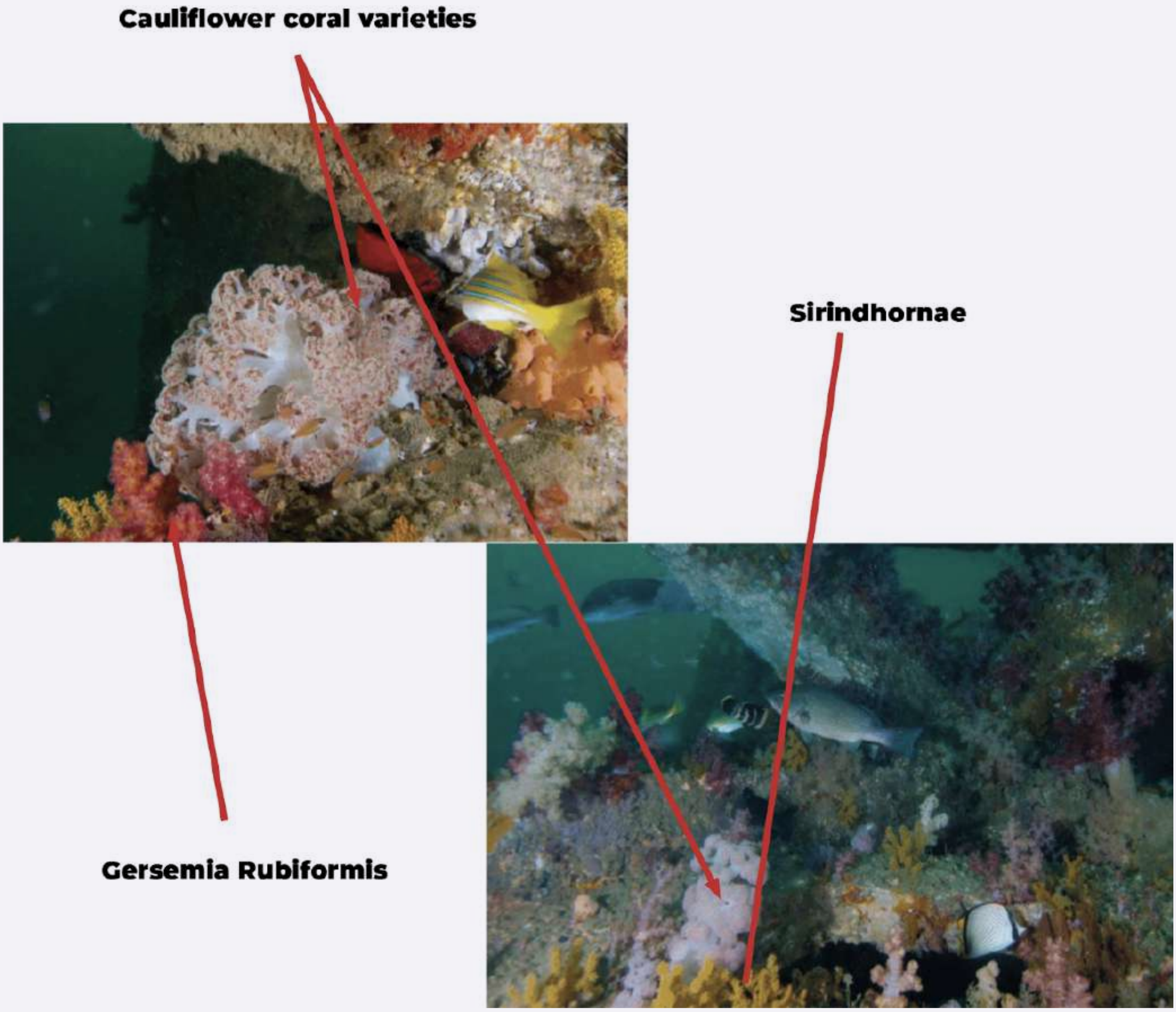
Figure 9. Coral growth at 24 month

Natural reefs can take decades or even centuries to mature and begin sequestering carbon. This process starts with coral larvae settling on a substrate, followed by the growth of coral colonies and the eventual colonization of the reef by algae, sponges, and fish. The resulting complex ecosystem can sequester large amounts of carbon through biomass growth and storage in the reef structures.

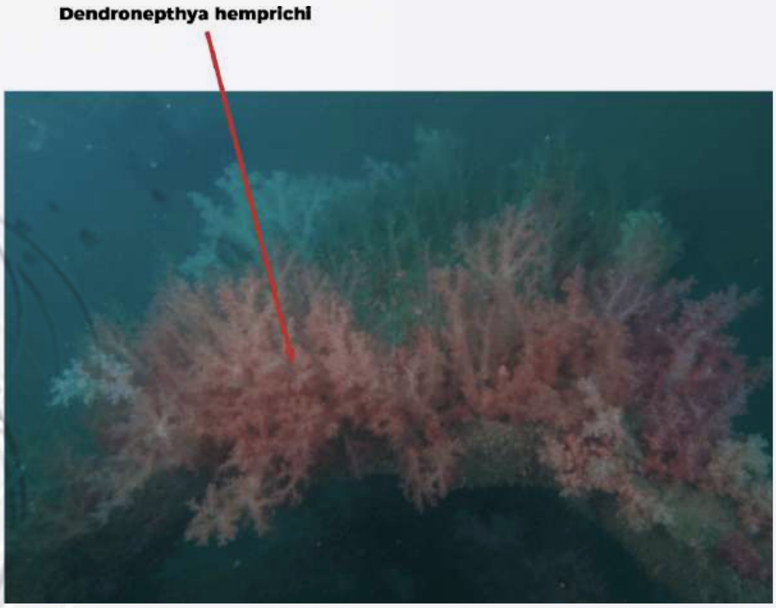
Artificial reefs can expedite this process. Designed with materials that encourage marine organism growth and placed in favorable environmental conditions, artificial reefs can establish a functional ecosystem in a shorter timeframe, leading to faster biomass accumulation and carbon storage. The exact timeline varies depending on the design, environmental conditions, and colonizing species.

After 18 month and 24 month check ins on the Haejoo reef system at Oman, the quantitative growth rate of coral in an artificial reef environment has proven to be vastly more significant when compared to that of an organic reef system. After 18 months, a wide array of coral species began to proliferate and with them the introduction of marine life such as fish and algae where it was previously barren. After 24 months, coral growth has continued to develop with no signs of degradation.





https://docs.google.com/document/d/1tr22jl7AELfUXSNasvJAjdARM51-A3MBYsqhpwbi_zk/edit#heading=h.kmp1gfcbq0hf



Quantitative Assessment of Carbon Capture Capacity of the Artificial Reef in Oman

Taking into account the carbon sequestration rates we have determined in this study, we will apply these rates to assess the carbon sequestration capacity of the artificial reefs. This analysis aims to evaluate the carbon sequestration rates across different components of the reefs. By quantifying the ability of these artificial reef structures to capture and retain carbon dioxide from the surrounding marine environment, we can gain valuable insights into their effectiveness in mitigating carbon emissions. Through meticulous calculations and thorough comparisons, this evaluation provides a comprehensive understanding of the Haejoo reefs' role in carbon mitigation efforts and their contribution to fostering a healthier marine ecosystem.

Carbon Sequestration Rates of Different Reef Components

Examining the carbon sequestration rates of different components within reef ecosystems is crucial for understanding the potential of artificial reefs to capture and store carbon, contributing to the fight against climate change. In the subsequent paragraphs, we have discussed the sequestration rates of various components found within reef ecosystems. While it's important to note that these specific items, components, or organisms may not be native to our area, in the absence of local data, we can utilize these rates as a reference point to gain initial insights into the sequestration potential of similar components in our region.

Seagrass

Studies have shown that the colonization of a Mediterranean bay by Cymodocea nodosa resulted in an increase in the organic carbon (Corg) store at a rate of approximately 40 g C m^2 y^{r-1}[16] . Although Cymodocea nodosa may not be present in our specific area, we utilized this information as a proxy due to the absence of data on the specific seagrass in our study site.

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[16] Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M. A., Apostolaki, E. T., Kendrick, G. A., McGlathery, K. J., & Serrano, O. (2012). Seagrass ecosystems as a globally significant carbon stock.

Kelp

Although kelp is currently absent in our focus reef, it is worth noting that the inclusion of information regarding its potential cultivation is crucial. This acknowledgment stems from the understanding that the introduction of kelp cultivation on this site holds significant promise in dramatically increasing the carbon sequestration rate of the Oman reef. By recognizing the absence of kelp and emphasizing its potential impact, we underscore the importance of future considerations and the substantial benefits that can be attained by incorporating kelp cultivation to enhance the overall carbon sequestration capabilities of the reef system.The dominant kelp species (Ecklonia radiata) on Australian reefs have an average annual production rate of 3.9 Mg C ha^{-1} $year^{-1}$ (± 0.9 SD). Based on the most reliable current estimate of the proportion of net primary production (NPP) that becomes sequestered through burial in deep ocean sediments or transport below the mixed layer in the deep sea, the average sequestration rate per unit area of kelp forest is estimated to be 0.39 Mg C ha^{-1} $year^{-1}$ (± 0.09 SD)[17].

Seaweed

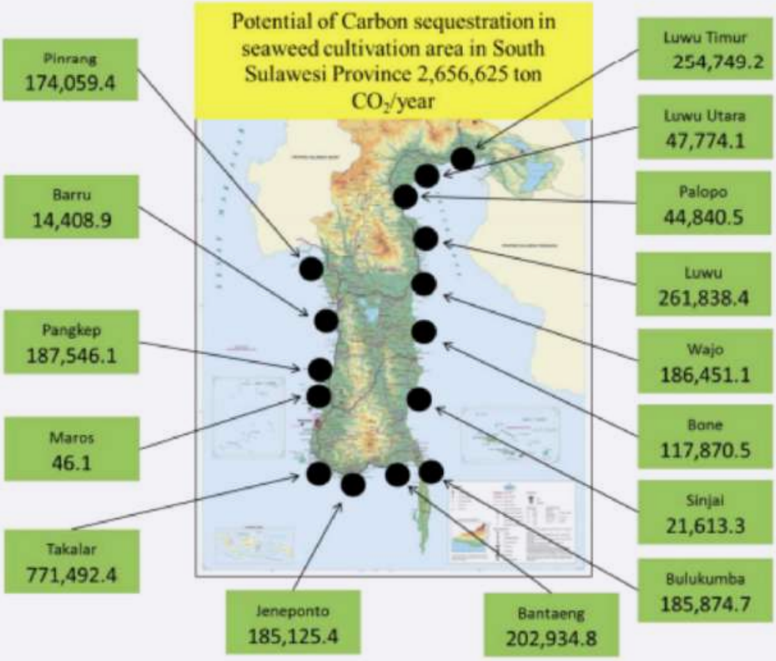

Figure 7. Potential for carbon sequestration by cultivated seaweed in South Sulawesi (ton $CO_2 \cdot year^{-1}$)

Source: S Mashoreng et al 2019 IOP Conf. Ser.: Earth Environ. Sci. 370 012017

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[17] Filbee-Dexter, K., Wernberg, T. Substantial blue carbon in overlooked Australian kelp forests. Sci Rep 10, 12341 (2020). https://doi.org/10.1038/s41598-020-69258-7

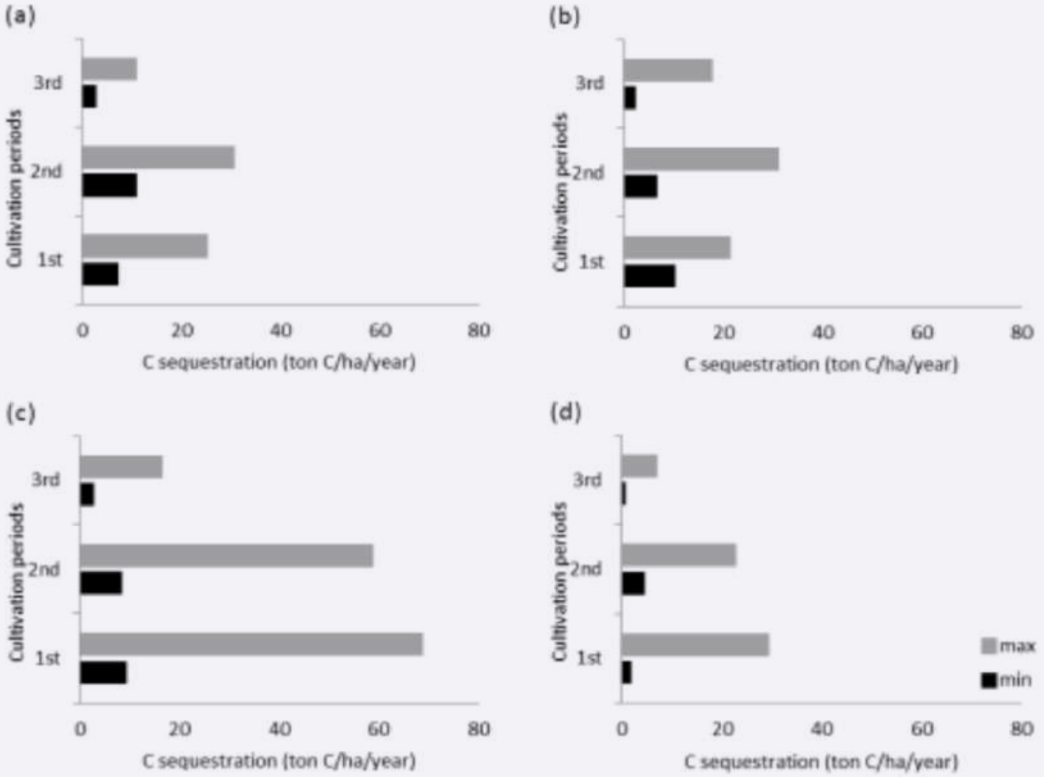

Fig. 2 **Range of C sequestration by four seaweed variants cultured in Gerupuk Bay, West Nusa Tenggara, Indonesia: (a) *K. alvarezii* var. Maumere; (b) *K. alvarezii* var. Tambalang; (c) *E. denticulatum*; (d) *K. striatum*.**

Source:The Use of Seaweeds Aquaculture for Carbon Sequestration: A Strategy for Climate Change Mitigation Erlania and I Nyoman Radiarta Center for Aquaculture Research and Development, Ministry of Marine Affairs and Fisheries Republic of Indonesia, South Jakarta12540, Indonesia

According to a study, mariculture seaweed can sequester an estimated 57.64 tons of CO2/ha/year, while pond-cultured seaweed can sequester 12.38 tons CO2/ha/year. The research suggests that seaweed cultivation in South Sulawesi can sequester a total of 2,656,625 tons CO2/year from mariculture and 621,377 tons CO2/year from pond culture[18]. According to a different study on Kappaphycus alvarezii var. Tambalang and Maumere, K. striatum and Eucheuma denticulatum, it was found that E. denticulatum has the highest rate of carbon sequestration, with a range of 16.08-68.43 tons C/ha/year, while the other variants have relatively similar values. The carbon sequestration potential of seaweed can be affected by factors such as seaweed variants, cultivation duration, and age of the seaweed during cultivation[19].

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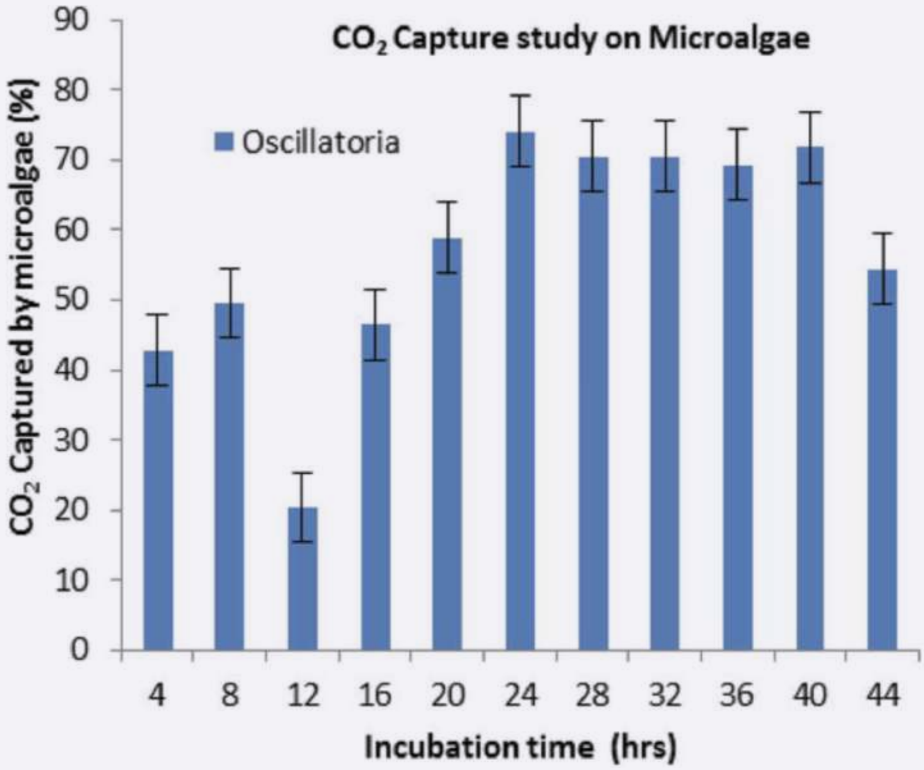
[18] S Mashoreng et al 2019 IOP Conf. Ser.: Earth Environ. Sci. 370 012017https://iopscience.iop.org/article/10.1088/1755-1315/370/1/012017

[19] Erlania, Radiarta IN (2015) The use of seaweeds aquaculture for carbon sequestration: A strategy for climate change mitigation. Journal of Geodesy and Geomatics Engineering 2(2015): 109-115.

Algae



Source: Anguselvi, V., Ebhin Masto, R., Mukherjee, A., & Kumar Singh, P. (2019). CO2 Capture for Industries by Algae. IntechOpen. doi: 10.5772/intechopen.81800

According to the study, one kilogram of algal dry cell weight utilizes around 1.83 kg of CO2. An area of 1 acre (equivalent to 4000 m^2) has the potential to capture approximately 2.7 tons of CO2 per day[20]. Given this straightforward information, we will utilize this specific figure as the carbon sequestration rate of algae in our context, without further calculations.

Phytoplankton

A study conducted at the Mediterranean Egyptian coast examined the potential of the development of an inland oligotrophic marine ecosystem in Qattara Depression to mitigate the increasing atmospheric carbon dioxide levels. The study investigated phytoplankton composition, biomass, and productivity at three selected sites, each representing varying nutrient concentrations and water transparency. Among the sites, it was observed that site 2 exhibited a peak in both gross and net production, reaching values of 793.9 and 355.9 gC/m^3/

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[20] Anguselvi V, Masto R, Mukherjee A, Singh P. CO2 Capture for Industries by Algae. IntechOpen. 2019 May 29.

year, respectively[21]. Based on the expected water intake of the project, the estimated net primary production (C sequestration) of phytoplankton was found to be 355 g m^{-3} year^{-1}.

Coral

Despite extensive research efforts, accurately determining a precise and universally applicable figure for the carbon sequestration rate of corals remains challenging. The complex interplay of numerous factors, including coral species, environmental conditions, and varying methodologies employed in carbon sequestration studies, contributes to the lack of a definitive and trustworthy value. However, to provide a reference point, assumptive figures can be considered based on the intricate process of coral calcification, where corals utilize dissolved carbon dioxide in water to form calcium carbonate structures, thereby sequestering carbon. We will use this equation: Ca2+ + 2 HCO3– CaCO3 + CO2 + H2O

According to a study, the average growth rate per year of Porites lutea corals was investigated at two stations. At the windward (north) station, the average growth rate per year was determined to be 1.20 cm/year. Similarly, at the leeward (south) station, the average growth rate per year was found to be 1.11 cm/year[22]. For the sake of simplicity, we will consider the average growth rate of corals as 1 cm per year. According to research, the average density of coral sands in China ranges from 2.73 to 2.83 g/m^3, while in Japan, it is reported to be 2.80 g/m^3 [23].

Based on our research, we have gathered the following data to approximate the carbon sequestration rate of coral. The chemical equation involved in coral calcification is as follows: Ca2+ + 2 HCO3– CaCO3 + CO2 + H2O. Furthermore, considering a coral sand density of 2.80 g/m^3 and an average growth rate of 1 cm per year, we can utilize these values to estimate the

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[21] Predicted Study of Carbon Sequestration by Phytoplankton in South Coast of Mediterranean Sea Opposite the Projected Canal Connected to Qattara Depression Medhat Khafagy, Mona S. Zaki, Mohamad S. Abd El-Karim and Ahmed I. Noor El-Din American-Eurasian J. Agric. & Environ. Sci., 5 (2): 184-188, 2009 ISSN 1818-6769 © IDOSI Publications, 2009

[22] Zamani, N. P., & Arman, A. (2016). The Growth Rate of Coral Porites Lutea Relating to the El Niño Phenomena at Tunda Island, Banten Bay, Indonesia. Procedia Environmental Sciences, 33, 505-511. https://doi.org/10.1016/j.proenv.2016.03.103

[23] Binbin Xu, Aijun Zhuge. Review of Research on Physical Properties of Coral Sands. 10.2991/iceep-16.2016.156

carbon sequestration capacity of coral. By taking into account the molar mass of CO_2 (44.01 g/mol) and $CaCO_3$ (100.0869 g/mol), we find that 28 kg of CO_2 can be absorbed by a coral organism with a surface area of 1 m^2.

Therefore, based on these calculations, the estimated carbon sequestration capacity of a 1 m^2 coral surface area amounts to 12.32 kg of CO_2. This information provides valuable insights into the potential role of corals in sequestering atmospheric carbon and highlights their significance in mitigating climate change.

Some of the specific hard and soft coral species currently present at the Oman site:

- Octocorallia - Alcyonaria
- Scleractinia - Stony corals
- Hexacorallia
- Dendronephthya hemprichi - Soft coral
- Porifera - Sea sponges
- Cauliflower corals
- Gersemia Rubiformis
- Discosoma, Ricordea & Rhodactis varieties

Fish

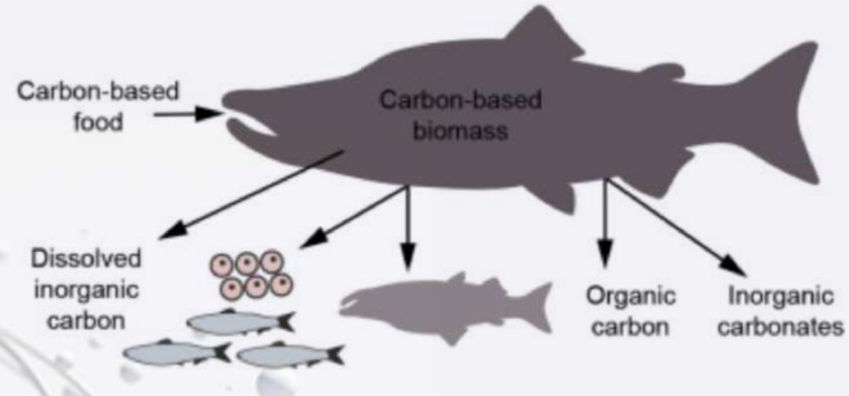

Figure 3 Functional carbon interactions of a fish

Source: Martin, A. H., Pearson, H. C., Saba, G. K., & Olsen, E. M. (2022). Erratum: Integral functions of marine vertebrates in the ocean carbon cycle and climate change mitigation (One Earth (2021) 4(5) (680–693), (S2590332221002384), (10.1016/j.oneear.2021.04.019)). One Earth, 5(4), 443-445. https://doi.org/10.1016/j.oneear.2022.03.004

While extensive research efforts have been dedicated to the investigation of carbon sequestration capacity in fish, the availability of a comprehensive published study remains elusive. Nevertheless, it is crucial to acknowledge the inherent potential of fish to sequester carbon upon their descent to the ocean floor following mortality. Notably, a study published in Science Advances reveals that the average carbon content of a single fish is estimated to be approximately 12.5 percent of its weight[24]. While this preliminary information provides a starting point for calculations, it falls short of providing a comprehensive basis for determining the actual sequestration rate. To achieve a more accurate estimation, additional data and meticulous considerations must be taken into account. Factors such as the fish's growth rate, mortality rate, sinking probability, decomposition dynamics, sediment burial efficiency, and carbon remineralization processes within the marine ecosystem all necessitate thorough examination.

Below, we present a compilation of fish species found in the waters of Oman, exemplifying the remarkable biodiversity and ecological significance of this region.

Carcharhinus leucas	Bull shark
Aetobatus ocellatus	Spotted eagle ray
Stephanolepis diaspros	Reticulated leatherjacket
Argyrops spinifer	King soldierbream
Velifer hyposelopterus	Sailifin velifer
Nemipterus bipunctatus	Delagoa threadfin bream
Terapon puta	Small scaled terapon
Decapterus russelli	Indian Scad
Pristipomides filamentosus	Crimson jobfish, Bluespotted fish
Heniochus acuminatus	Common bannerfish

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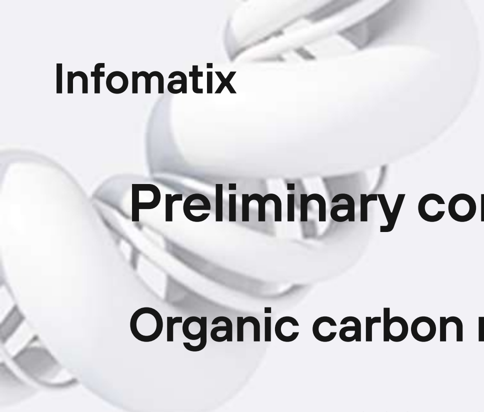
[24] Mariani, G., L. Cheung, W. W., Lyet, A., Sala, E., Mayorga, J., Velez, L., Gaines, S. D., Dejean, T., Troussellier, M., & Mouillot, D. (2020). Let more big fish sink: Fisheries prevent blue carbon sequestration—Half in unprofitable areas. Science Advances.https://www.science.org/doi/10.1126/sciadv.abb4848

Lutjanus bengalensis	Bengal snapper
Acanthurus xanthopterus	Yellowfin surgeonfish
Lutjanus ehrenbergii	Blackspot snapper
Lutjanus sanguineus	Humpherd snapper, Bloodsapper
Alutera monoceros	Unicornfish Leatherjacket filefish
Diodontidae	Porcupinefish
Antennarius indicus	Indian frogfish
Acanthurus sohal	Lined surgeonfish
Saurida undosquamis	Brushtooth Lizardfish
Parupeneus macronema	Longbarbel goatfish, Banddot goatfish
Lutjanus madras	Indian snapper
Scolopsis vosmeri	Whitecheek monocle bream, Silverflash spinecheek
Chaetodon gardneri	Gardeners butterflyfish
Scolopsis ghanam	Arabian monocle bream, Dotted spinecheck
Sphyraena flavicauda	Yellowtail barracuda
Pomadasys stridens	Striped piggy
Cephalopholis aurantia	Orange rockcod, Golden hind
Chaetodon nigropunctaus	Mystery butterflyfish, Dark butterflyfish
Lutjanus coeruleolineatus	Blueline snapper
Epinephelus coioides	Epaulet grouper
Cephalopholis hemistiktos	Yellowfin hind
Lutjanus lutjanus	Bigeye snapper
Pomacanthus maculosus	Maculosus angelfish
Plectorhinchus orientalis	Oriental sweetlips

Oriental sweetlips	Leopard whipray
Diagramma pictum	Painted sweetlip
Lethrinus nebulosus	Spangled Emperor
Carangoides malabaricus	Malabar trevally
Plectorhinchus sordidus	Sordid rubberlip
R. Remora	Remora
Scarus persicus	Parrot fish
Abudefduf saxatilis	Sergeant Major
Neopomacentrus cyanomos	Regal Damselfish
Cheilodipterus novemstriatus	Two spot cardinal fish
Platax orbicularis	Orbicular batfish
Acanthopagrus bifasciatus	Two-bar Sea Bream
Lethrinus lentjan	Pink ear Emperor
Gnathanodon speciosus	Golden Trevally
Lutjanus malabaricus	Malabar Snapper
Epinephelus bleekeri	Duskytail Grouper
Carangoides bajad	Goldspotted Trevally
Rhabdosargus sarba	Silver Bream
Valamugil seheli	Bluespot Mullet
Scomberomorus commerson	Kingfish
Synanceia verrucosa	stone fish
Syngnathoides biaculeatus	pipe fish
Seriola dumerilii	Greater Amberjack
Evynnis SP	Humped red seabream
Lutjanus malabaricus	Arabian Pandora

Pterois volitans	lionfish
Caranx heberi	Blacktip trevally
Epinephelus areolatus	areolated grouper
Mulloidichthys vanicolensis	yellowfin goatfish
Platycephalus indicus	bartail flathead
Gymnothorax favagineus	Honeycomb moray eel
C. harengus pallasii	Herring
Scomeroides commersonnianus	Queen fish
Siganus canaliculatus	Rabbit fish
Decapterus Sp.	Jack mackeral
Restrelliger kanagurta	Indian mackeral
Seriola rivoliana	Almaco jack
Ostorhinchus fleurieu	Flower cardinalfish
Alectis ciliaris	Threadfin jack

Having examined the carbon sequestration rates of various reef components, the discussion now turns to the broader positive impacts of artificial reefs on marine ecosystems. The following section explores how artificial reefs enhance fish habitat, promote coral colonization, support reef conservation and restoration, and provide additional benefits to the marine environment.



Preliminary concepts

Organic carbon metabolism- Equation 1

Photosynthesis $CO_2 + H_2O$ Æ $CH_2O + O_2$

Plants and algae in the water take in carbon dioxide from the environment, and using chlorophyll, convert this gas to sugar (CH_2O). Only photosynthetic organisms do this, such as plants and zooxanthellae (algae) that are found in the tissues of corals.

Respiration- Equation 2

$CH_2O + O_2$ Æ $CO_2 + H_2O$

Animals and plants produce carbon dioxide during cellular respiration, which happens in the mitochondria, the energy organelles found inside cells (cells other than bacteria).

Inorganic carbon metabolism Calcification- Equation 3

$2HCO_3^- + Ca^{2+}$ Æ $CaCO_3 + CO_2 + H_2O$ Bicarbonate (HCO_3^-)

Combines with calcium ions in the water to make calcium carbonate ($CaCO_3$, limestone). This process can occur both within organisms such as corals or as a simple chemical reaction in the water itself. In corals, calcium carbonate or limestone is the building block of coral reefs. As corals produce calcium carbonate they slowly add on to their existing reef structure allowing the reef to grow in size.

Dissolution of carbonate-Equation 4

$CaCO_3 + CO_2 + H_2O$ Æ $2HCO_3^- + Ca^{2+}$

Calcium carbonate can combine with carbon dioxide and water to make bicarbonate, a process that releases calcium ions (Ca^{2+}). Equilibrium and inorganic carbon metabolism Both calcification and dissolution of carbonate exist in equilibrium. This means that if there is an increase in one of the compounds on one side of an equation, all of the compounds on that side of the equation react to produce more of the compounds on the other side of the equation. Chemical equilibrium plays a large role in ocean chemistry and influences life in the ocean as follows.

The investigation of methods for measuring carbon sequestration rates in artificial reefs has not yielded a foolproof approach. To circumvent this, the study used carbon sequestration rates of coral reefs as a surrogate for measuring artificial reefs' carbon sequestration potential. This method can offer an informed estimate of artificial reefs' carbon sequestration capabilities, assisting in evaluating their role in climate change mitigation.

One study focused on Lophelia pertusa, a deep-water coral species that forms reefs under specific conditions. It estimated the carbon storage of two Lophelia reef areas in Scottish waters: the Darwin Mounds and the Mingulay Reef complex. The Darwin Mounds' carbon storage capacity is solely from living coral colonies, while the Mingulay Reef Complex also includes accumulations of relict calcareous material. The estimated carbon stock on the reef, based on coral mass per unit area calculations, is 9,375 g Cinorg m^2. Accounting for loss due to bioerosion and chemical dissolution, the net sequestration rate is 35 g Cinorg m^2 yr^1 [25].

These calculations give us a hint of the potential carbon sequestration from artificial reefs, drawing parallels from the accumulation rates of Lophelia pertusa mounds. Artificial reefs that mimic natural reefs and support coral and other organisms' growth can potentially store significant amounts of carbon.

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[25] Hendriks, Kees & Gubbay, Susan & Arets, Eric & Janssen, John & Dige, Gorm & Erhard, Markus. (2022). Carbon stocks and sequestration in terrestrial and marine ecosystems: a lever for nature restoration? A quick scan for terrestrial and marine EUNIS habitat types.

Calculating the Carbon Sequestration rate of the 4280 module Oman artificial reef.

Given that such a diverse ecosystem of corals and sponges has developed on the Oman site we will use a matrix comprised of the individual organisms described above to derive carbon sequestration rates

Carbon sequestration rate of the coral biomass

The combined surface area of the artificial reef modules is 103,000 square meters (m^2). Through previous research, we have established that a coral organism with a surface area of 1 m^2 can absorb 28 kg of CO2. Considering the conversion factor of 0.44, the estimated absorption rate per square meter is determined to be 12.32 kg. By multiplying this absorption rate by the total surface area, we can calculate the carbon sequestration rate of the reef.

Calculation:

GIVEN:
Surface area of the reef: 103,000 m^2
Absorption rate per square meter: 12.32 kg
Carbon Sequestration Rate = Absorption Rate per square meter × Surface Area

SUBSTITUTING THE VALUES:
Carbon Sequestration Rate = 12.32 $kg/m^2 \times 103{,}000\ m^2$

CALCULATION RESULT:
Based on our study detailed in this document, we have determined that the estimated carbon sequestration capacity of a 1 square meter coral surface area amounts to 12.32 kilograms of CO_2. This calculation takes into consideration the coral growth rate, sand density, and the molar masses of CaCO3 and CO2. By multiplying this absorption rate by the total surface area of our reef, which is measured to be 103,000 square meters, we can calculate the carbon sequestration rate of the entire reef. Applying the aforementioned value, we find that the reef has the potential to sequester approximately 1,268,960 kilograms or 1,268.96 metric tons of CO_2.

Carbon sequestration rate of total Oman individual ecosystem components at maturity

Our footprint encompasses an area of 140,000,000 square meters, obtained by multiplying the dimensions of 20,000 meters by 7,000 meters. To determine the carbon sequestration rate within this footprint, we will refer to the carbon sequestration data previously studied and documented for seagrass and seaweed.

Calculation:

Seagrass

Based on this estimate, the carbon sequestration rate for our area can be calculated as follows:

Carbon sequestration rate = Area × Carbon sequestration rate per unit area

= 140,000,000 m^2 × 40 g C m^2 yr–1

= 5,600,000,000 g C/yr

To convert this figure to metric tons, we divide the result by 1,000,000 since there are 1,000,000 grams in a metric ton:

Carbon sequestration = 5,600,000,000 g C/yr / 1,000,000

Carbon sequestration = 5,600 metric tons of carbon per year

If the seagrass concentration is 30 percent, we can calculate the total sequestration of carbon per year using the given carbon sequestration rate of 5,600 metric tons:

Total sequestration = Carbon sequestration rate * Seagrass concentration

Total sequestration = 5,600 metric tons * 0.30

Total sequestration = 1,680 metric tons of carbon per year

Therefore, based on the assumption of a 30 percent seagrass concentration, the total sequestration of carbon from seagrass per year is estimated to be approximately 1,680 metric tons.

Seaweed

According to a study, mariculture seaweed has been found to have a carbon sequestration rate of approximately 57.64 tons of CO2 per hectare per year.

To calculate the carbon sequestration rate for a given area, we will consider the provided footprint of 140,000,000 square meters.

Convert the footprint area to hectares:

Footprint area in hectares = 140,000,000 square meters / 10,000 = 14,000 hectares

Calculate the carbon sequestration rate for the footprint:

Carbon sequestration rate = Sequestration rate per hectare * Footprint area in hectares

Carbon sequestration rate = 57.64 tons CO2/ha/year * 14,000 hectares = 805,960 tons CO2 per year

However, since we are considering a 15 percent concentration of seaweeds, we need to adjust the calculation accordingly:

Therefore, based on the provided study and considering a 15 percent concentration of seaweeds, the estimated carbon sequestration rate for the given footprint of 140,000,000 square meters is approximately 120,894 tons of CO2 per year. (2)

Carbon sequestration rate of microorganisms and fish supported by the reef.

The total water volume within the specified area is approximately 2.8 billion cubic meters, obtained by multiplying the dimensions of 20,000 meters by 7,000 meters and further considering a minimum average depth of 20 meters. In order to determine the carbon sequestration rate of this voluminous water body, we will consider the contributions of various elements such as phytoplankton, algae, and fish. Firstly, we will calculate the sequestration rate individually for each of these components. Once we have obtained these rates, we will sum them together to arrive at the comprehensive carbon sequestration rate.

The calculation for Phytoplankton:

GIVEN DATA:

Net primary production (C sequestration) of phytoplankton: 355 g/m^3/year (this number is taken from our study available in this document)

CONVERT THE GIVEN DATA TO KILOGRAMS:

Net primary production = 355 g/m^3/year * (1 kg / 1000 g)

1. Net primary production = 0.355 kg/m^3/year

Now, let's calculate the carbon sequestration for our specific area:

Calculate the total carbon sequestration for the given area:

2. Total carbon sequestration = Net primary production * Volume

GIVEN THE VOLUME YOU MENTIONED AS 2.8 BILLION CUBIC METERS:

Total carbon sequestration = 0.355 kg/m^3/year * 2.8 billion m^3

Now, let's calculate the final answer:

Total carbon sequestration = 0.355 kg/m^3/year * 2.8 billion m^3

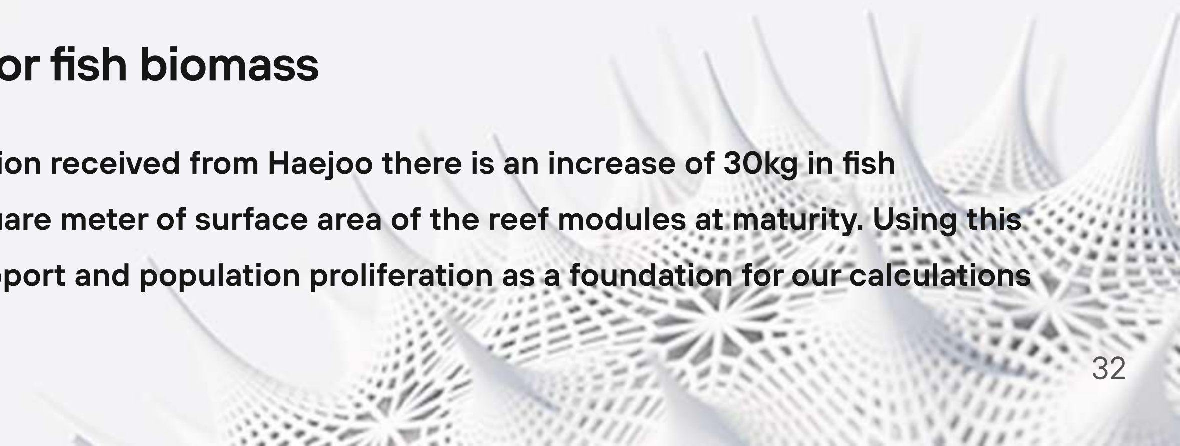
CALCULATING THIS EXPRESSION GIVES US:

Total carbon sequestration = 994 million kilograms or 994,000 metric tons

Therefore, the estimated total carbon sequestration for our area, based on the given data, would be approximately 994 million kilograms or 994,000 metric tons of carbon per year.

However in ocean desert areas Phytoplankton levels are 25% of the levels we find in reef environments therefore 75% of the 994,000 tonnes is directly attributable to the work done by Haejoo. (745,000 Tonnes)

Calculation for fish biomass



Based on information received from Haejoo there is an increase of 30kg in fish population per square meter of surface area of the reef modules at maturity. Using this increase in life support and population proliferation as a foundation for our calculations

we use the above mentioned figure of 12.5% of fish mass attributable to permanent carbon captured and review below.

1. Carbon Sequestration Rate of Fish Biomass:
    - Estimated carrying capacity of fish biomass per cubic meter of reef 30 kg/m^3
    - Average carbon content of a single fish: 12.5% of its whole-body wet weight
    - Calculation:
        - 30kg of fish biomass x 12.5% carbon content = 3.75kg

Total surface area of modules = 103,200 m2 x 3.75kg = 387,000 kg or 387 metric tonnes of carbon

The calculation for Algae

As per our research, it has been determined that a reef with an area of 4000 m^2 has the potential to capture approximately 2.7 tons of CO2 per day.

Based on this information, we conducted calculations to estimate the amount of CO2 captured per year for a given area.

To begin, we calculated the rate of carbon sequestration per year by multiplying the daily CO2 capture rate by the number of days in a year. Using the provided rate of 2.7 tons of CO2 per day, the calculation is as follows:

CO2 captured per year for an area of 4000 m^2 = 2.7 tons/day * 365 days/year = 985.5 tons/year

So per square meter it is 985.5 tons/4000 m^2 = 0.246375 metric tons

With this rate established, we then applied it to the given surface area 103,200 m2 to determine the total CO2 captured per year. The calculation is as follows:

Total CO2 captured per year = CO2 captured per year per square meter * surface area

Total CO2 captured per year = 0.246375/year * 103,200 m2 = 25,426 tons/year

Therefore when taking into account all our individual values

Coral Biomass - 1,268.96 metric tons of CO_2

Seagrass - 1,680 metric tons of CO_2

Seaweed - 120,894metric tons of CO_2

Phytoplankton - 745,000 metric tons of CO_2

Fish - 387 metric tons of CO_2

Algae - 25,426 tons metric tons of CO_2

We estimate the Oman reef built by Haejoo capable of sequestering 894,655.96 metric tons of CO_2

The Remarkable Carbon Sequestration Capacity of the Artificial Reef in Oman

An average passenger vehicle emits approximately 4.6 metric tons of carbon dioxide (CO2) annually. In addition, the emissions from a gallon of gasoline and diesel are estimated to be 8,887 grams and 10,180 grams of CO2, respectively[26]. The combustion of 1 short ton of coal generates about 2.86 short tons[27].

We can assess the carbon dioxide (CO2) sequestration equivalences provided by the artificial reef in Oman:

Passenger Vehicles:

The artificial reef has an impressive sequestration capacity of 894,655.96 metric tons of CO_2. By utilizing this capacity, we can offset the yearly emissions of approximately 194,490 passenger vehicles

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[26] https://www.epa.gov/greenvehicles/tailpipe-greenhouse-gas-emissions-typical-passenger-vehicle#burning

[27] https://www.eia.gov/coal/production/quarterly/co2_article/co2.html

Gasoline Emissions:

Considering that a gallon of gasoline emits about 8,887 grams of CO2, the sequestration capability of the artificial reef is equivalent to offsetting the emissions from approximately 100,670,187 gallons of gasoline.

Diesel Emissions:

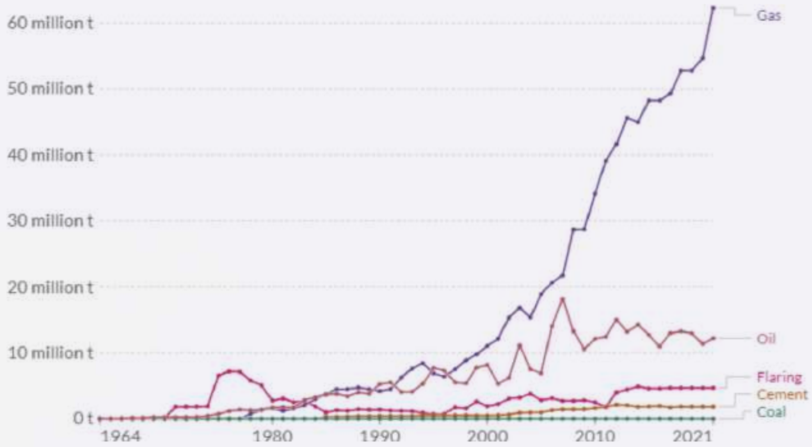
The emissions from a gallon of diesel amount to approximately 10,180 grams of CO2. Consequently, the sequestration potential of the artificial reef would offset the emissions stemming from approximately 8788368 gallons of diesel fuel.

Coal

The combustion of 1 short ton of coal generates about 2.86 short tons. Therefore, the sequestration capacity of the artificial reef would offset the emissions equivalent to approximately 312,816 tons of coal.

The artificial reef designed and built by Haejoo in Oman has a remarkable capacity to sequester a significant amount of CO2, including emissions from coal combustion. Its sequestration rate offsets emissions from passenger vehicles and extensive gasoline and diesel usage. This highlights its effective role in mitigating environmental impacts across various sectors.

CO2 emissions by fuel or industry, Oman



Source: Hannah Ritchie, Max Roser, and Pablo Rosado (2020) - "CO₂ and Greenhouse Gas Emissions". Published online at OurWorldInData.org

After successfully calculating the carbon sequestration rate of our artificial reefs, the next crucial step is to explore methods for further enhancing their carbon capture capacity. By implementing innovative strategies and adopting proactive approaches, we can leverage the potential of these artificial reefs to become even more effective carbon sinks. In this section, we will delve into various techniques and practices that can be employed to boost the sequestration capabilities of our reefs. Through targeted interventions and ecosystem management, we aim to optimize the reef's ability to absorb and store carbon dioxide, thus contributing to climate change mitigation efforts. Let us now explore the key methods that can be employed to increase the carbon capture capacity of our artificial reefs.

Methods for Assessing Carbon Capture Rates

Remote sensing

Remote sensing is a technique used to collect data about the environment and objects from a distance. It involves the use of sensors and instruments on satellites or aircraft to measure and analyze the characteristics of the earth's surface, including vegetation, water bodies, and carbon sequestration. Remote sensing can capture spatial variability, quantify uncertainty, and improve carbon estimates. Remote sensing is critical for national carbon monitoring programs that fulfill IPCC level 3 data requirements. Therefore, NDCs supplement the existing need for remote sensing monitoring of WC systems. The gap between these scales will increasingly rely on earth observation. System-specific estimates are often extrapolated from limited in situ data, but remote sensing can capture spatial variability, quantify uncertainty, and improve carbon estimates[31].

Remote Sensing and Machine Learning-Based Biomass Estimation

The biomass of the sponge Spongosorites coralliophaga and the coral Lophelia pertusa was calculated from images extracted from remotely operated video footage. Environmental variables derived from acoustic data, such as depth, BPI, rugosity, backscatter, and slope, were utilized to create a biomass predictive map using a random forest model approach. This map enabled the estimation of standing stock biomass, annual carbon turnover, and exploration of the potential food supply to the reef[32]

In-situ measurements

In-situ measurements, including optical technology, semiconductor gas sensing, and mass spectrometry, have been commonly used for measuring dissolved gases in seawater. Mass

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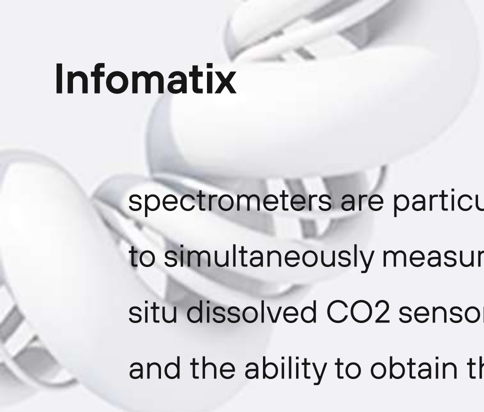
[31] Anthony D Campbell et al 2022 Environ. Res. Lett. 17 025009 https://iopscience.iop.org/article/10.1088/1748-9326/ac4d4d

[32] De Clippele, L.H., Rovelli, L., Ramiro-Sánchez, B. et al. Mapping cold-water coral biomass: an approach to derive ecosystem functions. Coral Reefs 40, 215–231 (2021). https://doi.org/10.1007/s00338-020-02030-5



spectrometers are particularly versatile sensor systems due to their high sensitivity and ability to simultaneously measure multiple chemical species[33]. As per the study, a fiber-integrated in-situ dissolved CO2 sensor using CRDS was developed with a detection sensitivity of 1.8 ppm and the ability to obtain the whole absorption spectrum of CO2 within 90 seconds. The developed sensor shows promise in achieving high-precision detection of dissolved gas in seawater and supporting investigations on the ocean's vertical dissolved CO2 profile and long-term dissolved CO2 monitoring under deep-sea extreme environments[34].

Benthic chamber measurements

Benthic chamber measurements for assessing carbon sequestration rates involve deploying a sealed chamber onto the benthic ecosystem of interest. The chamber allows researchers to measure the exchange of gases, particularly carbon dioxide (CO2), between the sediment and the water column. By collecting water and gas samples at regular intervals, the concentration changes of CO2 and other greenhouse gases can be measured over time. These measurements provide valuable insights into the carbon sequestration potential of benthic ecosystems, helping us understand their role in mitigating climate change and the efficiency of different carbon sequestration methods.

Sediment analysis

Sediment analysis is a widely utilized method for assessing carbon sequestration rates in marine environments. It involves collecting sediment samples from the seafloor or nearshore areas and analyzing them to determine their carbon content. Various techniques, such as combustion or elemental analysis, are employed to measure the organic carbon content in the sediments. Sediment analysis provides valuable insights into the carbon storage potential of marine ecosystems, helping researchers understand the role of sediments in carbon sequestration processes. By quantifying the carbon content in sediments, scientists can assess the effectiveness of marine environments in mitigating climate change by acting as carbon sinks. In sediment analysis, various instruments and techniques are used to analyze sediment

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[34] Zhang, H., Jin, W., Hu, M., Hu, M., Liang, J., & Wang, Q. (2021). Investigation and Optimization of a Line-Locked Quartz Enhanced Spectrophone for Rapid Carbon Dioxide Measurement. Sensors (Basel, Switzerland), 21(15). https://doi.org/10.3390/s21155225

samples. Common instruments include spectrometers, elemental analyzers, and combustion analyzers. These instruments allow for the measurement of parameters such as organic carbon content, elemental composition, and other geochemical properties of the sediments.

Biological monitoring

Biological monitoring for measuring carbon sequestration rates in marine environments involves the use of various instruments and techniques. This includes underwater vehicles equipped with cameras and sensors to collect data on the distribution and abundance of marine organisms. Plankton nets, acoustic technologies, and sediment corers are also employed to study different biological indicators. Integrating data from these instruments helps scientists assess the carbon sequestration potential of marine ecosystems and their role in mitigating climate change impacts.

Water column measurements

Water column measurements are important in understanding marine ecosystems. These measurements involve collecting data on various parameters within the water column to analyze ecological processes. Key measurements include dissolved inorganic carbon (DIC) and total alkalinity (TA) to assess carbon species concentration, partial pressure of carbon dioxide (pCO2) to understand carbon exchange, and nutrient concentrations and chlorophyll-a concentration to evaluate nutrient availability and primary producer biomass. Through water column measurements, scientists gain valuable insights into the dynamics and characteristics of marine ecosystems.

Exploring these diverse strategies to calculate sequestration rates has been instrumental in our efforts to accurately assess the carbon capture potential of our artificial reefs. These methodologies have provided valuable insights into the sequestration rates achieved by our reefs, enabling us to gain a deeper understanding of their contribution to carbon sequestration. With this knowledge, we can make informed decisions and implement targeted measures to enhance the sequestration capacity of our artificial reefs. We will now shift our focus to the native species present in Oman's waters and their significant role in the carbon sequestration process.

Appendix

Native species present in Oman’s water

The coastal waters of Oman are home to a diverse array of native species, including seagrass and seaweed, that play a crucial role in the carbon sequestration dynamics of this marine ecosystem. Through dedicated studies and research, we have gained valuable insights into the characteristics, distribution patterns, and ecological significance of these native species.

Seagrass

In a study on seagrass communities along the coast of Oman, the researchers focused on the western side of Masirah Island. The study investigated the distribution, abundance, and biomass of seagrasses to gain insights into the ecological characteristics of these ecosystems. Two dominant seagrass species, Halodule uninervis (Forssk.) Aschers. and Halophila ovalis (R. Brown) Hook., were identified, showing overlapping depth distributions but an inverse relationship. Halodule predominated in the intertidal zone, while Halophila was more prevalent in the deep subtidal areas. The biomass allocation analysis revealed that Halophila displayed an equal distribution between leaves and below-ground structures, whereas Halodule had significantly lower leaf biomass. Additionally, the study documented the occurrence of Syringodium isoetifolium (Aschers.) Dandy in Umm ar Rasas Bight, adding to the total seagrass species recorded in Oman. These findings contribute to our understanding of seagrass dynamics in Oman's coastal ecosystems[35].

Seaweed

The coastal zone of the Oman Sea, specifically in the Sistan and Baluchestan province, encompasses a 300 km stretch and serves as a diverse habitat for various species of seaweeds. To investigate the species identification and distribution of seaweeds in this region, the study selected 11 stations and conducted seasonal samplings using the scuba-diving

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[35] Jupp, B., Durako, M., Kenworthy, W., Thayer, G., & Schillak, L. (1996). Distribution, abundance, and species composition of seagrasses at several sites in Oman. Aquatic Botany, 53(3-4), 199-213. https://doi.org/10.1016/0304-3770(96)01023-6

method. The study identified a total of 42 seaweed species, comprising 3 species of green algae, 17 species of brown algae, and 22 species of red algae. Among the brown algae, the dominant species included Stoechospermum marginatum, Padina australis, Dictyota sp., Sargassum glaucescens, and Cystoseira indica. Notable red algae species with economic significance included Gracilaria corticata, Gelidiella acerosa, Gelidium micropterum, and Hypnea musciformis. Green algae were exclusively found in the Passabandar and Chabahar regions, with Ulva fasciata being the primary species. The study also measured various environmental factors, such as sea and ambient temperature, salinity, pH, growing depth, dissolved oxygen, substrate structures, slope, and transparency. The maximum and minimum growing depths of seaweeds were observed in the Tang and Gwatr areas, respectively[36].

Below is a table presenting the data on biodiversity in Oman.

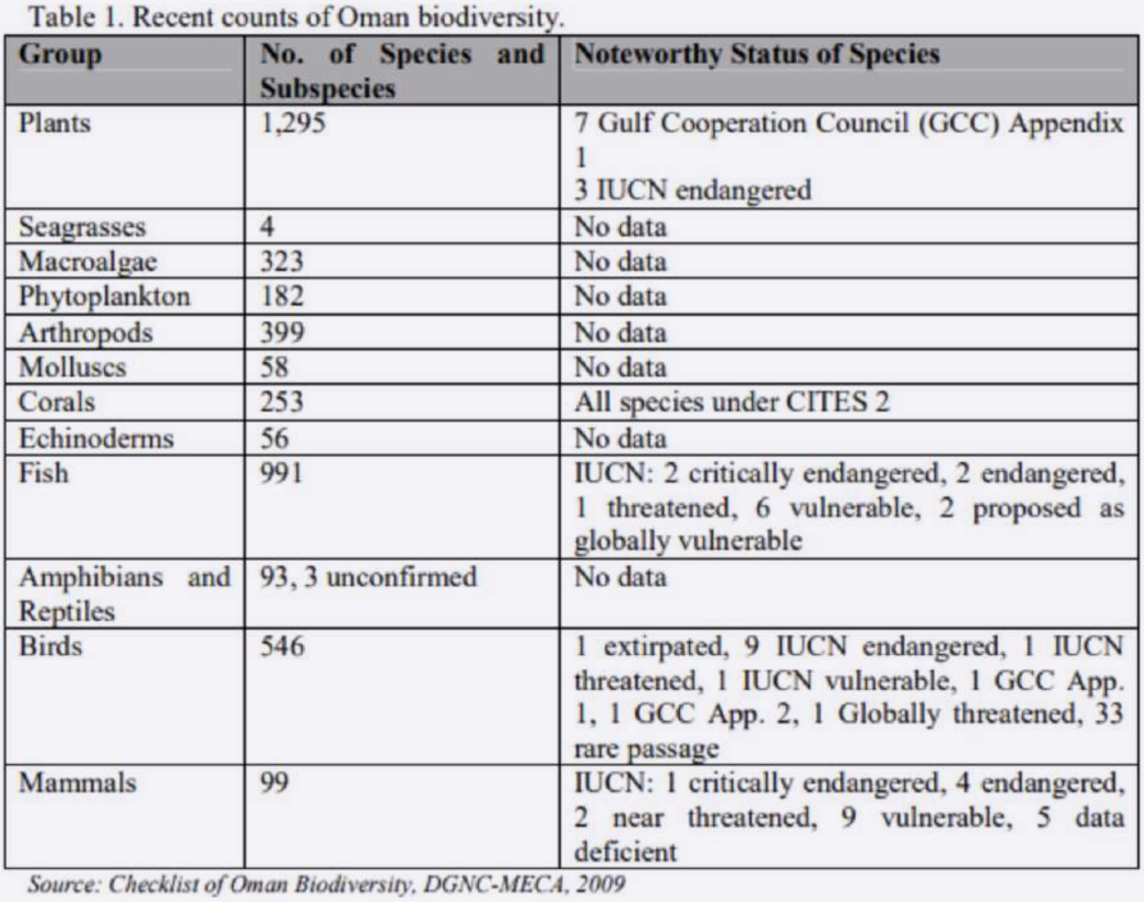

Table 1. Recent counts of Oman biodiversity.

Group	No. of Species and Subspecies	Noteworthy Status of Species
Plants	1,295	7 Gulf Cooperation Council (GCC) Appendix 1 3 IUCN endangered
Seagrasses	4	No data
Macroalgae	323	No data
Phytoplankton	182	No data
Arthropods	399	No data
Molluscs	58	No data
Corals	253	All species under CITES 2
Echinoderms	56	No data
Fish	991	IUCN: 2 critically endangered, 2 endangered, 1 threatened, 6 vulnerable, 2 proposed as globally vulnerable
Amphibians and Reptiles	93, 3 unconfirmed	No data
Birds	546	1 extirpated, 9 IUCN endangered, 1 IUCN threatened, 1 IUCN vulnerable, 1 GCC App. 1, 1 GCC App. 2, 1 Globally threatened, 33 rare passage
Mammals	99	IUCN: 1 critically endangered, 4 endangered, 2 near threatened, 9 vulnerable, 5 data deficient

Source: Checklist of Oman Biodiversity, DGNC-MECA, 2009

Table source: FOURTH NATIONAL REPORT TO THE CONVENTION ON BIOLOGICAL DIVERSITY, Ministry of Environment and Climate Affairs Sultanate of Oman

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[36] Gharanjik, B. M. IDENTIFICATION AND DISTRIBUTION OF SUBTIDAL SEAWEEDS IN THE OMAN SEA. Jan. 2003.