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An overview of strategies for enhancing coral reef resilience

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Index

ABSTRACT

Coral reefs are a highly diverse marine ecosystem that provide many services, alongside economic opportunities for humans; however, four decades of extreme climate changes, diseases and unprecedented habitat loss have severely impacted their wellbeing making them endangered. Coral reefs damage and losses are predicted to continue unless their resilience to their stressors is increased. Passive restoration has always been the first choice when talking about enhancing coral reefs' resilience. However, in recent years, active restoration efforts have started to emerge and show promising results. This thesis aims to provide a comprehensive overview of both methods, presenting the strengths and weaknesses of each approach and discussing their respective impact on the ultimate goal of coral reef restoration without the presumption of identifying what the best method may be.

1. INTRODUCTION

1.1. *What are corals*

Corals are marine invertebrates within the call Anthozoa of the Phylum Cnidaria [National Geographic, 2011]. Cnidarians have two basic forms: swimming medusae and sessile polyps, both of which are radially symmetrical with mouths surrounded by tentacles that bear cnidocytes: cells that fire harpoon-like structures used to capture prey, defend themselves and, in some cases, as an anchor [Chen et al. 2020, Thorp and Covich 2001].

There are two major groups of corals: soft and scleractinian (hard corals). Soft corals are soft and bendable and do not have stony skeletons; instead, they grow wood-like cores and fleshy rinds for protection. These corals are non-reef-building ones. [Coral Reef Alliance, n.d.]. Many scleractinian corals (or hard corals) possess polyps that are filled with symbiotic photo-synthetic zooxanthellae from which they get almost 90% of their energy. Zooxanthellae and corals have a mutualistic relationship: the latter ones provide algae with a protected environment and compounds they need for photosynthesis; whereas algae produce oxygen and help the coral to remove waste. Zooxanthellae provide the host with glucose, glycerol and amino acids (the products of photosynthesis) [US Department of Commerce, National Oceanic and Atmospheric Administration, 2019]. The coral uses these products to make proteins, fats and carbohydrates and produce calcium carbonate. This relationship between the algae and the polyp facilitates the tight recycling of nutrients in nutrient-poor tropical waters. In addition, zooxanthellae are responsible for the variety of colors of many stony corals [National Geographic, 2011]. Almost all of them are colonial organisms, so they are composed of hundreds to hundreds of thousands of very small polyps, averaging 1 to 3 millimeters in diameter. The skeletons of stony corals are secreted by the lower portion of the polyp. This process produces a cup, or calyx, where the polyp sits. Periodically the polyp will lift off its base and secrete a new basal plate above the old one, creating a small chamber in the skeleton. While the coral is alive, calcium carbonate is deposited elevating the polyp [Hughes, 1987]. Hard corals grow in different morphologies [figure 1] with particular characteristics: we can find ones that look like flowers, others resembling very intricate tables; some are flat elongated uni-polyp corals that lay on the ground, whereas some grow vertically looking like stalagmites. There are brain-looking corals with a very strong structure but a slow growth rate (massive corals) or tree-looking ones with a very fast growth rate but a weaker structure (branching corals). All these differences make them diverse and versatile so that they can occupy different niches creating a variety of ecological services for their ecological role in both solitary colonies and reefs [Darwin 1976, Moczek 2020].

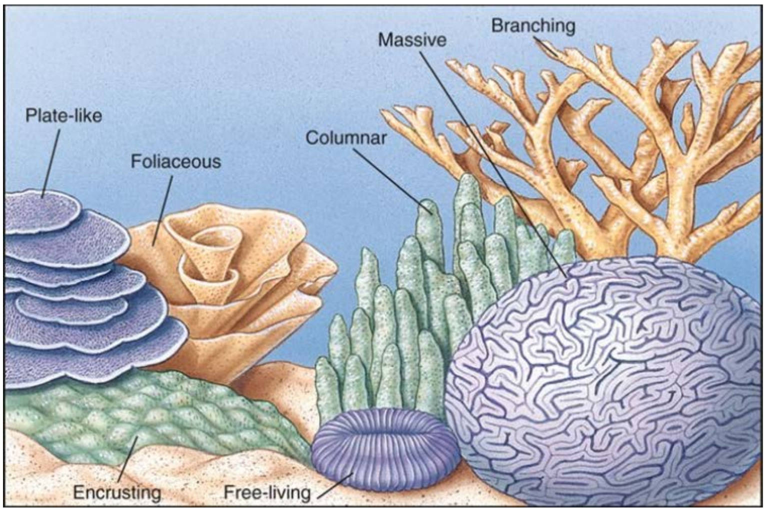

Figure 1: Visualization of the different types of corals. Picture of The McGraw-Hill companies.

1.2. What are coral reefs

A coral reef is an underwater ecosystem characterized by reef-building corals. Reefs begin to form when free-swimming coral larvae attach to submerged rocks or other hard surfaces along the edges of islands or continents [NOAA, 2019]. This happens thanks to coral sexual reproduction, which differs depending on the species. As the corals grow, expand and reproduce, reefs can take one of these major characteristic structures: fringing, atoll, barrier or platform [Coral Reef Alliance n.d., Darwin, 1976].

1.3. Why are they important

Corals provide food, shelter and nurseries for more than 25% of all marine species and support over five hundred million people around the world, despite only covering 0,1% of the earth's surface. These environments, when healthy, support six million fisheries in nearly 100 countries [Cinner et al. 2012] and provide jobs, education opportunities, tourism, and recreational activities for an estimated income of $367 billion to the global economy each year [Prayaga, 2017]. Thanks to their structures, reefs also protect shorelines from up to 97% of the energy from waves, storms and floods, helping to prevent loss of life, property damage and erosion [van Zanten, van Beukering and Wagtendonk, 2014]. The biodiversity is considered, among other things, key to finding new medicines: many organisms found on reefs produce chemical compounds that have been used in treatments for different types of diseases such as ulcers, leukemia, lymphomas and cancer [Coral Reef Alliance n.d.]. To ensure that people and wildlife can continue to rely on the numerous services this incredible environment provides, we must concentrate our efforts on decreasing stressful factors that are severely compromising coral reefs' health and balance.

1.4 Threats and solutions

There are several risks to the coral reef ecosystem that have both natural and anthropogenic origins. Most issues considered a risk to coral reefs are a direct (and indirect) product of human activities on land and in the ocean. Natural impacts such as an increase in natural predators, diseases and climate effects such as El Niño and storms are just the tip of a sinking iceberg: pollution (chemical and physical), unsustainable tourism, overfishing and injurious practices of fishing (blast fishing or ground scraping), sedimentation and global warming must be included in what is killing coral reefs [El-Naggar, 2020]. The most striking example of the results of the aforementioned threats is coral bleaching [figure 2].

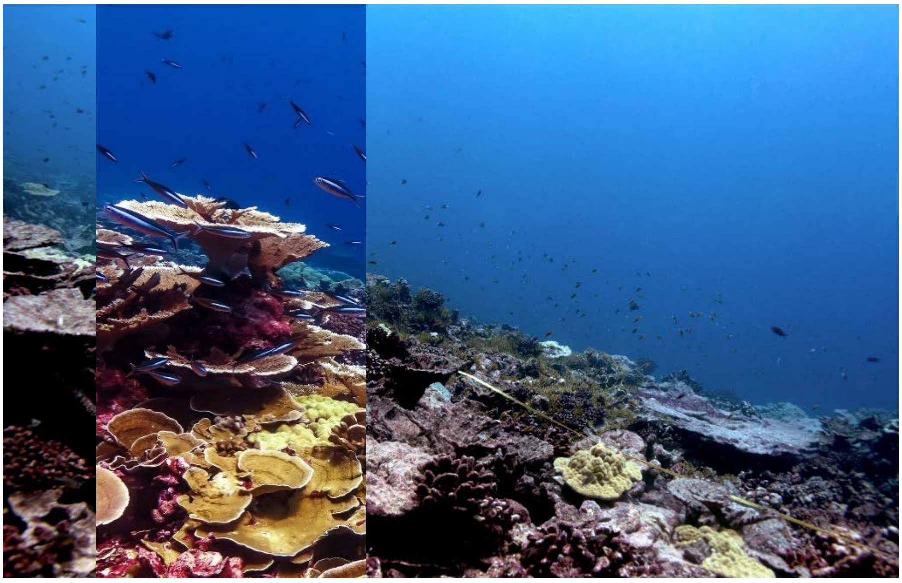

Figure 2: Collage of two photographs taken by Kieran Cox and Christina Tietjen of the before and after the bleaching event of 2016 on Christmas Island.

In fact, coral bleaching, or the reversible loss of zooxanthellae, is a general signal of a variety of abiotic and biotic stressors. When under stress, corals expel zooxanthellae disrupting their mutualistic relationship, allowing the white skeleton to become visible. When this happens, they are deprived of their internal photosynthetic energy which can lead to their death. This phenomenon has been known for more than a hundred years and, from the late 90s, we've had five mass-bleaching events leading to the loss of more than half of all the known reefs [Plass-Johnson et al., 2014]. The combination of stressors is damaging corals at an incredible rate, much faster than their natural growth cycle, making it impossible for them to keep up. Coral reefs take hundreds of years to form and, if the current situation doesn't change, 90% of all reefs in the world will disappear in our lifetimes [Boström-Einarsson et al., 2020]. To prevent this, different conservation and restoration methods have been adopted and more are currently being tested.

2. DISCUSSION

Resilience is defined as the capacity of a system to maintain key functions and processes in the face of stressors by resisting, recovering from and adapting to change. Coral reef resiliency is determined by various ecological and socio-ecological characteristics such as high levels of biodiversity (including genetic diversity, species diversity and morphological diversity) that increase chances of varied responses to threats [Cinner and Barnes 2019, Cinner and Kittinger, 2015].

2.1 Corals innate resilience

Corals have the ability to recover on their own from stresses using different mechanisms.

2.1.1 Reproduction

Corals can reproduce both sexually and asexually [Figure 3]. Asexual reproduction can

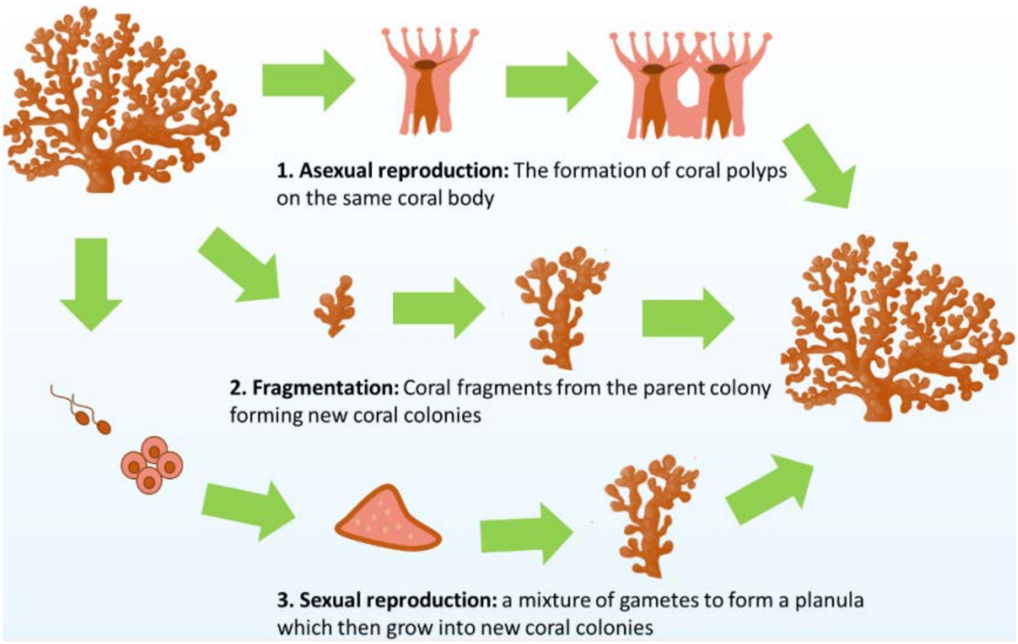

Figure 3: Schematic illustration of coral life cycle. Image taken from Islam I., 2020.

happen through fragmentation or polyp budding [Randall et al., 2020]. Sexual reproduction, on the other hand, happens through internal and external fertilization. Similar strategies can be found in many beings. Reproducing both ways grant different benefits; for instance, an organism might desire to reproduce asexually to establish a large, uniform population if the environment is highly stable and there are enough resources available. The same organism can, however, take advantage of sexual reproduction to produce a population that it's more diversified and, consequently, is able to tolerate better different conditions. [Friedl, 2017]

2.1.1.I Asexual reproduction

Fragmentation

Many corals are frequently broken into live fragments, often as a result of physical disturbances. These pieces are capable of sexual reproduction and autonomous survival. In circumstances in which sexual recruitment is difficult, fragmentation can be the primary mode of population growth [Bruno, 1998]. Because the risk of mortality is dispersed over many pieces, the genet (all colonies descended from the same sexual recruit) may benefit from fragmentation in the long term. In addition, it is widely believed that asexual reproduction by fragmentation is adaptive and that it has evolved as a result of natural selection, as it can help postpone or eliminate mechanical size limits in tree-like colonies [Smith and Hughes, 1999]. Furthermore, fragmentation may facilitate the colonization of unstable sediments where larvae struggle to settle [Bothwell, 1981].

Polyp budding

This is an accretive process through which polyps of a colony clone themselves and reproduce directly on the colony surface [Sakai, 1998]. The bud can be intra-tentacular or extra-tentacular; the former is the process by which the parent polyp splits into two or more daughter polyps, whereas the latter occurs when daughter polyps grow outside of the tissue, close to the parent. In comparison to its neighbors, the new polyp is often smaller, although it eventually grows [Gateño and Rinkevich, 2003]. This process allows the coral to grow, resulting in a larger amount of polyps and, consequently, more gametes and more cnidocytes. Thanks to polyp budding, the colony will be stronger both genetically and physically so will have more chances to survive and share its genetic material.

2.1.1.II Sexual reproduction

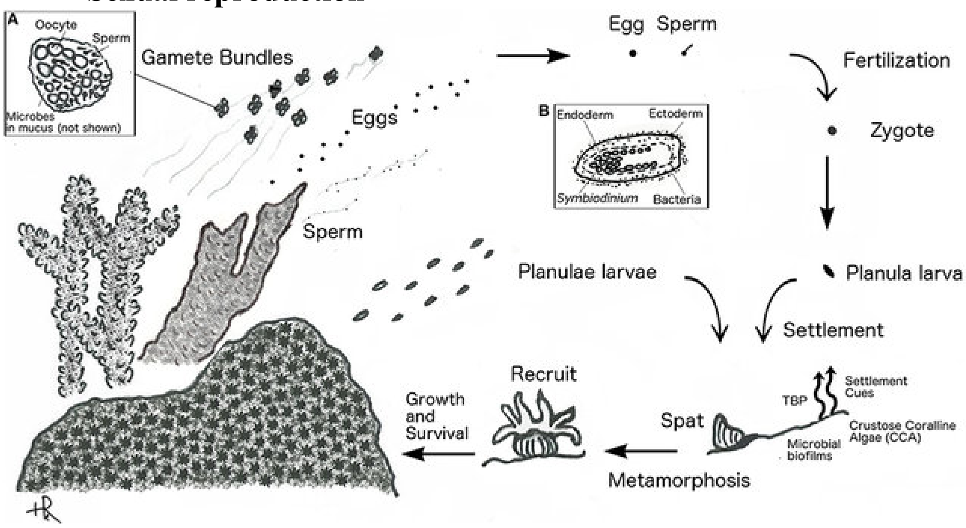

Figure 4: Sexual reproduction cycle. Picture from Thompson et al., 2015

Corals sexually reproduce by either internal or external fertilization [Picture 4]. The former consists in swimming male gametes fertilizing eggs, which are then brooded by the polyp for days or weeks and then free-swimming larvae are released into the water to settle on the reef. External fertilization, on the other hand, happens in the water column thanks to the mass spawning sometimes synchronous to maximize fertilization [Moczek 2020, Fadlallah, 1983]. In this case, when released, eggs are fertilized to form free-floating larvae called planulae [Chen et al. 2020]. After the fertilization, larvae will start swimming in search of the most appropriate spot to settle; planulae settling is determined by physical conditions such as light and noise and by chemical stimulations [NOAA 2019].

Corals can be classified as belonging to one of four fundamental sexual reproductive patterns: hermaphroditic broadcast spawners, hermaphroditic brooders, gonochoric broadcast spawners, or gonochoric brooders [Harrison, 2011]. As opposed to gonochoric corals, which have separate sexes, hermaphroditic corals have both sexes developed in their polyps and colonies; these corals either spread spawn their gametes for external fertilization, where they develop into embryos and larvae, or they internally fertilize their gametes and brood embryos and planula larvae within their polyps. The spreading of gametes or larvae happens through synchronous and asynchronous spawning. We can define two main types of synchronous spawning: mass spawning and multispecific spawning. This is the synchronous spawning of two or more species according to definition, whereas mass spawning was originally used to describe the highly synchronous nighttime spawning of several coral colonies of numerous species from a variety of scleractinian families [Harrison and Booth, 2007].

2.1.2 Algal selection and change

Coral reef ecosystems are based on the coral-zooxanthellae symbiosis. Most corals obtain their own zooxanthellae (*Symbiodinium spp.*) from their surroundings during the beginning stages of this process. Yamashita et al. observed that the acquisition of certain species of zooxanthellae is not random, but rather that corals tend to prefer certain species over others [Yamashita et al., 2014]. The reason of this choice remains unknown, but what was observed is that some S*ymbiodinium spp.* have more thermal resistance than others. This means that corals that host this type of algae will be less susceptible to bleaching events [Sampayo et al., 2008]. Bleaching is the loss of the hosted algae as a generalized reaction/consequence brought on by a number of environmental factors outside of the usual [Buddemeier and Fautin, 1993]: for example, corals that are exposed to sea water 1.5 to 2 degrees Celsius above the average experience dramatic reductions in the pigmentation and photosynthetic activity of the dinoflagellates which causes Symbiodinaceae to be ejected from the coral tissue and disrupt the mutualistic interaction, causing the white coral skeleton to be seen through the transparent animal tissues. Despite the decrease in fitness, some bleached colonies are able to recover pigmentation and functionality. The only distinguishable difference between the fragments that were able to recover after the stress and those that were not, was the presence of substantial colonies of *Ostreobium spp*. close to the surface of the skeleton. This particular type of algae that blooms near the skeletal surface, thanks to the ability to modulate light levels that arise within the bleached coral tissue, facilitate the recovery [Galindo-Martínez et al., 2022].

2.1.3 Coral fluorescence

Many coral species contain a variety of non-photosynthetic pigments of host origin that are not diminished in concentration or lost during bleaching events. These pigments can result in bleached corals that appear pink, chartreuse, purple, yellow or other colors, rather than the more typical white [Baker, Glynn and Riegl, 2008]. The purpose of this change in coloration is still under investigation but it is currently believed to be a self-defense strategy against UV and/or a mechanism to be more easily found by zooxanthellae [Salih et al., 2000; Roth and Deheyn, 2013].

2.1.4 Disease resistance

Resistance is described as an organism's innate or learned capacity to preserve its capacity to withstand the impacts of an antagonistic agent, such as a pathogenic bacterium, toxin, or medicine. Corals have intrinsic or natural immunity: a general capacity to respond to a wide range of potentially harmful organisms that is unaffected by subsequent exposure [Mullen, Peters and Harvell, 2003]. A key aspect of the generalized innate response in scleratinian colonies is the shedding of thick sheets of mucus, which clears colonies of debris and possible pathogens [Reed, Muller and Van Woesik, 2012]. Also, in response to disease exposure, resistant species showed similar differences in the gene expression patterns that support immunity. It was demonstrated that these genes, involved in the coral natural defenses, are highly correlated with the lesion progression rate. This correlation suggests that the immune system is activated when the infection spreads through the tissue and the coral tries to fight it [MacKnight et al., 2022].

2.2 Restoration methods

Despite the great self-recovering efforts of corals, they rarely are enough. This is why it's important to help coral resilience strengthen with all our might.

2.2.1 Passive restoration methods

Passive restoration aims to reduce the factors that contribute to reef deterioration hoping to give the ecosystem a chance to heal itself via the mechanisms described in Section 2.1. This approach includes the creation of management strategies to enhance the environment. This enhancement can be both intentional and unintentional: for example, the air quality improvement during the Covid 19 pandemic can be a good example of the latter [Nie, Shen and Wang, 2021]. Direct intervention on the habitat without actually interfering with corals, is also considered passive restoration. For instance, Crown-of-thorn starfish population breakouts undermine the integrity and obduracy of reef ecosystems by causing significant loss of coral cover; the removal of such natural coral predators can enhance the habitat resilience [Vercelloni, Caley and Mengersen, 2017]. Intentional interventions also include the institution of Marine Protected Areas (MPAs) or the drafting of legislation that can protect marine habitats. It has been demonstrated that MPAs have improved the resistance and recovery of coral reef community structure in response to a variety of disturbances [Mellin et al., 2016]. Although the usual way of conservation is "protecting first, restoring later", in the years was demonstrated that protected areas often have inadequate implementation and administration, and they cannot ensure the preservation of unaltered habitat, species populations, or natural ecosystems [Possingham, Bode and Klein, 2015]. Sometimes passive restoration alone is not enough to improve the habitat resilience so that it can recover for itself, therefore, it's important to keep ameliorating active restoration with pioneering research.

2.2.2 Active restoration methods

The scientific field of actively restoring denuded coral reef regions has received a lot of interest in the last two decades as it has been clear that this ecosystem rarely recovers spontaneously from anthropogenic stress without intervention. As a result, restoration efforts conducted all around the world over the past twenty years have gained recognition as a key instrument for reef rehabilitation. To enhance coral reef regeneration, a number of different restoration approaches have been proposed. [Rinkevich, 2005].

2.2.2.1 Asexual Propagation methods

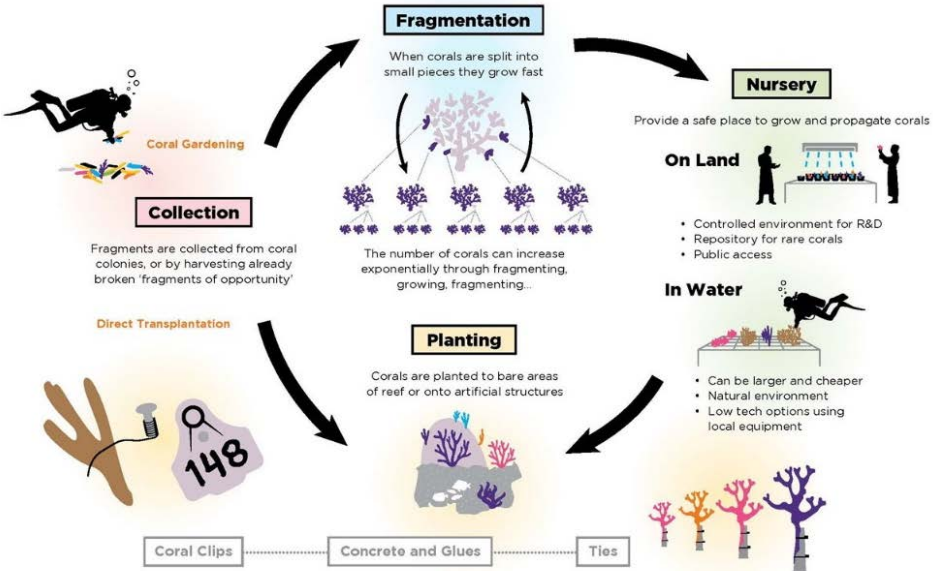

Figure 5: Schematic explanation of the steps of the asexual propagation methods and the differences between Coral Gardening and Direct Transplantation. Picture from Reef Ecologic, 2018.

Direct transplantation

This method involves the transplantation from a donor to a recipient reef. Whole coral colonies, pieces taken from donor colonies in the wild, and detached fragments recovered from the reef ("corals of opportunity") have all been used as transplants [Figure 5]. It is important to note that direct transplantation should normally be attempted only in areas where local anthropogenic effects are managed in some way. To reduce transplant complications, avoid transplanting right before the stormy season and during the time of year when water temperatures are at their peak. The more time transplants have to self-adhere to the substrate before the harshest weather period, the better. [Gomez, Edwards and Dizon, 2010].

Coral gardening

Coral gardening is the most widely used active restoration method. This strategy is based on the concepts of silviculture and is a two-step process [Precht, 2006]. The first step is called the *nursery phase* that involves the creation and maintenance of colonies in underwater coral nurseries under ideal circumstances, with each colony starting from a coral fragment or a coral nubbin. The nurseries can be both in-situ or ex-situ (e.g. in aquariums) [Petersen et al., 2005]. The latter is especially used when research needs to be carried out on the collected species. Currently, many studies focus on genetic research [Baums, 2008] and the special symbiosis between coral and algae. It's very useful to have the possibility to conduct research both in loco and in the aquariums so to have a wider picture of all the paths a study can follow. When the nursery-farmed coral colonies have grown to an appropriate size, it's time for the *transplantation phase*, where fragments are out-planted into deteriorated reef sections [Rinkevich, 2021]. This method, being a type of transplantation, works under every circumstance cited in the above section.

2.2.2.II Sexual propagation methods

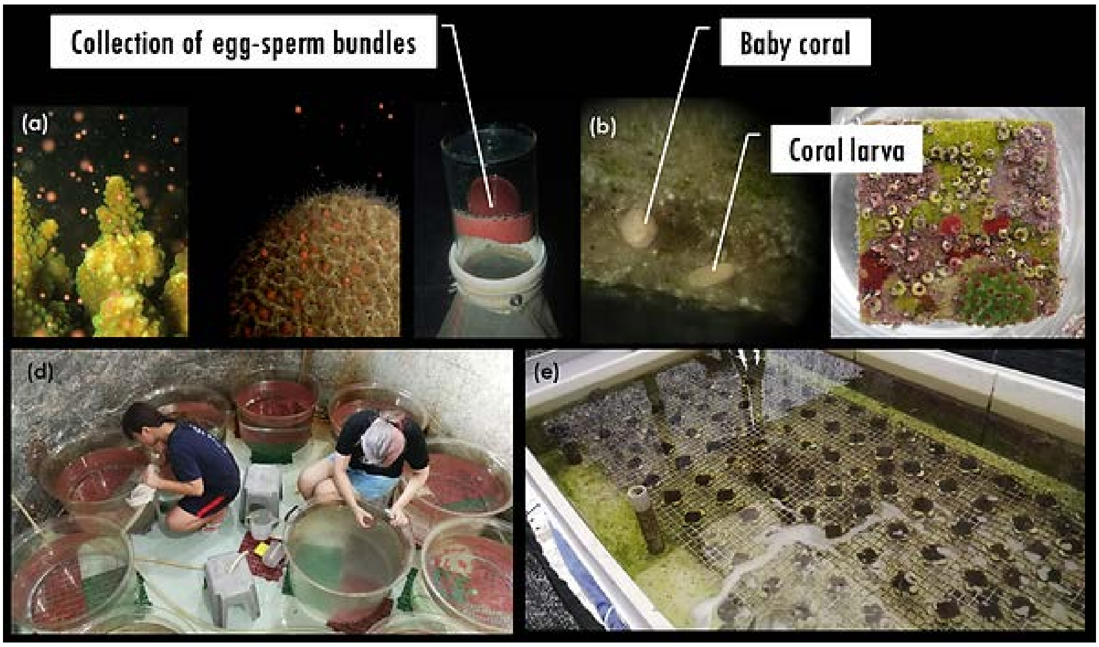

Figure 6: Steps of farming sexually propagated corals in a laboratory. Picture from ©Coral Academy.

As an alternative to coral transplantation, sexual propagation has been widely proposed. This technique works by putting non-invasive collection devices around individual colonies, gametes from broadcast spawning corals and brooding corals may be collected in situ. Alternatively, corals can be collected and kept in hatcheries prior to spawning events. Once the larvae are collected, fertilization is accomplished mostly by combining sperm and eggs in a container with fresh, filtered sea water [Figure 6]. It may be useful to transfer planula larvae into tanks containing zooxanthellae prior to settling; this is because the sooner zooxanthellae bind to larvae, the sooner the larvae may use the different photosynthates produced by algal photosynthesis [Barton, Willis and Hutson, 2015]. The main benefit of this collection is avoiding the loss of potential offspring in the dispersion. By capturing most of gametes and keeping them in high densities, fertilization and settlement success is increased. In the absence of suitable stimuli for settling and transformation, planulae may remain in their larval stage and perish, that's why it's important to provide the right substrate [Linden and Rinkevich, 2011]. Sexual propagation that harnesses the corals' high fertility, holds the promise of increased genetic variety and minimal harm to source colonies, yet established sexual propagation procedures remain elusive due to high post-settlement death rates in the first year [Wilson and Harrison, 2005; Boch and Morse, 2012].

2.2.2.III Substrate enhancement

Artificial Reef

Figure 7: The Reef Ball is just an example of artificial reef. On the right we can see the wanted outcome in every type of structure. Left picture taken by Dave C. Right picture taken from the Reef Ball Foundation brochure.

Artificial reefs (AR) are man-made structures that are built in aquatic settings to provide habitat or refuge for creatures [Vivier et al., 2021]. They also alter currents, consolidate rubble, impede fishing or serve as a tourist attraction.

The difficulties connected with reef destruction (such as ship grounding), with fishes and some macroinvertebrates are typically not the direct loss of the animals per se, but the loss of refuge provided by coral and epifaunal structure. As a result, providing required shelter is the primary purpose of artificial structure in coral reef restoration operations [Spieler et al., 2001]. These structures have been built using a range of materials, including wood, steel, fiberglass, PVC, materials-of-opportunity, tires, electro-deposition of CaCO3 /Mg(OH)2, stones and concrete [Grove et al., 1991]. In most cases, though, the last two or a combination of them has been the material of choice because they provide a substrate of comparable composition to that replaced, they are durable, have a heavy strength for stability, are economical, and, in most circumstances, they are accessible [Spieler et al., 2001]. The majority of artificial reefs are built on the seafloor (bottom-founded) and must be placed in shallower water settings [Figure 7]. This puts the structures in close proximity to dangers including coastal development and pollution. Therefore, some paired them with modular very large floating structures (VLFS), maximizing the ecological benefits found in new ecosystems created around offshore platforms [Luo et al., 2022].

Substratum stabilization

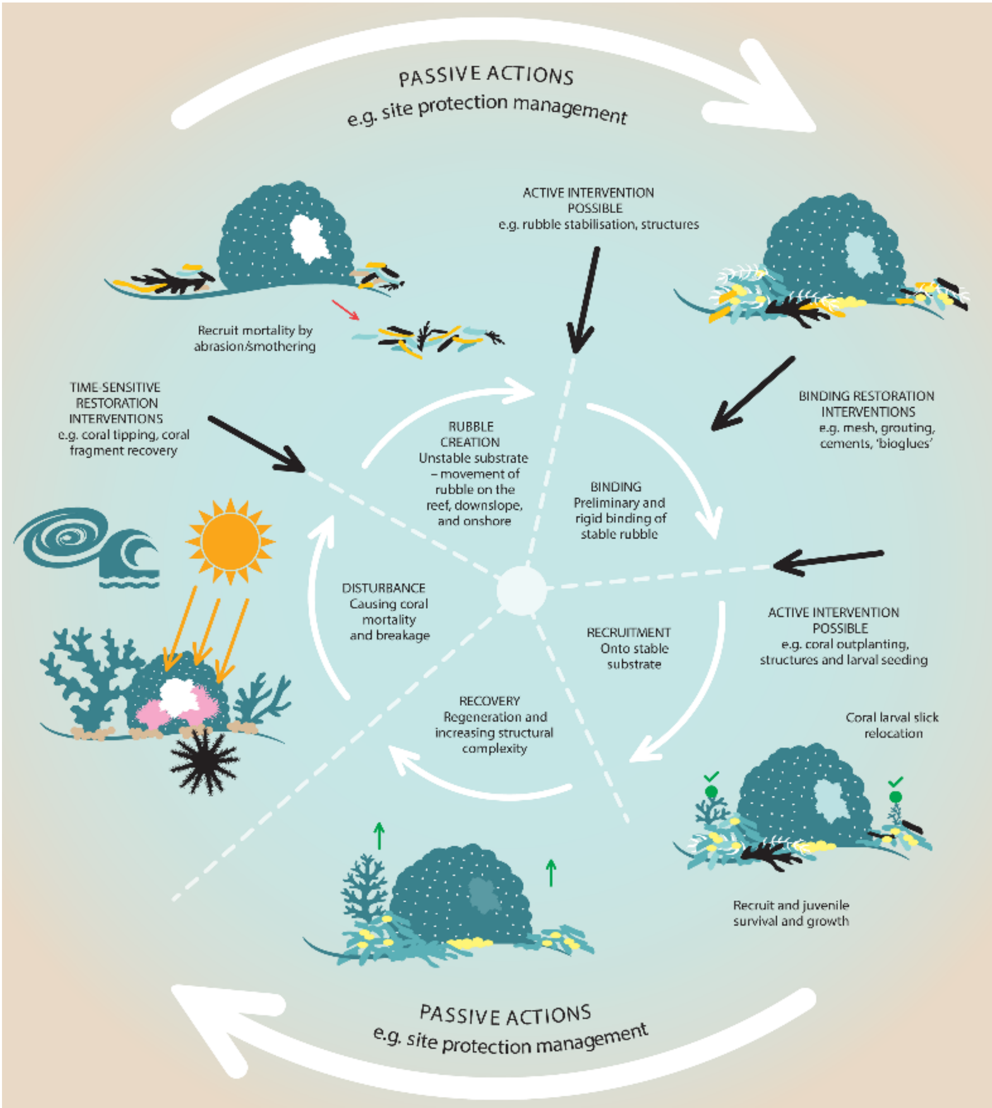

Figure 8: Schematic explanation of when active work may be needed. The inner ring shows the natural progression of rubble formation and settlement. When this process it's not possible, can be artificially induced. Picture from Ceccarelli et al., 2020.

Habitat degradation heavily contributes to the decline of coral reefs worldwide. Rubble areas are a natural element of the intricate habitat diversity of coral reefs, but their fragility and lower structural complexity can be associated with poor coral species assemblages. Unattached rubble – defined as reef rocks and dead coral skeleton dislodged by chemical and mechanical causes – can operate as a "death field" for corals, preventing coral recruit survival and the creation of adult coral colonies, and it can cause further damage by rolling and damaging surviving living coral colonies under high surge conditions.

Human activities, such as ship grounding and blast fishing, and climate-related stresses can both decrease reef's structural complexity that is predominantly given by scleractinian corals and is essential for maintaining a biodiverse reef environment and moderating ecological processes such as recruitment, predation, and competition. For rubble it is possible to settle naturally, with the help, of course, of algae and sponges that eventually grow and bind the different pieces [Ceccarelli et al., 2020]. When this natural settlement is not possible, active restoration comes in handy [Figure 8]. Cementation, encrustation, and sponge stabilization have all been documented as biological methods for substrate stability, providing adequate foundation for multi-species coral colonization [Perry, 1999].

Electric enhancement

In the 1970s, architect W. Hilbertz invented a unique process that employs electrolysis of saltwater to precipitate calcium and magnesium minerals to "generate" a crystalline covering over artificial structures to manufacture construction materials. This mineral mimics the physical and chemical properties of limestone, which is the result of the remains of coral skeletons and green algae. [Goreau and Hilzbert, 1996]. This process is possible thanks to a low-voltage direct current trickle charges where calcium carbonate and magnesium hydroxide precipitates at the cathode, while at the anode are produced oxygen and chlorine [Goreau, 2014]. The goal of this mineral deposition is to promote coral polyp calcification, hence increasing colony development and resilience to stresses. The effectiveness of this procedure is not clear though, as some studies highlighted increased growth and survival, whereas others described slower growth [Romatzki, 2014], all of this often related to the same species [Boström-Einarsson et al., 2020]. This makes it impossible to draw firm conclusions concerning the mineral accretion process.

Algae removal

When macroalgae proliferation persists outside of usual seasonal bloom, it can shift ecological dominance away from corals and result in a permanently changed system [McCook, 1999]. Despite an abundance of coral larvae, such an affected ecosystem is unlikely to recover spontaneously because macroalgae reduces coral settlement and survival. These effects happen because of both direct and indirect interactions. This can include shade, abrasion, disease transmission in the first case and allelopathy [Rasher et al., 2011], microbialization or herbivory-related process in the second one [Vermeij et al., 2012]. When all of these interactions combine, it may constitute a barrier to coral recruitment making improbable natural recovery even with an abundance of coral larvae [Smith et al., 2022]. It is important to highlight the

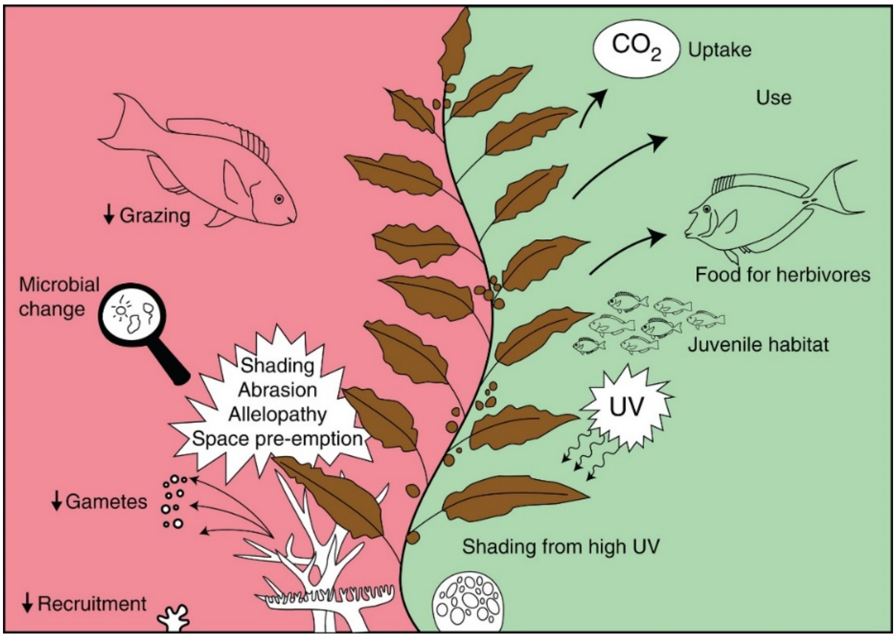

Figure 9: Illustration of the negative and positive effects of macroalgae on coral reefs. Picture from Ceccarelli et al., 2018

essential work these algae do for the reefs: they protect corals from damaging sun irradiation, offer food and shelter to a variety of reef fishes and invertebrates, and act as an ocean carbon sink [Ortega et al., 2019]. Given the variety of recognized serious implications of macroalgae on corals, manual algae removal has been advocated as one strategy to improve reef resilience. The elimination of macroalgae has the power to remove a biological barrier to natural reef regeneration by expanding room for the development of existing coral colonies and increasing accessible seafloor space for coral recruitment. Unfortunately, the negative effects of decreasing their presence in reefs are not well studied.

3. CONCLUSION

Humans are recognized as a vital element of ecological processes. People's ability to adapt and evolve while also recognizing disturbances as chances for adaptive transformation is a significant factor to enhance coral resilience through restoration programs. [Hein et al., 2019].

In comparison to other ecosystems like forests and wetlands, coral reefs' restoration is currently in its early stages and is heavily focused on small-scale, short-term details such as the growth and survival properties of coral pieces post-transplantation. While they are required for better restoration designs, essential information on whether coral restoration may successfully enhance reef resilience is still absent [Hein et al., 2017].

A comparison on the effectiveness of coral restoration methods cannot be done because of different limitations. While a method may be very successful in one situation, it may fail in another. This is because coral restoration is not an exact science. It involves so many factors that it is almost impossible to have two identical situations. Firstly, different locations mean different available species, different substrate, different water temperature and salinity. So, for example, a successful project in Maldives using the gardening method with *Pocillopora Damicornis* may not be possible in Bahamas, where this specie is not naturally found. The chosen method also depends on human factors such as who is financing the project (more funds mean more possibilities), wanted outcome: in fact, a project that aims to restore the benthic community will need a very different approach compared to an embellishment of the reef for touristic purposes.

The future of coral restoration is bright. Since the 80's, when active restoration was first introduced, science has made huge progress. Today we can rely on a mixture of different sciences to enhance the possibility of success of our restoration projects. It's worth mentioning all the incredible genetical findings through CRISPS and Cas9 methods to understand better the molecular and genetic role in stress [Cleves et al., 2020]. Futuristic is, without any doubt, the ongoing project of the QUT's *larvalbot*: a robot that releases a huge amount of planulae (we are talking about 1.4 million larvae in a 1500m^2 area) on a chosen reef hovering directly over it and enhancing settlement success [Queensland University of Technology, 2018]. Corals are changing, they are adapting to survive in this changing world we live in. Evolving is part of nature and as it evolves, our way of studying it must evolve too.

BIBLIOGRAPHY

1. Baker, A.C., Glynn, P.W. and Riegl, B. (2008). Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine, Coastal and Shelf Science*, 80(4), pp.435–471.

2. Barton, J.A., Willis, B.L. and Hutson, K.S. (2015). Coral propagation: a review of techniques for ornamental trade and reef restoration. *Reviews in Aquaculture*, 9(3), pp.238–256.

3. BAUMS, I.B. (2008). A restoration genetics guide for coral reef conservation. *Molecular Ecology*, [online] 17(12), pp.2796–2811.

4. Boch, C.A. and Morse, A.N.C. (2012). Testing the effectiveness of direct propagation techniques for coral restoration of Acropora spp. *Ecological Engineering*, 40, pp.11–17.

5. Boström-Einarsson, L., Babcock, R.C., Bayraktarov, E., Ceccarelli, D., Cook, N., Ferse, S.C.A., Hancock, B., Harrison, P., Hein, M., Shaver, E., Smith, A., Suggett, D., Stewart-Sinclair, P.J., Vardi, T. and McLeod, I.M. (2020). Coral restoration – A systematic review of current methods, successes, failures and future directions. *PLOS ONE*, 15(1).

6. Bothwell, A.M. (1981). Fragmentation, a means of asexual reproduction and dispersal in the coral genus Acropora (Scleractinia: Astrocoeniida: Acroporidae) — a preliminary report.

7. Bruno, J.F. (1998). Fragmentation in Madracis mirabilis (Duchassaing and Michelotti): how common is size-specific fragment survivorship in corals? *Journal of Experimental Marine Biology and Ecology*, 230(2), pp.169–181.

8. Buddemeier, R.W. and Fautin, D.G. (1993). Coral Bleaching as an Adaptive Mechanism. *BioScience*, [online] 43(5), pp.320–326.

9. Ceccarelli, D.M., Loffler, Z., Bourne, D.G., Al Moajil-Cole, G.S., Boström-Einarsson, L., Evans-Illidge, E., Fabricius, K., Glasl, B., Marshall, P., McLeod, I., Read, M., Schaffelke, B., Smith, A.K., Jorda, G.T., Williamson, D.H. and Bay, L. (2018). Rehabilitation of coral reefs through removal of macroalgae: state of knowledge and considerations for management and implementation. *Restoration Ecology*, 26(5), pp.827–838.

10. Ceccarelli, D.M., McLeod, I.M., Boström-Einarsson, L., Bryan, S.E., Chartrand, K.M., Emslie, M.J., Gibbs, M.T., Gonzalez Rivero, M., Hein, M.Y., Heyward, A., Kenyon, T.M., Lewis, B.M., Mattocks, N., Newlands, M., Schläppy, M.-L., Suggett, D.J. and 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).

11. Chen, C.-J., Chen, W.-J., Shikina, S., Denis, V. and Chang, C.-F. (2020). The plasticity of gonad development of sexual reproduction in a scleractinian coral, Porites lichen. *General and Comparative Endocrinology*, 285, pp.113-270.

12. Cinner, J.E. and Barnes, M.L. (2019). Social Dimensions of Resilience in Social-Ecological Systems. *One*

Earth, 1(1), pp.51–56.

13. Cinner, J.E. and Kittinger, J.N. (2015). Linkages between social systems and coral reefs. *Ecology of Fishes on Coral Reefs*, [online] 1(9781107089181).
14. Cinner, J.E., McClanahan, T.R., Graham, N.A.J., Daw, T.M., Maina, J., Stead, S.M., Wamukota, A., Brown, K. and Bodin, Ö. (2012). Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. *Global Environmental Change*, 22(1), pp.12–20.
15. Clark, S. and Edwards, A.J. (1995). Coral transplantation as an aid to reef rehabilitation: evaluation of a case study in the Maldive Islands. *Coral Reefs*, 14(4), pp.201–213.
16. Cleves, P.A., Shumaker, A., Lee, J., Putnam, H.M. and Bhattacharya, D. (2020). Unknown to Known: Advancing Knowledge of Coral Gene Function. *Trends in Genetics*, [online] 36(2), pp.93–104.
17. Coral Reef Alliance. (n.d.). *Hard Corals*. [online] Available at: https://coral.org/en/coral-reefs-101/hard-corals/.
18. Coral Reef Alliance. (n.d.). *Soft Corals*. [online] Available at: https://coral.org/en/coral-reefs-101/soft-corals/.
19. Coral Reef Alliance. (n.d.). *Types of Coral Reefs*. [online] Available at: https://coral.org/en/coral-reefs-101/types-of-coral-reef-formations/#:~:text=Scientists%20generally%20agree%20on%20four.
20. Coral Reef Alliance. (n.d.). *Why Care About Coral Reefs?* [online] Available at: https://coral.org/en/coral-reefs-101/why-care-about-reefs/.
21. Darwin, C. (1976). *The Structure and Distribution of Coral Reefs*. University of California Press. doi:10.1525/9780520327337.
22. El-Naggar, H.A. (2020). Human Impacts on Coral Reef Ecosystem. *Natural Resources Management and Biological Sciences*. [online].
23. Fadlallah, Y.H. (1983). Sexual reproduction, development and larval biology in scleractinian corals. *Coral Reefs*, 2(3), pp.129–150.
24. Friedl, E. (2017). *Organisms that reproduce sexually and asexually*. [online] Study.com. Available at: https://study.com/academy/lesson/organisms-that-reproduce-both-asexually-sexually.html. [Accessed 17 Oct. 2022].
25. Galindo-Martínez, C.T., Weber, M., Avila-Magaña, V., Enríquez, S., Kitano, H., Medina, M. and Iglesias-Prieto, R. (2022). The role of the endolithic alga Ostreobium spp. during coral bleaching recovery. *Scientific Reports*, 12(1).
26. Gateño, D. and Rinkevich, B. (2003). Coral polyp budding is probably promoted by a canalized ratio of two morphometric fields. *Marine Biology*, 142(5), pp.971–973.
27. Gomez, E., Edwards, A. and Dizon, R. (2010). Methods of Coral Transplantation. In: *Reef Rehabilitation Manual*. St Lucia, Qld: The Coral Reef Targeted Research & Capacity Building for Management Program,

pp.103–116.

28. Goreau, T.J. (2014). Electrical Stimulation Greatly Increases Settlement, Growth, Survival, and Stress Resistance of Marine Organisms. *Natural Resources*, 05(10), pp.527–537.

29. Goreau, T.J. and Hilzbert, W. (1996). *Reef Restoration Using Seawater Electrolysis in Jamaica*. 8th Coral Reef Symposium.

30. Grove, R. S. and C. J. Sonu. 1985. Fishing reef planning in Japan. pp. 187–251 in F. M. D'Itri, ed.Artificial reefs in marine and freshwater applications. Lewis Publishers, Chelsea, Michigan.589

31. Harrison, P.L. (2011). Sexual reproduction in scleratinian corals. *Coral Reefs: An Ecosystem in Transition*, p.pp. 59-85.

32. Harrison, P.L. and Booth, D.J. (2007). Coral Reefs: Naturally Dynamic and Increasingly Disturbed Ecosystems. In: *Marine ecology*. Oxford University Press, pp.316–377.

33. Hein, M.Y., Birtles, A., Willis, B.L., Gardiner, N., Beeden, R. and Marshall, N.A. (2019). Coral restoration: Socio-ecological perspectives of benefits and limitations. *Biological Conservation*, 229, pp.14–25.

34. Hein, M.Y., Willis, B.L., Beeden, R. and Birtles, A. (2017). The need for broader ecological and socioeconomic tools to evaluate the effectiveness of coral restoration programs. *Restoration Ecology*, 25(6), pp.873–883.

35. Hughes, T. (1987). Skeletal density and growth form of corals. *Marine Ecology Progress Series*, 35, pp.259–266. doi:10.3354/meps035259.

36. Islam, I. Zeolite-microfragmenting Media: A Potential Strategy to Accelerate Coral Growth. Preprints 2020.

37. Kass-Simon, G. and Scappaticci, Jr., A.A. (2002). The behavioral and developmental physiology of nematocysts. *Canadian Journal of Zoology*, 80(10), pp.1772–1794.

38. Linden, B. and Rinkevich, B. (2011). Creating stocks of young colonies from brooding coral larvae, amenable to active reef restoration. *Journal of Experimental Marine Biology and Ecology*, 398(1-2), pp.40–46.

39. Lirman, D. (2000). Fragmentation in the branching coral Acropora palmata (Lamarck): growth, survivorship, and reproduction of colonies and fragments. *Journal of Experimental Marine Biology and Ecology*, 251(1), pp.41–57.

40. LOYA, Y. (1976). Skeletal regeneration in a Red Sea scleractinian coral population. *Nature*, 261(5560), pp.490–491.

41. Luo, D., Wang, B., Bao, D.W. and Ward, S. (2022). Opportunities for further development of 3D-printed floating artificial reefs. *Journal of Aquaculture and Marine Biology*, 11(1), pp.58–63.

42. MacKnight, N.J., Dimos, B.A., Beavers, K.M., Muller, E.M., Brandt, M.E. and Mydlarz, L.D. (2022).

Disease resistance in coral is mediated by distinct adaptive and plastic gene expression profiles. *Science Advances*, 8(39).

43. McCook, L.J. (1999). Macroalgae, nutrients and phase shifts on coral reefs: scientific issues and management consequences for the Great Barrier Reef. *Coral Reefs*, 18(4), pp.357–367.

44. Mellin, C., Aaron MacNeil, M., Cheal, A.J., Emslie, M.J. and Julian Caley, M. (2016). Marine protected areas increase resilience among coral reef communities. *Ecology Letters*, 19(6), pp.629–637.

45. Moczek, A.P. (2020). Invertebrate Embryology and Reproduction. By Fatma El-Bawab. Academic Press. Amsterdam (The Netherlands) and New York: Elsevier. $140.25 (paper). xiii + 918 p.; ill.; index. ISBN: 978-0-12-814114-4. 2020. *The Quarterly Review of Biology*, 95(4), pp.344–344.

46. Mullen, K.M., Peters, E. and Harvell, C.D. (2003). Coral Resistance to Disease. pp.377–400.

47. National geographic (2011). *Corals | National Geographic*. [online] Animals. Available at: https://www.nationalgeographic.com/animals/invertebrates/facts/corals-1.

48. Nie, D., Shen, F. and Wang, J. (2021). Changes of air quality and its associated health and economic burden in 31 provincial capital cities in China during COVID-19 pandemic. *Atmospheric Research*, [online] 249(0169-8095), p.105-328.

49. NOAA (2019). *How Do Coral Reefs Form - Corals: NOAA's National Ocean Service Education*. [online] Noaa.gov. Available at: https://oceanservice.noaa.gov/education/tutorial_corals/coral04_reefs.html.

50. Ortega, A., Geraldi, N.R., Alam, I., Kamau, A.A., Acinas, S.G., Logares, R., Gasol, J.M., Massana, R., Krause-Jensen, D. and Duarte, C.M. (2019). Important contribution of macroalgae to oceanic carbon sequestration. *Nature Geoscience*, 12(9), pp.748–754.

51. Perry, C.T. (1999). Reef Framework Preservation in Four Contrasting Modern Reef Environments, Discovery Bay, Jamaica. *Coastal Research*, 15(3), pp.796–812.

52. Petersen, D., Hatta, M., Laterveer, M. and Bergen, D. van. (2005). Ex situ transportation of coral larvae for research, conservation, and aquaculture. *Coral Reefs*, 24(3), pp.510–513.

53. Plass-Johnson, J.G., Cardini, U., van Hoytema, N., Bayraktarov, E., Burghardt, I., Naumann, M.S. and Wild, C. (2014). Coral Bleaching. *Environmental Indicators*, pp.117–146.

54. Possingham, H.P., Bode, M. and Klein, C.J. (2015). Optimal Conservation Outcomes Require Both Restoration and Protection. *PLOS Biology*, 13(1),.

55. Prayaga, P. (2017). Estimating the value of beach recreation for locals in the Great Barrier Reef Marine Park, Australia. *Economic Analysis and Policy*, 53, pp.9–18.

56. Precht, W.F. (2006). The Coral Gardening Concept and the Use of Underwater Nurseries: Lessons Learned from Silvics and Silvicultures. In: *Coral Reef Restoration Handbook*. CRC Press, pp.291–303.

57. Randall, C., Negri, A., Quigley, K., Foster, T., Ricardo, G., Webster, N., Bay, L., Harrison, P., Babcock, R. and Heyward, A. (2020). Sexual production of corals for reef restoration in the Anthropocene. *Marine*

Ecology Progress Series, 635, pp.203–232.

58. Rasher, D.B., Stout, E.P., Engel, S., Kubanek, J. and Hay, M.E. (2011). Macroalgal terpenes function as allelopathic agents against reef corals. *Proceedings of the National Academy of Sciences*, 108(43), pp.17726–17731.

59. Reed, K.C., Muller, E.M. and Van Woesik, R. (2012). Coral Immunology and Resistance to Diseases. *Diseases of Aquatic Organisms*, 90, pp.85–92.

60. Reef Ecologic. (2018). *Reef Restoration Training Hub | Reef Ecologic*. [online] Available at: https://reefecologic.org/project/reef-restoration-training-hub/

61. Rinkevich, B. (2005). Conservation of Coral Reefs through Active Restoration Measures: Recent Approaches and Last Decade Progress. *Environmental Science & Technology*, 39(12), pp.4333–4342.

62. Rinkevich, B. (2021). Augmenting coral adaptation to climate change via coral gardening (the nursery phase). *Journal of Environmental Management*, 291(3109701), pp.112-727.

63. Romatzki, S.B.C. (2014). Influence of electrical fields on the performance of*Acropora*coral transplants on two different designs of structures. *Marine Biology Research*, 10(5), pp.449–459.

64. Roth, M.S. and Deheyn, D.D. (2013). Effects of Cold Stress and Heat Stress on Coral Fluorescence in reef-building Corals. *Scientific Reports*, 3(1).

65. Sakai, K. (1998). Effect of Colony Size, Polyp Size, and Budding Mode on Egg Production in a Colonial Coral. *The Biological Bulletin*, 195(3), pp.319–325.

66. Salih, A., Larkum, A., Cox, G., Kühl, M. and Hoegh-Guldberg, O. (2000). Fluorescent pigments in corals are photoprotective. *Nature*, [online] 408(6814), pp.850–853.

67. Sampayo, E.M., Ridgway, T., Bongaerts, P. and Hoegh-Guldberg, O. (2008). Bleaching susceptibility and mortality of corals are determined by fine-scale differences in symbiont type. *Proceedings of the National Academy of Sciences*, 105(30), pp.10444–10449.

68. Smith, H.A., Brown, D.A., Arjunwadkar, C.V., Fulton, S.E., Whitman, T., Hermanto, B., Mastroianni, E., Mattocks, N., Smith, A.K., Harrison, P.L., Boström-Einarsson, L., McLeod, I.M. and Bourne, D.G. (2022). Removal of macroalgae from degraded reefs enhances coral recruitment. *Restoration Ecology*, 30(7).

69. Smith, L.D. and Hughes, T.P. (1999). An experimental assessment of survival, re-attachment and fecundity of coral fragments. *Journal of Experimental Marine Biology and Ecology*, 235(1), pp.147–164.

70. Spieler, Richard & Gilliam, David & Sherman, Robin. (2001). Artificial substrate and coral reef restoration: What do we need to know to know what we need. Bulletin of Marine Science. 69. pp.1013-1030.

71. Technology (QUT), Q.U. of (2018). *Restore the Great Barrier Reef*. [online] QUT. Available at: https://www.qut.edu.au/engage/giving/support-research/great-barrier-reef.

72. Thompson, J.R., Rivera, H.E., Closek, C.J. and Medina, M. (2015). Microbes in the coral holobiont:

partners through evolution, development, and ecological interactions. *Frontiers in Cellular and Infection Microbiology*, [online] 4.

73. THORP, J.H. and COVICH, A.P. (2001). Ecology and classification of North American freshwater invertebrates. *Choice Reviews Online*, 39(01), pp.39-312.

74. US Department of Commerce, National Oceanic and Atmospheric Administration (2019). *Zooxanthellae...What's That - Corals: NOAA's National Ocean Service Education*. [online] Noaa.gov. Available at: https://oceanservice.noaa.gov/education/tutorial_corals/coral02_zooxanthellae.html.

75. US Department of Commerce, N.O. and A.A. (n.d.). *Corals: NOAA's National Ocean Service Education*. [online] oceanservice.noaa.gov. Available at: https://oceanservice.noaa.gov/education/tutorial_corals/media/supp_coral03h.html.

76. van Zanten, B.T., van Beukering, P.J.H. and Wagtendonk, A.J. (2014). Coastal protection by coral reefs: A framework for spatial assessment and economic valuation. *Ocean & Coastal Management*, 96, pp.94–103.

77. Vercelloni, J., Caley, M.J. and Mengersen, K. (2017). Crown-of-thorns starfish undermine the resilience of coral populations on the Great Barrier Reef. *Global Ecology and Biogeography*, 26(7), pp.846–853.

78. Vermeij, M.J.A., van der Heijden, R.A., Olthuis, J.G., Marhaver, K.L., Smith, J.E. and Visser, P.M. (2012). Survival and dispersal of turf algae and macroalgae consumed by herbivorous coral reef fishes. *Oecologia*, 171(2), pp.417–425.

79. Viehman, T., Hench, J., Griffin, S., Malhotra, A., Egan, K. and Halpin, P. (2018). Understanding differential patterns in coral reef recovery: chronic hydrodynamic disturbance as a limiting mechanism for coral colonization. *Marine Ecology Progress Series*, 605, pp.135–150.

80. Vivier, B., Davin, J.-C., Navon, M., Rusig, A.-M. and Mussio, I. (2021). Marine artificial reefs, a meta-analysis of their design, objectives and effectiveness. *Global Ecology and Conservation*, [online] 27,.

81. Wilson, J. and Harrison, P. (2005). Post-settlement mortality and growth of newly settled reef corals in a subtropical environment. *Coral Reefs*, 24(3), pp.418–421.

82. Yamashita, H., Suzuki, G., Kai, S., Hayashibara, T. and Koike, K. (2014). Establishment of Coral–Algal Symbiosis Requires Attraction and Selection. *PLoS ONE*, 9(5).