Applications of Synthetic Biology Within Coral Conservation

Kayla Chin *†

March 25, 2024

Abstract

Several studies have been done on genetic engineering in agriculture and plants to ensure their successful survival and adaptation through changing climatic conditions. This paper will focus on the applications of genetic modification within animals, specifically synthetic biology in combating coral bleaching. The interactions between humans and animals have affected both populations tremendously, but ever since industrialization centuries ago, animals have experienced the brunt of the negative effects. As a result, many species that are essential to maintaining balance in nature are endangered or even extinct. To prevent animals from being further harmed, we must take drastic measures in the form of a dramatically reduced carbon footprint, or finding a way to directly help the animals adapt. Synthetic biology, a type of genetic modification, involves creating new biological functions or systems to have an organism have a desired ability. The application of genetic engineering in animals was mostly limited to agricultural ones for many years, but its success combined with the success seen in plants has raised the question of whether it is a viable option for wildlife. Coral, in particular, has been the source of some of the first synthetic biology experiments with animals. Due to climate change, many coral reefs are experiencing irreversible bleaching effects. However, several scientists are applying new methods of synthetic biology to allow them to withstand higher temperatures. Success in synthetic biology with coral may also aid in the further development of similar technologies within other wildlife species. Understanding the multitude of ways in which synthetic biology can be used to benefit coral as well as the ethical risks can help us develop and execute a plan that will allow future generations to experience the vast biodiversity that the world has to offer.

*Advised by: James Truncer of Harvard University
†Student of Los Altos High School

1 Introduction

Although the first major coral bleaching event was recorded relatively recently in 1998, the effects seen from climate change on reefs around the world have continued to exponentially increase [SL18]. Many scientists have attributed the phenomenon of coral bleaching to rapidly climbing temperatures. Rising temperatures drive away algae, leaving the coral "bleached" and vulnerable to disease. Since 1998, at least 75 percent of coral reefs around the world have experienced bleaching to some degree, with 30 percent experiencing such detrimental effects that they die [autte]. The largest reef in the world, the Great Barrier Reef, has experienced over 90 percent bleaching across its 1,500-mile-long system [McG22]. The effects of coral bleaching are not only seen in the loss of color along Australia's coast. Coral provides the most efficient marine environment for wildlife, supporting thousands of wildlife species. When coral bleaches, it becomes much more delicate, negating almost all of the benefits that it provides both to humans and marine wildlife. Since the late 1900s, ideas surrounding genetic engineering have been at the forefront of many new technological advances. With the rising dramatic effects of climate change, scientists have begun to apply genetic engineering to organisms. Some scientists desire to bring back some species from extinction using methods of back-breeding or cloning. These methods may help to increase overall biodiversity and possibly allow species to utilize the diversity to increase their adaptability as a species. However, the process of back-breeding and the subsequent evolution needed to increase their adaptability would likely take far too long to keep up with the quickly changing environment. On the other hand, less extreme methods of genetic engineering are already present in everyday life. Genetically modified organisms or GMOs make up a majority of popular agricultural products [aut22]. Drought-tolerant crops such as corn, cotton, and rice are becoming increasingly important as annual rainfalls decrease. And genetic modification has not only been applied to essential plants. It is also used to create seed-free watermelon and apples that are slower to brown. Despite the numerous benefits that GMOs have proven to provide, there are still some who are hesitant to accept them. Drawbacks like lack of nutrition, allergic reactions, and even "superbugs" are cited as cons surrounding the use of GMOs. However, GMO technology is still being developed and many of these drawbacks are currently being solved. As revolutionary as GMOs have proven to be, even more advanced methods present the opportunity to create totally new traits. This method is called synthetic biology and is currently mostly being studied in the context of CRISPR technologies. It is a type of genetic modification, but is usually distinguished by its ability to create a whole new biological system, and thus, new traits that have not been present in previous organisms of that species [NMVM22]. For example, scientists have been able to create silkworms that produce ultra-strong silk using spider DNA [aut23]. However, synthetic biology is not without its risks. There are growing worries about those who may take advantage of the applications of synthetic biology, possibly causing more harm than good. In addition, the selectivity of certain genes within large coral populations also has the potential to reduce

biodiversity. However, with the right regulations, synthetic biology has the potential to be the answer to helping our coral reefs recover from bleaching. Coral needs a way to mitigate the effects of bleaching and climate change quickly, one of the many reasons why scientists have chosen coral as one of the first animals to undergo synthetic biology. Up until now, heat-tolerant corals have only been attained through selective breeding and assisted evolution. But as technology surrounding synthetic biology continues to advance, the prospective applications of it within coral continue to increase. In this paper, I will investigate how coral bleaching can be combated through genetic engineering, specifically synthetic biology. I will also delve into the ethical implications that come with genetic experimentation, especially with its application in animals in addition to plants. The application of synthetic biology technologies on coral to make them more heat-tolerant and adaptable to the changing environment is crucial to ensure that this keystone species is preserved. This genetic modification technique has already proven to be very successful within plants, and its extensive benefits are also pivotal in establishing adaptability in wildlife [KBE19]. Coral is essential to both humans and wildlife and despite the numerous ethical risks, the use of synthetic biology should be explored to minimize the effects of climate change. Success found in synthetic biology with coral can also be applied to other necessary species in the future.

2 Discussion

2.1 Coral

People often mistake coral as a plant rather than an animal. However, coral is actually a colonial organism. It is made up of thousands of different animals known as polyps with tentacles that are used to capture food [aut13b]. There are over six thousand species of coral found all across the world and can be found almost everywhere in the ocean [aut13b]. Despite the many different types of coral, they can be divided into two distinct categories, soft and hard coral. Soft coral does not use calcium carbonate to create a structure. It instead releases limestone in a structure called sclerites to keep its shape [Fre22]. Due to its lack of a distinct structure, soft coral also relies on chemical defenses. On the other hand, hard coral is usually what most people think of when they think of coral reefs. Hard coral uses carbon from its surroundings to create calcium carbonate to use as its structure [aut21]. Young polyps grow on this structure, slowly building it over time. As polyps die, their skeletons create the foundation for more polyps to continue to grow the reef [aut21]. Although coral, specifically the polyps that make it up, is an animal, it does not have a brain and has a very simple nervous system [Fre22]. It is challenging for scientists to be sure about whether or not certain animals can feel pain, but many conclude that the coral is likely not able to truly feel pain due to its nervous system being unable to send pain signals without a brain.

2.1.1 Coral Bleaching

As our world continues to change, so do the challenges that coral reefs encounter. The diseases that coral face such as black and white band disease, white-pox, and stony coral can likely be attributed to the rapidly changing environment [aut13a]. This biological stress can lead to a great susceptibility to disease. However, other factors can be more directly linked to climate change such as the coral bleaching epidemic. On the surface, coral bleaching appears to be when coral changes from its previous vibrant color to a pale, chalky white color. The process that the coral undergoes that results in its new appearance is much more complex. Although coral bleaching can be caused by a variety of factors, the most recent major events have been caused by sudden increases in water temperature. Due to temperature stress, many organisms that live within the coral might leave to find a more suitable environment. The loss of these organisms results in the lack of color, and also deprives the coral of a stable nutrient source, causing even further harm [RvW22]. Without enough organisms to provide nutrients to the coral, it often ends up dying from starvation and is extremely challenging to recover. As scientists have continued to research, they have also found that certain areas are more susceptible to coral bleaching, specifically areas that experience high rates of intense temperature change, like in the Indian Ocean [RvW22]. Though exact areas of coral bleaching are variable, the following figures show the immense difference in less than a year of the number of high alert areas.

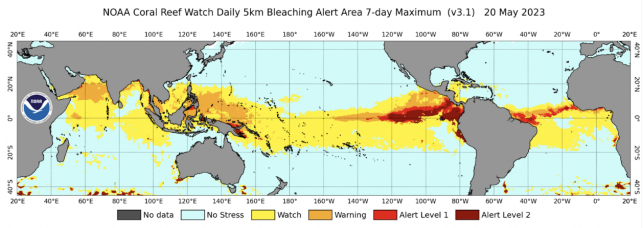

Figure 1: NOAA coral bleaching alert area on May 20, 2023 [aut18].

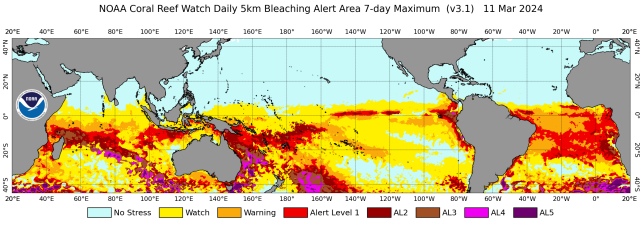

Figure 2: NOAA coral bleaching alert area on March 11, 2024 [aut18].

Other factors such as light intensity, nutrient availability, and water flow can

also affect coral bleaching rates [RvW22]. For example, even at higher temperatures, a lower light level generally results in less bleaching [RvW22]. Specific types of symbiotic algae have also been found to be more heat-tolerant when compared to others. Some have recommended introducing more heat-tolerant symbiotes to algae to slow coral bleaching, but this solution is likely not viable for long-term usage [RvW22]. Coral can recover after bleaching, but it can take around a decade and they often still struggle due to higher disease susceptibility and unstable calcification abilities [RvW22]. As the number of coral bleaching events continues to climb, marine ecosystems are becoming increasingly at risk. For coral recovery to progress at the necessary rate, some scientists are discussing the use of genetic engineering. In previous years, many have argued that genetic engineering methods are far too radical, but the benefits of coral reef preservation are far too essential to settle for a relaxed approach.

2.1.2 Benefits of Coral Reefs

Although all animal species are important, coral is arguably one of the most important organisms due to the numerous benefits they present to both humans and the environment. Every year, coral reefs contribute over 375 billion dollars to the worldwide economy [aut11]. Coral reefs provide hundreds of thousands of jobs in both tourism and fishing industries. Not only do coral reefs provide economic benefits for humans, but they also act as protection against waves, storms, and floods.

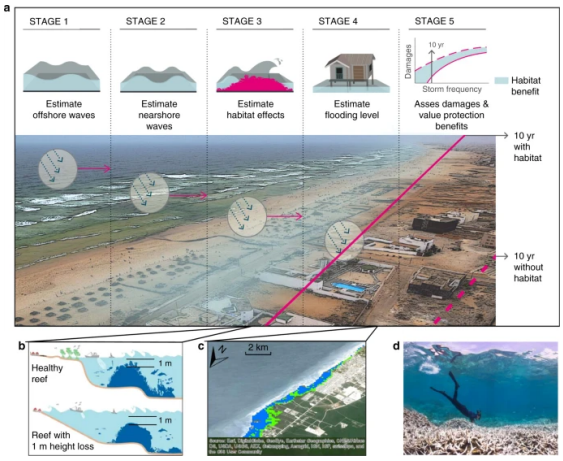

Figure 3: Image showing difference in effects of waves, floods, and storms on homes with and without coral habitats nearby [MWB18].

By acting as a barrier between the coastlines and the water, coral reefs prevent fatal disasters as well as possible property damage for almost 200 million people [OHGK19]. This coastline protection will only continue to become even

more essential in allowing us to adapt to changing environmental conditions. Coral reefs also provide a habitat for about 25 percent of all marine life, including about one million different species of fish, mammals, plants, and more [OHGK19]. Without coral reefs, many of these species would cease to exist, drastically upsetting the balance of nature, the effects of which can already be seen today. Due to the enormous biodiversity found in these coral reefs, scientists have also begun to research them for medicinal benefits. Many coral species have developed chemical defenses to protect themselves from possible predators. These defenses are now being used in the creation of medicinal treatments, supplements, and even cosmetic products [NOA23]. In addition, many of the organisms that rely on coral reefs are also major contributors to sequestering carbon. With carbon pollution as one of the leading causes of climate change, it is even more essential to protect our coral to prevent further environmental damage and help us adapt to our changing world.

2.2 Genetic Engineering with Coral so Far

Genetic engineering, simply put, is deliberately changing an organism's genetic code to achieve a desired result. Genetic engineering has seen many successes since its discovery including the development of high crop yields, growth hormones, and several well-known vaccines. In coral specifically, techniques such as selective breeding and artificial gene flow have been used to increase heat tolerance within certain species. Selective breeding entails using fragmentations of certain coral species that have shown higher heat tolerance and breeding them with those that don't possess the same traits. The result, possessing some heat-tolerant genes, is then cultivated in a lab before being moved to parts of the ocean where more heat-tolerant coral is needed, to encourage permanent evolution in that population. A different approach with similar goals is artificial gene flow. This strategy entails introducing diverse gametes within certain coral species to encourage more heat-tolerant offspring. Many scientists argue that this approach will result in much more successful offspring since introducing gametes is less costly and does not carry the possibility of foreign pathogens like introducing developed organisms does [MHM21]. Artificial gene flow was attempted with fresh gametes to ensure optimal results, however, gametes are only viable for a short period of time [MHM21]. This makes it challenging to move the gametes to the correct coral population before the likelihood of successful artificial gene flow drops. However, new technologies with cryopreservation have made transporting live coral gametes viable, with comparable success rates to coral fertilized with fresh sperm when convenience is taken into account [MHM21]. This technique was used in an experiment conducted by scientists in 2018 in Curaçao with frozen gametes taken from around the world. Results showed that frozen foreign gametes did have a lower fertilization rate, however viability after fertilization was similar, and sometimes even higher compared to eggs fertilized with local fresh sperm [MHM21]. The success of this very new technique shows its high viability in future usage to increase biodiversity and adaptive characteristics within coral and other species. This approach has also

shown the benefits of genetic engineering for conservation purposes, and will likely inspire future modification concepts.

2.3 Synthetic Biology

Synthetic biology is often referred to as a subsegment of genetic engineering. Up until recently, genetic engineering has mostly consisted of manipulating a set number of genes while keeping it reasonably similar to the original organism [NMVM22]. On the surface, synthetic biology seems similar as it also includes changing an organism's genes. However, synthetic biology is often described as a whole new entity when compared to other genetic engineering techniques. Synthetic biology is when scientists essentially redesign all of an organism's biological system [NMVM22]. This means that scientists can add or remove whole functional systems, manipulating an organism's genes far beyond what previous genetic modification has allowed for. CRISPR, a new genetic engineering technique has made the process of synthetic biology even more viable for further usage. CRISPR uses a specific protein to precisely splice DNA segments, making it much more efficient to edit genes accurately according to scientists' wishes [NMVM22]. There are a couple of different ways in which scientists can go about creating synthetic biological systems. They can use unnatural molecules to replicate natural biological systems, creating a new, artificial organism [BS05]. They can also use parts that already exist in natural biological systems, and put them together to create a new, artificial product [BS05]. Either way, synthetic biology has opened up a whole new world of possibilities within the field of genetic engineering. In addition, it has also been found that synthetically created organisms can undergo evolution, selection, and mutation, resembling adaptive characteristics of natural organisms [BS05]. As scientists explore the possibilities of synthetic biology, the idea of artificial life living among natural organisms will likely become a reality.

2.4 Synthetic Biology in Plants

The idea of synthetic biology is relatively new, but it has already begun to be implemented in plants. As populations continue to grow along, the agricultural industry must make adjustments to meet the growing demand for food. Currently, the agricultural industry mostly uses techniques such as selective breeding and special cultivation approaches have allowed for production to continue to keep up with demand. Genetically modified organisms have also continued to grow in popularity, some even making up the majority of their respective agricultural output. GMOs have allowed plants to become more pest-resistant and heat-tolerant, and even stay fresh for longer. Despite these incredible advances in this field, the ever-growing human population has begun to outgrow the limits of even the most complex GMOs. However, scientists have started to look into other methods to make agricultural production even more efficient, specifically, by improving the way plants convert light into biomass [KBE19]. Synthetic biology has presented a viable option to make this happen by improving the rate

at which the plants can perform carbon fixation [KBE19]. Carbon fixation is the process in which plants convert carbon into organic molecules, an essential step in photosynthesis and the Calvin cycle. By making this process more efficient, plants would be able to grow and reproduce at a faster rate than is currently possible. There are several approaches that scientists have suggested to improving carbon fixation including engineering Rubisco, enhancing the expression of enzymes, and developing carbon concentrating mechanisms [KBE19].

2.4.1 Engineering Rubisco

Rubisco is one of the main enzymes present during the Calvin cycle and takes in a majority of the carbon during the carbon fixation process. Despite its abundance, Rubisco is known to be one of the most inefficient enzymes due to its ability to accept oxygen in addition to carbon, and its tendency to process inorganic molecules slowly [KBE19]. Several experiments have shown that when plants can process higher levels of carbon dioxide, their productivity also increases. These findings have led scientists to focus on reengineering Rubisco to become more efficient and process higher levels of carbon. Researchers have attempted to reengineer Rubisco in many different ways, but have never succeeded to the desired extent. However, the science of synthetic biology is still relatively new, and reengineering Rubisco is still a viable option for increased plant productivity in the future.

2.4.2 Enhancing the Expression of Enzymes

Even without reengineering Rubisco, there are still a multitude of ways that scientists can utilize synthetic biology to make the Calvin cycle, and thus plant production, more efficient. One of those ways is by enhancing the expression of enzymes that are used in the regeneration of RuBP within the Calvin cycle [KBE19]. When a plant is in an environment with high levels of carbon, it was found that the efficiency of the enzymes was inhibiting productivity rather than the Rubisco. Whether the environment has high or optimal levels of carbon dioxide, the overexpression of certain enzymes leads to increased photosynthesis rates [KBE19]. These findings have encouraged scientists to look into how to engineer permanently over expressive enzymes due to the complexity of reengineering Rubisco.

2.4.3 Carbon Concentrating Mechanisms

To encourage Rubisco to take in less oxygen and more carbon, some plants have developed carbon concentrating mechanisms (CCMs), directing carbon dioxide to Rubisco sites [KBE19]. However, many of our most essential plants such as wheat, oats, and rye, do not possess CCMs. There are two ways in which scientists are trying to introduce CCMs to certain types of plants: introducing biophysical CCMs from other organisms or applying the anatomy of CCM-possessing plants [KBE19]. The first way requires an inorganic carbon

transporter, and preliminary experiments have already shown how specific types of transporters can increase carbon intake and plant productivity. The second way has begun to be further researched with simplified carboxysome structures, but it has currently been concluded that for this method to be successful, implementing functional carbon transporters must be done first.

2.5 Synthetic Biology in Coral

The successes of synthetic biology within plants have raised questions about whether it is also a viable option for animals. Many scientists have introduced the idea of using synthetic biology to bring back extinct species and protect other endangered animals. Although the science of synthetic biology presents many fascinating possibilities, most agree that the technology is still too new to use on most living organisms. However, coral is one of the few animals that synthetic biology is currently being researched with. It is general knowledge that coral needs help during the current extreme environmental changes. However, many are attempting to reverse these environmental impacts through reducing carbon emissions, using less electricity, and other common practices. All of these actions are important to reducing the impact of climate change and helping coral reefs, but at the current rate of environmental changes, we need a faster and more direct solution. This is where synthetic biology comes in. Due to exponentially rising levels of coral bleaching, scientists have turned to synthetic biology to create more heat-tolerant species of coral to adapt to its changing environment. There is an abundance of ways in which researchers have proposed modifying coral genetics, some of which have already been done and some that are still in the preliminary stage. However, all synthetic biology-based experiments are still being discussed, and have not yet been conducted.

2.5.1 CRISPR Methods

One way that has been proposed is to identify the specific genes within more heat-tolerant coral species and use those genes in other coral to create a new biological system [EVHR22]. This approach is one of the more common ones and has higher guarantees of success given that heat-tolerant genes are already present in some coral species. This technique is also similar to those being explored in other genetic engineering methodologies, however, the synthetic biology version requires the use of CRISPR technologies. Stanford researchers have been experimenting with injecting sgRNAs into coral gametes to produce mutations in the developing organisms [PACM18]. They used three different types of coral during the course of the experiment, injecting the organisms with just Cas9 or both Cas9 and sgRNAs. This research has found that some sgRNAs, when used in tandem with Cas9 in the coral gametes, can produce considerable and varying mutations that continue to develop during the first few cell cycles [PACM18]. After injection, both the mutated gametes and the control gametes continued to develop at roughly the same pace. They also displayed comparable survival percentages of all test subjects with multiple injections and days. To

further study the mutations that were induced, scientists cloned and sequenced fragments of the test subjects, and found that the mutations were similar to those observed in other studies that also used Cas9 and sgRNAs [PACM18]. Researchers also noted that almost half of the injected coral gametes displayed their mutation in the predicted region. This shows that they maintain a similar genetic efficiency as noted in other organisms of similar studies [PACM18]. The study was considered a success since it proved that using CRISPR technologies in coral was a viable option to create a species of coral with certain mutations. CRISPR will likely play a major role in the future regarding synthetic biology, and having evidence of its benefits towards coral will be essential if this idea is further explored. However, it will likely take many more trials before scientists are able to produce a specific heat-tolerant mutation that can be applied full-scale.

2.5.2 Manipulating Microorganisms

Another way that scientists may be able to use synthetic biology is through the microorganisms that live within the coral. Although coral itself is a relatively simple organism, it is often regarded as one of the most complex beings due to the various species that rely on it. Many of these microorganisms play an important role in the health of the reef, which encouraged scientists to look into ways to engineer these prokaryotes to help coral. Coral's various prokaryotes form microhabitats, help bolster its defenses, and give necessary products to the coral following carbon and nitrogen fixation [KDvO17].

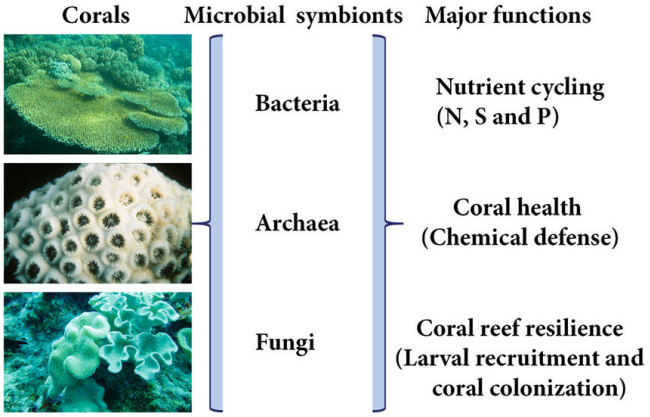

Figure 4: Image showing a few microbial symbionts that coral rely on and the functions of such symbionts [WSL16].

The structure of the coral's microbiome can vary depending on the surrounding environment and is especially subject to change during climate change. Typically, elevated water temperatures and thus coral bleaching are likely due to the influx of pathological bacteria present rather than the usual healthy prokary-

otes [KDvO17]. However, some types of microorganisms have been observed to remain steady in health despite environmental stressors. In an optimal environment, coral would be able to remain healthy due to the microorganism's ability to protect them and continue providing essential resources. Still, the adaptability of some microorganisms can provide beneficial abilities to their host coral, allowing the coral to adapt to the changing environment rather than depending on a healthy environment. Scientists have experimented with transplanting certain microorganisms in coral around the world and monitoring the results. They found that coral fragments with a transplanted microbiome generally fared better against heat stress than their counterparts. Transplanting microorganisms has not only shown promising benefits for increased heat tolerance, but some microorganisms can also degrade oil WSFs [KDvO17]. By transplanting these types of microorganisms into coral, experiments found that coral with the transplant were able to preserve water quality amid an oil spill, combatting any negative impacts. Due to the significant positive benefits that such experiments have shown for certain microorganisms, scientists are now looking into how to manipulate naturally present prokaryotes within coral to reproduce these same benefits. Probiotic treatments have already garnered lots of support and success when used within other industries like agriculture and medicine, reinforcing the viability of their usage within coral. The preliminary experiments of transplanting certain prokaryotes within coral have also shown the many benefits it can provide. However, the process of manipulating the naturally present microorganisms within the coral, negating the need for transplantation, is still a work in progress. Many beneficial microorganisms are prokaryotes, so implementing synthetic biology techniques and manipulating their genes will likely prove to be simpler than with coral polyps.

2.6 Ethical Complications

The general population has been wary regarding the ethics of genetic modification since it was first introduced in the scientific community. However, the public's perception regarding genetic manipulation is slowly starting to change as they've started to accept that many of the resulting products are necessary in this changing world. In fact, many major agricultural foods are now made up of mostly genetically modified organisms. Still, the idea of synthetic biology is vastly different from many of the other genetic modification techniques being currently used. As of now, scientists have barely begun to dip their toes into the world of synthetic biology, even in plants, much less animals. Since the public took a while to get acclimated to the ideas around selective breeding and assisted evolution, it would only make sense for them to be wary regarding the change of a whole biological system. Although some studies are already underway to research more about the applications of synthetic biology in coral, it is still important to take note of the public's opinion, as their support will be crucial in the future. A study was conducted amongst Australian citizens regarding their support for various Great Barrier Reef conservation efforts. There were several different questions about perceived threats, possible consequences, and

new technologies. Due to the many benefits that the reef provides, a majority of citizens supported many of the proposed conservation ideas. However, due to the risks that come with the use of synthetic biology, many citizens were more likely to support less aggressive approaches such as manual pest control and rubble stabilization [AMC21]. In addition, the study found that personal threat, rather than just public threat, was correlated to what extent citizens supported different conservation approaches. Still, despite the risks, almost half of the surveyed participants supported the use of genetic modification in coral conservation.

Factor:	Mean participant responses on a scale of 1-5 with 1 being not at all and 5 being definitely
Intention to support	3.69
Willingness to visit reef post-gene tech implementation	3.79

Figure 5: Image showing mean survey results surrounding the possible implementation of synthetic biology in coral reefs [AMC21].

An even larger percentage of civilians said that they'd be willing to visit parts of the reef where genetically modified organisms had already been implemented. Many participants also ranked technological benefits and effectiveness higher than potential risks in terms of importance [AMC21]. The large drawback in citizens' support for the genetic modification of coral reefs was found when there were 70 percent or more healthy coral reefs remaining. A large increase in support was found when there was only 5 percent to 20 percent of healthy coral still left [AMC21]. This study showed how the support for the use of synthetic biology in coral is usually correlated with other factors such as perceived personal threat and relative benefits. However, the large percentage of participants that were in support of synthetic biology shows the growing necessity of implementing technology in wildlife conservation. The support for these new technologies also helps to cement synthetic biology as a positive and viable future option for conservation once the technology is further developed. Still, despite the growing support for genetic engineering in conservation, there are other ethical drawbacks to consider. Altering an organism's genetic makeup will always carry some risk that it will have negative consequences for the organism, the environment, and humans. There is also a lot of controversy surrounding interfering with nature and God's plan. These ethical implications will only become more important as synthetic biology progresses and the need for new conservation approaches grows.

2.7 Applications in Animals Other than Coral

Genetic engineering is not only at the forefront of conservation discussions with coral, but also in a variety of other wildlife. Topics of de-extinction are becoming more popular with techniques like back breeding and cloning. More aggressive

selective breeding and other assisted evolution approaches are also being discussed in order to encourage more adaptive genes. For example, the idea of selective breeding has already been used in fish to produce more biodiversity and encourage faster evolution. Genetically modified animals are also becoming more common within livestock, though not for conservation purposes. However, applications of synthetic biology within animals are a lot more challenging than previous genetic modification techniques. Selective breeding entails selecting organisms with desired traits and breeding them in hopes of producing offspring with similar traits. Synthetic breeding entails gene editing and creating a new, artificial biological system. This makes it a lot more challenging to implement into any organism. Currently, experiments are being conducted with plants and are beginning to be discussed within coral. However, it will likely be a long time before it can be conducted full-scale in any of these organisms. Still, scientists are thinking about how synthetic biology could be useful in a variety of organisms and applications, especially CRISPR. CRISPR can be implemented in a variety of different ways in genetic engineering, and will likely be at the forefront of synthetic biology within wildlife. Its gene editing capabilities will allow scientists to create and apply adaptive genes within all sorts of creatures. It will also be able to create traits that didn't exist before, such as resisting pathogens or allowing organisms to function with lower levels of water. Although synthetic biology is not yet developed enough to apply in organisms past simple plants, it promises many benefits to the field of wildlife conservation in the future.

3 Conclusions

Reducing our environmental footprint is still essential in saving Earth and the abundance of life it houses. However, scientists have acknowledged the possibility that changing life on Earth, rather than Earth itself, may be a more effective approach to dealing with climate change. This approach entails artificially aiding organisms to evolve and become more adaptable to their ever-changing environment. This idea is currently widely used within agricultural industries in tandem with traditional climate change prevention techniques and has shown a lot of promise. For example, there are several varieties of drought-resistant plants and more nutrient-rich plants to supplement the lower produce supply. The success seen within GMOs, specifically in agriculture, has encouraged scientists to pursue genetic engineering techniques in animals. Some animals have already been subject to genetic modification techniques, especially livestock, to produce traits like higher milk and fat production. On the other hand, genetic engineering for conservation purposes has taken a backseat, until now. Important keystone species are beginning to struggle with the immense pressures of climate change, and scientists have turned to environmental modification to help these species adapt. One of these keystone species is coral. Coral acts as a habitat for a multitude of organisms and is crucial in keeping marine life healthy. However, due to rising water temperatures, major coral bleaching events have taken place, throwing entire ecosystems off balance. Currently, scientists have

experimented with selective breeding and artificial gene flow, both with reasonably high levels of success, to increase heat tolerance within specific species of coral. These basic methods of genetic engineering have resulted in coral that possesses some heat-tolerant traits, however, the effects will likely still be insufficient due to the relatively slow pace of these approaches combined with steadily increasing temperatures [CDQ21]. Indeed, more drastic measures need to be taken to produce a whole generation of heat-tolerant coral. To achieve more substantial genetic changes, new technologies have been developed, such as CRISPR, that allow scientists to change entire biological systems. The alteration of an organism's biological system, rather than a simple trait, has come to be known as synthetic biology. Since synthetic biology is relatively new, it has not been tested on many organisms. However, recently some scientists have experimented with using CRISPR technologies on some coral gene sequences. The results of this experiment show that using CRISPR in the future to produce heat-tolerant coral is a viable option [PACM18]. Other scientists have also introduced the idea of artificial biological systems within the organisms that help keep coral alive, rather than coral itself [KDvO17]. This approach involves intervening with prokaryotic organisms, rather than eukaryotes, so the process would likely be much more streamlined. Regardless of the method, synthetic biology still poses a multitude of challenges that must be addressed before fully implementing the technology within living organisms. There have been many ethical arguments surrounding the use of basic genetic intervention since its introduction, arguments that have only increased tenfold since the development of synthetic biology. However, various surveys have found that, despite some level of hesitation, the majority of citizens support the use of genetic engineering within coral due to increasing necessity [AMC21]. Even scientists who are currently working on gene-editing projects are uncertain about all the aspects of genetic engineering. However, studies have shown that a majority of scientists continue to support the use of genetic modification for treatment and prevention, such as heat-tolerance traits, rather than enhancement [MWC21]. Although we are still distant from using any major genetic modification techniques within other animals, scientists hope that success found with synthetic biology in coral will soon correlate to support for its implementation within other animal species.

4 Recommendations

Genetic engineering has made its name within both agricultural and conservation fields. Simple methods with little to no risks such as selective breeding have been successfully utilized for many years within these industries. These techniques have created organisms that possess traits such as drought tolerance and higher nutrient production. However, these basic approaches are limited to small genetic changes. Many times this means that genes that an organism currently possesses are simply amplified. Although the results of these methods have had a significant impact, it would be beneficial to research more drastic

measures that may need to be taken to maximize conservation efforts. This is where the idea of synthetic biology and CRISPR comes into play. These techniques can create new biological systems with a wide variety of traits that haven't yet been present in that organism. Synthetic biology has begun to be used with some varieties of plants, but it is far from a full-fledged initiative yet. These radical methods have yet to be implemented in animals, as it's a slow process, hindered by a variety of variables. However, these obstacles should not prevent scientists from continuing to pursue all the possibilities that environmental engineering presents. Some research has already been done that shows positive results with CRISPR technologies in coral genes [PACM18]. Scientists must continue to test their methods with multiple different genes and simple organisms with positive results before they can fully apply the procedure with more complex beings like coral. Understandably, the amount of research that is necessary before synthetic biology can be considered "safe" will take more time than we have. Although synthetic biology presents one of the most effective genetic conservation techniques, there is still much more to be explored within other methods. Currently, researchers are working towards more complex assisted evolution procedures, both with coral and the surrounding microorganisms. These experiments have already produced successful results, with scientists continuing to test different variations of coral and microorganisms together. Results of these trials were found to have up to 84 percent more heat tolerance in comparison to the less heat-tolerant parent [EJHA21]. With further research, scientists are certain that they will be able to discover even more efficient ways to produce heat-tolerant coral that can adapt to the changing environment. As was discussed in this paper, the ethical complications surrounding genetic engineering, specifically synthetic biology, currently make it challenging to make the necessary progress. If we hope to put genetic engineering at the forefront of conservation efforts, using more "popular" methods presents the most feasible option. This is not to say that synthetic biology, after further investigation, is not the more efficient or "better" option. In fact, in the future, synthetic biology will likely come out as one of the more popular approaches. However, currently, many researchers agree that we need to take action now. This means focused efforts on improving and executing current genetic modification techniques to create a new generation of heat-tolerant coral. With concerted efforts on these methods, scientists will likely be able to apply their findings to other keystone species that are threatened as well. More research in genetic engineering will also lead to more discoveries within synthetic biology, even if it is not at the focal point of new research. This approach to genetic engineering with coral and other wildlife will almost certainly yield the most success. This paper has outlined several procedures, both "basic" and "radical", that can be used to combat the challenges that coral face in the ever-changing environment.

References

[AMC21] Elizabeth V. Hobman Aditi Mankad and Lucy Carter. Genetically engineering coral for conservation: Psychological correlates of public acceptability. *Frontiers in Marine Science*, 2021.

[aut11] No author. Coral reefs support jobs, tourism, and fisheries. *NOAA*, 2011.

[aut13a] No author. Coral diseases. *NOAA*, 2013.

[aut13b] No author. What are corals? *NOAA*, 2013.

[aut18] No author. Coral reef watch home. *NOAA*, 2018.

[aut21] No author. How reefs are made. *Coral Reef Alliance*, 2021.

[aut22] No author. Gmo crops, animal food, and beyond. *FDA*, 2022.

[aut23] No author. Science tech spotlight: Synthetic biology. *U.S Government Accountability Office*, 2023.

[autte] No author. Coral reefs. *NOAA*, No date.

[BS05] Steven A. Benner and A. Michael Sismour. Synthetic biology. *Nature Reviews Genetics*, 2005.

[CDQ21] Carlo Caruso Crawford Drury and Kate Quigley. Selective breeding to support the long-term persistence of coral reefs. *Eco Evo Rxiv*, 2021.

[EJHA21] YI JIN LIEW JOHN A. BURT ELI MEYER EMILY J. HOWELLS, DAVID ABREGO and MANUEL ARANDA. Enhancing the heat tolerance of reef-building corals to future warming. *Science Advances*, 2021.

[EVHR22] Lucy Carter Elizabeth V. Hobman, Aditi Mankad and Chantale Ruttley. Genetically engineered heat-resistant coral: An initial analysis of public opinion. *PLOS ONE*, 2022.

[Fre22] Michelle Frey. All about soft corals. *Ocean Conservancy*, 2022.

[KBE19] Armin Kubis and Arren Bar-Even. Synthetic biology approaches for improving photosynthesis. *Journal of Experimental Botany*, 2019.

[KDvO17] Nicole S. Webster Katarina Damjanovic, Linda L. Blackall and Madeleine J. H. van Oppen. The contribution of microbial biotechnology to mitigating coral reef degradation. *Microbial Biotechnology*, 2017.

[McG22] Rod McGuirk. Majority of great barrier reef coral studied in 2022 was bleached, australian scientists say. *PBS*, 2022.

[MHM21] Keri L. O'Neil Daisy M. Flores Lucas Tichy-Trinity Conn Valérie F. Chamberland-Claire Lager Nikolas Zuchowicz Kathryn Lohr Harvey Blackburn Tali Vardi Jennifer Moore Tom Moore Iliana B. Baums Mark J. A. Vermeij Mary Hagedorn, Christopher A. Page and Kristen L. Marhaver. Assisted gene flow using cryopreserved sperm in critically endangered coral. *Proceedings of the National Academy of Sciences*, 2021.

[MWB18] Pelayo Menéndez Borja G. Reguero Pedro Díaz-Simal Felipe Fernández Michael W. Beck, Iñigo J. Losada. The global flood protection savings provided by coral reefs. *Nature Communications*, 2018.

[MWC21] Teresa Edwards Gail E. Henderson Kristine J. Kuczynski-John M. Conley Paige Della-Penna Margaret Waltz, Eric T. Juengst and R. Jean Cadigan. The view from the benches: Scientists' perspectives on the uses and governance of human gene-editing research. *The CRISPR Journal*, 2021.

[NMVM22] Lars Nielson, Stephan Mahler, Claudia Vickers, and Esteban Marcellin. From genetic engineering to synthetic biology. *Small Things Big Changes*, 2022.

[NOA23] NOAA. What does the ocean have to do with human health? *NOAA*, 2023.

[OHGK19] Linwood Pendleton Ove Hoegh-Guldberg and Anne Kaup. People and the changing nature of coral reefs. *Regional Studies in Marine Science*, 2019.

[PACM18] Line K. Bay John R. Pringle Phillip A. Cleves, Marie E. Strader and Mikhail V. Matz. Crispr/cas9-mediated genome editing in a reef-building coral. *Proceedings of the National Academy of Sciences*, 2018.

[RvW22] Andréa G. Grottoli Rob J. Toonen Rebecca Vega Thurber Mark E. Warner Ann Marie Hulver Leila Chapron Rowan H. McLachlan Rebecca Albright Eric Crandall Thomas M. DeCarlo Mary K. Donovan Jose Eirin-Lopez Hugo B. Harrison Scott F. Heron Danwei Huang Adriana Humanes Thomas Krueger Joshua S. Madin Derek Manzello Lisa C. McManus Mikhail Matz Erinn M. Muller Mauricio Rodriguez-Lanetty Maria Vega-Rodriguez Christian R. Voolstra Jesse Zaneveld Robert van Woesik, Tom Shlesinger. Coral-bleaching responses to climate change across biological scales. *Global Change Biology*, 2022.

[SL18] Michon Scott and Rebecca Lindsey. Unprecedented 3 years of global coral bleaching, 2014–2017. *Climate.gov*, 2018.

[WSL16] Ramasamy Anbuchezhian Wei Sun and Zhiyong Li. Association of coral-microbes, and the ecological roles of microbial symbionts in corals. *The Cnidaria, Past, Present and Future*, 2016.