Applications of Selective Breeding, Three Dimensional Printing, and Modelling Technology in Coral Reef Restoration and Resilience

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Abstract (182 words)
The world's coral reefs support life for over a quarter of all marine species but their existence is in danger due to the effects of global warming which are acidifying and warming the oceans at an alarming rate. If nothing is done, it is predicted that almost all corals will be bleached or destroyed by 2100. The goal of this paper is to assess whether the current coral reef restoration method of Coral Gardening can be combined with new resilience enhancing methods of Assisted Breeding, three-dimensional printing, and three-dimensional modelling technologies in technological symbiosis to create an improved method of restoration that improves the efficiency of coral growth and increases survival rates of corals. Research identifies the flaws with the current methods of restoration and resilience and suggests that the weakness of each method could be improved by the strengths of the other methods. Combining the three methods of coral restoration and resilience will create an updated restoration process that could restore coral reefs faster than the warming planet.

1. Introduction

Coral reefs are a biologically diverse ecosystem that can only be found in tropical waters. They cover less than 0.1% of the ocean floor but 25% of the marine species on earth depend on them for energy (Heron, et al). Man-made global warming from the burning of fossil fuels has led to an increase in the amount of carbon dioxide in the atmosphere and has caused the world's oceans to warm and acidify. These higher temperatures and acidic environments cause problems for the corals as it affects their temperature and pH sensitive symbiotic dinoflagellates. Corals offer protection to these photosynthetic plankton in exchange for food, but when exposed to elevated temperatures or increased acidity, dinoflagellates leave the corals causing a "bleaching" event. These bleaching events can create widespread mortality for the reefs during periods of increased acidity and SST (Thomas et al. 2017), including temperatures increases of as low as 2°C (Donner et al. 2017).

Coral bleaching is a relatively new occurrence but has become increasingly common due to the SST and acidity increase. Coral reefs can grow back from a bleaching event but need at least a year to fully recover (Thomas et al. 2017), as well as the SST must return to normal. Unfortunately, the re-occurrence of increased SST and turbidity is outpacing the ability for corals to regenerate and recover. If these temperature changes in our oceans are not resolved it is likely that all the world's coral reefs will be destroyed in the next two centuries. Since 450 million people from more than 100 countries depend on coral reefs as a source of nutrition or income in some way (Pandolfi. 2011), the disappearance of corals would cause a collapse of a trillion dollar economy.

There are currently methods in place for restoration of coral reefs to help mitigate the loss, such as coral transplantation and gardening (Jaap. 2000). With the current threats to coral reefs it is important to evaluate new and advanced methods to ensure the survival of an important ecosystem. The purpose of this paper is to assess whether the current coral reef restoration method of Coral Gardening can be combined with new resilience enhancing methods of Assisted Breeding, three-dimensional printing, and three-dimensional modelling technologies in technologic symbiosis to create an improved method of restoration that improves efficiency of coral recovery and increases survival rates of corals.

2. Coral Nurseries and Transplantations

Coral "gardening" is the current method being used for restoration of damaged coral reefs and is composed of two parts. Floating nurseries are first created to allow coral fragments to grow along the nurseries. The nurseries provide a safe environment for the coral to grow, which supports a higher survival rate and year round availability of coral to allow immediate transplants to in-need reefs. These nurseries have grown more than 100 000 corals from 86 different species. The coral that is grown in the nurseries are parasite free as they are constantly monitored during growth. As well, nurseries attract inhabiting species as the coral grows which increases the biodiversity of the nursery. The nurseries are specially designed to swing, which allows more oxygen and food to circulate throughout the nursery (Rinkevich. 2014).

Once the corals are fully grown, they are then transplanted onto an active reef. There is an array of different methods for the transplantation process such as the drilling of holes into the substrate, which is followed by lining the nursery over targeted areas to allow growth (Rinkevich. 2014). Transplanted coral each require a certain amount of space to allow them to grow and reproduce functionally. If the corals are not spaced properly with the local coral, a fight for territory, growth reduction, or even the death of the coral can occur (Rinkevich 2014).

This method of restoration is not perfect. The process of transplantation requires a large amount of time to implant more than one coral colony. If a large restoration project is needed immediately, this current method cannot perform at that size. Coral Gardening can only provide immediate help to reefs in need, but the method has no process for predicting future environmental changes. Global warming has been steadily warming and acidifying the oceans faster than the capability of adapting coral gardening to a large scale method. Therefore a strategy to increase the capability of coral reef restoration to a global scale and to anticipate future environmental changes is needed.

3. Assisted Breeding Through the Identification of Genetic Markers

A newly introduced method of increasing resilience in coral reefs is Assisted Breeding (Jin et la. 2016). Assisted Breeding works by choosing coral that are genetically more tolerant to stressors for for fragmentation and reseeding. This process creates offspring which will have an increased resilience to environmental stressors. Dr. Jin and her team of researchers have been collecting samples of the coral *Acropora millepora* from the Great Barrier Reef in different latitudes. Using these samples, experiments were run that increased temperature or acidification to understand how some coral of the same species have the ability to survive in severe conditions while others do not. The experiments targeted the stress tolerance ability of Acropora millepora that have grown in different areas of the Great Barrier Reef to see if adaptations had been made in different ecosystems. What was discovered was that alleles at two genetic loci have the ability to influence its antioxidant capacity as well as its tolerance to environmental stress.

Table 1. Summary of Results. Results of three independent data sets and results from experimental heat stress. (Jin et al. 2016)

Data Set	**Locus C70S236**	**Locus C29226S281**
Gene-by-environment correlation (poor water quality, high SST range, and low mean SST)	Higher frequency of T allele	Higher frequency of G allele
2006 non-bleached versus bleached corals (temperature stress)	12% higher frequency of T allele in non-bleached colonies	No difference
2009 non-bleached versus bleached corals (salinity and turbidity stress)	No difference	28% higher frequency of G allele in non-bleached colonies
	Higher antioxidant capacity ($CoQH_2$) in TT genotypes: 35.2% explained by genotype	Higher antioxidant capacity ($CoQH_2$) in GG genotypes: 14.6% explained by genotype
Experimental Heat Stress	Resistance to photosynthetic damage (F_v/F_m) in TT genotypes: 10.5% explained by genotype	

As shown in table 1, Locus C70S236 was shown to have a connection to rapid SST changes. Higher antioxidant capacities and resistance of photosynthetic in homozygous genotypes were also discovered to have some correlation to the homozygous TT genotypes. Data from non-bleached corals in the summer, during increased SST, had an association with the C70S236 locus as well. Locus C29226S281 was shown to have an association with the tolerance of coral from bleaching due to poor water quality as well as having a slight association with SST and in a homozygous genotype of GG. Identification of these two locus could create the ability to selectively breed this species of coral using the newly discovered genetic markers to produce offspring with a higher tolerance to acidification and warming oceans. Using the method of assisted breeding in symbiosis with the current method of coral gardening could create an improved method of coral reef restoration that has the ability to be created on a global-scale due the ability of corals adapting to harsh environments that assisted breeding brings to the method.

Although the research appears to show that that the Assisted Breeding method increases resilience, there is still the possibility of a plateau effect. This would mean that some corals could only increase their resilience to a certain level and not be able to adapt anymore to the warming and acidifying waters. This field of genetic marker research is young and so far only the two loci in the species of Acropora millepora have been identified. Assisted breeding can become a viable method of increasing resilience of coral reefs if more research is able to identify genetic markers of other species. Even though it may not be possible at the moment, with the eventual research, this method has the ability to be combined with coral gardening to increase the effectiveness of the restoration and make for a more resilient reef.

4. Three-Dimensional Printing and Modelling Technologies

3-D printing is a new technology that has been created in the last decade. It allows for the creation of a three dimensional items through a printer, which continuously prints layers of material, one on top of the other, until a three dimensional item is produced. 3-D printers have the capability to be extremely precise and can produce intricate and complicated models that cannot be done without a 3-D printer (Ling, 2017). Due to their versatility, 3-D printing technologies have been implemented in a huge array of industries including manufacturing, medicine, dentistry, and robotics (Mohammed, 2016).

Recently, 3-D printing has begun to be implemented in the field of Oceanography and Marine Biology. In the first of its kind, a tangible three-dimensionally printed coral prop was created by Sustainable Oceans International (SOI, 2012). Unlike previously cast concrete coral props the 3-D printed props have the ability to create intricate designs similarly shaped to natural coral (Fig. 1.), copying the curvatures and tunnels that allow the props to be biologically diverse by facilitating various species of marine life (Pardo, 2013).

Fig. 1. Three-Dimensional reef unit from a patented sandstone material (SOI, 2012)

3-D printing is efficient in terms of the time and the ability to mitigate its carbon footprint compared to creating the props through molds. The printing only takes a day and can recreate exact replicas of previous made props since the data is stored in the computer prior to being made. The material used for the coral props is a patented non-toxic sandstone material that has a neutral pH level suitable for coral to grow on (Mohammed, 2016). Currently the coral prop units are being applied off the coast of Bahrain with around 3000 coral reef units and pre-cast concrete reef units submerged. It is yet to be determined if this technique is more cost efficient in the long term (Pardo, 2013). More of these props need to placed in varying environments to determine if this method is adaptable to a global scale. Using these neutral pH materials to construct the props allows for an increase in the resilience of the coral to withstanding ocean acidification as the coral will be in areas of neutral pH even if the surrounding environment is acidic, preventing the dinoflagellates from being forced to leave the corals.

A pressing issue in the production of artificial coral props and reefs is that the structures slightly alter the environment around them due to hydrographical and biological variables. This can cause the seafloor sediment around the reefs to alter which in turn, can change how marine life reacts to its environment and could create damage to coral reefs and the marine life using the reef as a habitat. An effective and precise three-dimensional monitoring method is needed in order to monitor the surrounding seabed to obtain maximum efficiency for the growth and survival of the coral reefs.

Some monitoring programs include, Multi-beam Echo Sounders. They work by sending multiple acoustic beams down to the reef with a distance between them of 15 centimetres. As the boat with the Multi-Beam Echo Sounder moves, the beams cover different angles of the reef and begin to overlap each other to create a 100% coverage of the reef being monitored. These instruments are able to provide exact measurements unlike SCUBA divers and ROV's which mostly rely on visual inspections that can be inaccurate due to water visibility and the level of the diver's experience, all of which can create outlier data (Tassettie, et al).

From the data received from the Echo Sounder, a specially designed software program compiles the data and then creates a three-dimensional model of the artificial reef. The model has an accuracy of 10-15 centimeters for depth and less than a meter accuracy for horizontal position. As more data is obtained, there is an improved ability to see how the artificial reef has changed the seafloor surrounding itself and how the artificial reef itself moved overtime as the seafloor changed around it (Tassettie, at al).

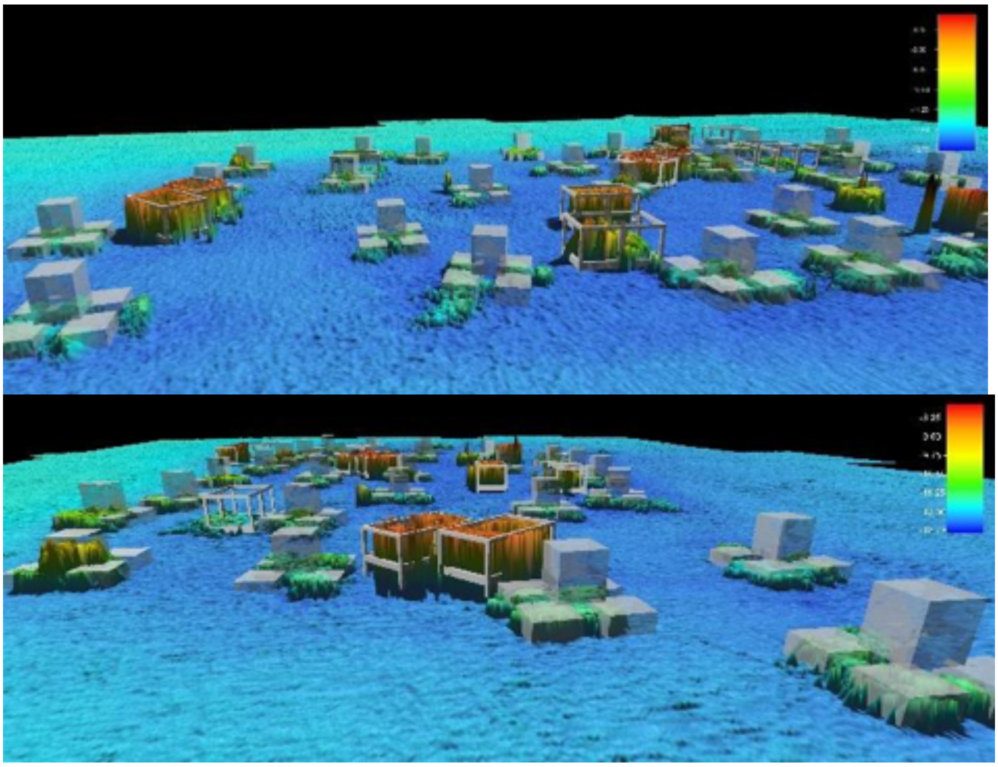

Figure 2. 3-D rendering of structures used in MBES data set from research. (Tassetti, 2015).

Even though the 3-D rendering of the structures appear accurate as seen in Figure 2, there are still issues with this technology. A Multi-Beam Echo Sounder needs prior dimensions of the structure and the seabed on where it is put is required before they can accurately measure how the structure itself moved. The area on which the props will be placed could cause challenges if they are needed in isolated locations. When it comes to monitoring artificial reefs this is not an issue because the dimensions were stored to create the three dimensional coral props (Tassettie, et al).

The three methods reviewed all offer a means for protecting and restoring coral, albeit each has its own unique challenges. Coral Gardening provides an immediate response to restoring reefs that were recently damaged. This allows the reefs to recover faster so if it is damaged again, it will not be worse than the previous condition but this method only restores the corals, it does not create any resilience. Assisted Breeding, on the other hand will not only restore the reefs health, it will also create increased resistance to the warming waters. Its greatest shortcoming is its limited scope to only two loci while coral gardening is applicable to more than 80 coral species (Rinkevich, 2014). Three-dimensional printing of coral props can also increase the resistance of corals by creating a neutral pH area surrounding the prop. This allows coral to attach to the prop much easier than in an acidic environment which forces the dinoflagellate phytoplankton to leave and while this method offers great promise, unlike Coral Gardening and Assisted Breeding it can create seafloor sediment misplacement (Tassettie, 2015). Even with Assisted Breeding and three-dimensional printing it is hard to accurately monitor how much these methods create resilience and their ability to recover from damage. That is why a three-dimensional modelling technology is needed to monitor a reefs recovery and how well it is resisting change. Using a Multi-Beam Echo Sounder can create an accurate and three dimensional model that can actively monitor the reef's health.

5. Conclusion

The state of coral reefs is in dire risk; if action is not taken soon to protect our environment and improve the current restoration methods for coral reefs they will be destroyed in a matter of decades.

This paper examined how through multiple fields of study in Oceanography, the restoration and resilience methods for coral reefs can be improved. It was concluded that by leveraging the existing restoration method of Coral "gardening" and integrating it with new methods of Assisted Breeding, three-dimensional printing, and modelling technologies increased the efficiency of coral growth, decreased mortalities of coral, and created an accurate model of the reefs.

Further research is required to discover more genetic markers of other species of coral to enhance the method of Assisted Breeding resilience before it can be implemented globally. An improved software program from Multi-Beam Echo Sounders is needed to create more accurate three dimensional models that can also distinguish how coral props and coral have changed over time without prior knowledge of dimensions.

Local Research is also required to fit specific variables that are not associated with other ecosystems which could affect the restoration process. This future work could include consideration of how these methods can be implemented to take into account local conditions such as varying species of corals, local currents, and local SST. An Adaptive Resilience-Based Management framework (ARBM) provides a set of guidelines for how coral reefs resilience can be enhanced (Anthony, 2015). Taking into consideration local variables, the current condition of the reef, and even the social-economic conditions of where the coral reef is located. ARBM could be used as a basis upon which to structure this research.

There is not a lot of time left to save the coral reefs, with less than a century until their demise and 450 million people relying on them for survival; there is not time for hesitation.

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