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IMPROVING THE HEAT TOLERANCE OF VULNERABLE CORALS THROUGH THEIR ALGAL SYMBIONTS

By Cathryn M. Bowling

ABSTRACT— Tropical coral reefs are one of the most impressive and diverse ecosystems on the face of the earth. Found in warm, tropical waters around the globe, these reefs are major supporters of the immense biodiversity of the area. The health of coral reefs is highly influential on the overall health of the entire ecosystem. In recent years, intensifying climate change has resulted in an accelerated rise in seawater temperatures and the frequency and severity of coral bleaching. Coral bleaching occurs in response to harsh environmental conditions that cause corals to enter a period of extreme stress. During this time, corals expel their algal symbionts – ending the symbiotic relationship with the zooxanthellae. Corals are especially vulnerable to permanent damage in this bleached state. As major supporters of the success of marine ecosystems and coastal communities alike, it is imperative that ecosystems are rehabilitated and protected from future harm. Coral polyps have long generation times, making them unable to keep up with the rate at which the climate is currently changing. Without human intervention, coral reefs will not survive the next century. Studies have indicated that the introduction of thermotolerant strains of Symbiodinium, the algal symbiont associated with corals, improves the heat tolerance of corals. This review examines the use of thermotolerant algal symbionts as a potential long-term rehabilitation and mitigation strategy. The thermal tolerance of zooxanthellae has been shown to transfer to coral species, making these species of corals more resilient to the increasing ocean temperatures and harsher conditions associated with climate change. Experimentally implanting thermotolerant strains of Symbiodinium may serve as a viable solution to the problem of corals' slow adaptation times. Additional mitigation strategies may be required during the conservation of coral reefs to ensure the overall health of the reef for years to come. Climate change has shown no indication of slowing down in future years. It is critical that mitigation efforts are implemented immediately to identify feasible, long-term solutions to assist vulnerable corals in beating the heat.

Keywords: Bleaching, Climate change, Symbiodiniaceae, Symbiodinium, Tropical corals, Zooxanthellae

I. INTRODUCTION

Tropical reef-building corals are frequently subjected to recurrent biological and physical disturbances; factors including severe storms, overfishing, and pollution as a direct result of coastal development have been identified as some of the largest contributors to reef damage

(Carilli et al., 2009; Hughes & Connell, 1999). However, the declining state of the coral reefs has been most critically impacted by the effects of climate change (Hughes & Connell, 1999). As coral reefs are one of the most biologically diverse ecosystems, accounting for approximately a quarter of all marine species, the critical endangerment of this ecosystem is significant. The current speed of climate change outpaces the natural rate of coral adaptation (Buerger et al., 2020). As sea temperatures continue to rise at an alarming rate, coral reefs are subjected to increasingly stressful environmental conditions. This has resulted in mass bleaching events causing significant losses of coral reefs around the world (Hoegh-Guldberg, 1999; Howells et al., 2016).

Over the last 100 years, sea temperatures in tropical regions have increased by almost 1°C and continue to increase by an average of 1-2°C per century for all areas (Descombes et al., 2015; Hoegh-Guldberg, 1999; Knowlton, 2001). The rapid increase in sea temperatures over the past few decades has resulted in an increased frequency of mass bleaching events (Hoegh-Guldberg, 1999). Global patterns of coral bleaching have been associated with El Niño-Southern Oscillation (ENSO), a climatic event causing periodic increases in sea surface temperature in the tropics (Sotka & Thacker, 2005). Alongside a general increase in sea temperatures, climate change has caused more frequent and more severe ENSO events. Without intervention, ecologists predict that coral bleaching will result in irrecoverable coral loss within decades (Baskett et al., 2009; Hoegh-Guldberg et al., 2018; Sotka & Thacker, 2005).

Tropical corals heavily depend upon their symbiotic relationship with *Synbiodinium* – a diverse genus of dinoflagellate algae living in the tissues of corals in high densities (Berkelmans & van Oppen, 2006; Putnam et al., 2017). More commonly referred to as zooxanthellae, *Symbiodinium* provides up to 90% of corals' nutritional requirements (Berkelmans & van Oppen, 2006).

Bleaching, a term commonly used to describe the ghostly white appearance of corals, refers to the partial or total expulsion of symbiotic algae from corals (Brown, 1996; Curran & Barnard, 2021; Douglas, 2003). While this phenomenon can be triggered by a variety of biological and physical disturbances, recent bleaching events have been attributed to rising seawater temperatures in concert with global climate change (Descombes et al., 2015; Douglas, 2003). By the time that corals appear completely bleached to the naked eye, the algal density has been reduced by approximately 70-90% (Douglas, 2003). Bleached corals will die during prolonged thermal stress as the zooxanthellae that were expelled are responsible for providing a majority of the nutrition and carbon necessary for coral polyp survival (Sotka & Thacker, 2005).

Bleaching events cause severe declines in the local biodiversity of coral reefs. As coral reef ecosystems are subjected to more severe and large-scale disturbances, corresponding changes in habitat structure are expected (Pratchett et al., 2011). These changes may result in declines in the abundance and diversity of marine species dependent upon the reefs.

The deterioration of coral reefs does not only impact the biodiversity of species living within the reefs. Coral reefs are a crucial source of income and resources for coastal communities. These communities rely on tourism, fishing, and coastal protection that coral reefs provide (Hoegh-Guldberg, 1999). In the tropics, billions of dollars are generated from tourism associated with the coral reefs alone; this economic sector is one of the fastest growing and is projected to increase substantially within the next few years (Hoegh-Guldberg, 1999). Additionally, fisheries provide millions of tonnes of fish catches to communities worldwide and employ millions of fishers (Hoegh-Guldberg, 1999). Finally, coral reefs protect coastlines from storm damage, erosion, and flooding, enabling the formation of essential habitats and associated ecosystems, such as seagrass beds and mangroves (Hoegh-Guldberg, 1999). The damage caused by the total loss of coral reefs would be significant and is not limited to the marine environment; the loss of coral reefs would also have profound impacts on the lives of humans. It is essential that coral reefs are protected in order to subsequently protect the surrounding ecosystem and economy of coastal communities.

The purpose of this review is to examine mitigation strategies focused on improving the mechanisms of heat tolerance in coral populations through adaptations of reef corals' algal symbionts. As the current literature is based primarily on experimental studies of methods of improving the heat tolerance of coral, there is a significant gap in information regarding the effectiveness of this in a real-world setting. Thermotolerant symbionts are physiologically taxing on coral species; reef corals with these more resistant species of zooxanthellae often have impacted growth, reproduction, and energetics. As a result, the viability of altering the algal symbionts in reef corals long-term is unclear and requires further study before implementing into areas where thermotolerant algal symbionts are not native.

II. MITIGATION STRATEGIES

A. Heat-Tolerant Algal Symbionts

Strains of *Symbiodinium* adapt differently to high amounts of thermal stress (Sotka & Thacker, 2005). Of the four major clades, two have been found to associate more commonly with corals in areas experiencing greater variations in temperature. Association with one of these two clades of zooxanthellae has been shown to provide environmental resistance to the corals themselves making these species of coral less vulnerable to increasing sea temperatures (Sotka & Thacker, 2005; Berkelmans & van Oppen, 2006). Further research has also shown that associations with

Symbiodinium D, one of the four major clades, transfer heat tolerance to the coral (Baker et al., 2004). Little is known about the process through which the symbionts change within coral populations and whether this shift in algal symbionts is a permanent change (Baker et al., 2004). However, knowing that certain strains of zooxanthellae provide heat tolerance to corals forms the foundation of a potentially revolutionary mitigation strategy – the assisted evolution of corals through the implantation of heat-tolerant algal symbionts.

The symbiotic relationship between coral polyps and zooxanthellae can be manipulated in the laboratory through a pattern of controlled bleaching and recovery to change the dominant strain of *Symbiodinium* (Cunning & Baker, 2020). Corals with a less heat-tolerant strain of *Symbiodinium* are placed into a controlled environment where they are subjected to bleaching conditions; the corals are held at this temperature until they are returned to control conditions and allowed to recover for several months (Cunning & Baker, 2020). During bleaching, corals undergo an exchange of their zooxanthellae, allowing more heat-tolerant strains of *Symbiodinium* to form a symbiosis with the corals. In experimental settings, this shuffling of algal symbionts has shown a marked improvement in the heat tolerance of once vulnerable corals (Cunning & Baker, 2020; Berkelmans & van Oppen, 2006).

The introduction of heat-evolved strains of algal symbionts into corals can increase the heat tolerance of coral polyps to bleaching events. Studies have shown that corals develop tolerance to heat by forming symbiotic relationships with more thermally tolerant species of zooxanthellae. Thus, the resilience of coral to an increasingly hostile environment can be developed and improved through assisted evolution by shuffling corals' algal symbionts (Buerger et al., 2020).

B. Transplantation and Acclimatization

As the viability of introducing thermotolerant algal symbionts into corals over an extended period of time is unknown, it is crucial to continue experimenting with alternative mitigation strategies. These may include the transplantation of corals into environments with warmer temperatures and more variable conditions. Transplantation is the process of regenerating damaged coral reefs by artificially establishing corals in an area where none previously existed (Harriott & Fisk, 1988). Species of corals found in naturally warmer environments have been identified as having higher resistance to bleaching temperatures; these corals can have higher thresholds of thermal tolerance when compared to conspecifics in cooler environments (Palumbi et al., 2014). These populations are ideal for research regarding the mechanisms of acclimatization in response to climate change due to their ability to avert bleaching during the stressful conditions associated with warmer environments. By identifying how certain populations adapt to increasing hostility within their environment, similar methods of adaptation can be encouraged and implemented into more vulnerable populations.

The thermal tolerance of corals can be tested in their natural environment by exposing coral polyps to experimental bleaching conditions. By artificially creating cyclical increases in water temperature similar to natural processes, researchers have been able to identify the ability of various coral species to respond to environmental changes. These studies have shown coral species native to warmer areas exhibit higher levels of thermal tolerance (Palumbi et al., 2014). However, transplantation of coral colonies to these warmer environments have yielded similar results. Regardless of where the corals originated, once exposed to the artificial increases in water temperature, coral colonies acquired, at the very minimum, part of the heat tolerance of the area that they were transplanted into (Palumbi et al., 2014). Over a longer period of time, transplanted corals have been shown to acclimate to their environment and achieve similar heat tolerance to what would be expected from the natural selection for heat resistance over many years (Palumbi et al., 2014).

The transplantation of coral polyps to create a nursery stock has been identified as an alternative method of naturally adapting corals. When creating a nursery stock, coral fragments from colonies of heat-tolerant species are removed and transplanted into a “coral nursery” (Caruso et al., 2021; Morikawa & Palumbi, 2019). Nurseries are heavily monitored and protected areas ensure that the fragments are allowed sufficient time to recover and grow to an adequate size before transplantation (Caruso et al., 2021). Newly grown coral fragments are often transplanted back into their original environment for recovery of the damaged reef; however, these fragments have also been transplanted and are maintained in novel environments with little variation in their bleaching resilience (Morikawa & Palumbi, 2019). Research has shown corals transplanted from nursery stocks experience two to three times less bleaching than their conspecifics that were not transplanted from a nursery (Morikawa & Palumbi, 2019). As research supports that nursery corals have increased resilience and tolerance to heat, they can be used as a sustainable source for the restoration of reefs with minimal damage to coral populations (Caruso et al., 2021).

Corals in highly variable environments have proven more resilient to stress than corals from less variable conditions (Palumbi et al., 2014). With this in mind, it may be possible to encourage the expansion of the thermal tolerance of more vulnerable coral species by transplanting them into environments more hostile than their natural habitat or by raising fragments of resilient coral species in a nursery habitat. This may ultimately provide a feasible long-term solution to supplement the current pitfalls of artificially injected algal symbionts.

III. Conclusion

Over the last few decades, climate change has had detrimental effects on marine ecosystems around the world. One ecosystem particularly devastated by climate change has been tropical coral reefs. Approximately a quarter of all marine organisms rely on coral reefs for their survival. The loss of corals would result in a consequential loss of a significant portion of the biodiversity of the ocean. The impacts of this loss on the surrounding ecosystem and communities would be lasting and potentially irreversible. Additionally, the impacts of the damage to corals have been demonstrated to extend beyond the surrounding marine ecosystems. Corals support the livelihoods of millions of individuals living in coastal communities reliant on tourism, fishing, and coastal protection provided by the reefs. Severe damage or total loss of the reefs would have significant impacts on coastal communities. These impacts would not be limited to the affected coastal areas as it is likely that the resulting economic collapse would be felt by communities around the globe.

As coral reefs have extremely long generation times and are unable to evolve fast enough to survive the rapidly changing conditions of their environment, it is imperative that researchers identify means of mitigating the effects of climate change. One of the most effective ways of lessening the impact of rising ocean temperatures is by improving the heat tolerance of local corals. Research has indicated that artificially evolving corals to form symbioses with more heat-tolerant algal symbionts increases the overall resilience of the corals and may be a viable solution to safeguarding the future of coral reefs. However, little is known regarding the viability of this solution in the long-term, so it is vital that alternative means of preservation and, eventually, restoration are identified. Alternative reef management strategies may include

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various forms of transplantation and acclimatization of reef corals. Transplantation can occur in a number of ways, but two of the more common techniques include acclimating corals to harsher conditions by transplanting them into these stressful environments and generating a colony of resilient corals through the establishment of a nursery consisting of heat-tolerant coral species. In both techniques, research has demonstrated successful acclimatization of these corals into stressful environments, indicating transplantation as an alternative means of preserving the health of coral reefs into the future.

The health of coral reefs across the globe has reached a critical point. Protection of these areas must begin forthwith to ensure that future generations of marine species and humans are able to survive and benefit from these highly productive ecosystems. The extensive research and implementation of highly advanced conservation strategies are guaranteed to fail without support from the general public. In any conservation or restoration project, education is one of the most important and effective strategies. It is paramount that humans are educated on the effect they are having on coral reefs to better understand how to limit their own contribution to the deterioration of the reefs.

Without coral reefs, the lure of abundantly diverse oceans would disappear entirely, leaving a barren wasteland as a reminder of what once was. There is no question that coral reefs are essential to the everyday life of marine species and humans alike. Failure to implement intervention and preservation techniques immediately has been predicted to result in a near-total coral loss by midcentury. Actions must be taken to mitigate and reduce the human footprint left on this vulnerable ecosystem before corals are driven to extinction.

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