Coral bleaching to starvation: Impending mass mortality and feasibility of sustainable conservation strategies

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Abstract

Coral reefs provide substantial benefits to humans by generating biologically diverse ecosystems and reducing coastal hazards. However, in recent years, mass mortality of coral reefs due to bleaching has been witnessed in the ocean worldwide. Bleaching induced by the loss of the symbiotic relationship between algae and coral is mainly attributed to climate change. Marine protected areas (MPAs) can effectively prevent local disturbances but are less likely to conserve the coral reefs from global events like climate change. Other conservation and restoration methods can be useful to protect and replenish the coral population temporarily, but whether they are feasible as sustainable conservation strategies is still equivocal. Coral reef mass mortality is not an exceptional occurrence but is linked to various instances of ecological loss, serving as an S.O.S. signal of severe prolonged climate extremes.

Keywords: global warming; cost; mass die-off events; symbiotic relationship; habitat loss

> "Coral and Algae used to coexist happily before suffering tragic deaths due to the burning of the ocean caused by greenhouse gases. Bleached by climate change-induced heat."
>
> In "Ghosts"; *The Kingfisher Story Collection* (Vuong, 2022)

The impending mass die-off of global coral reefs

The color white is often valued by individuals in many cases, including interior spaces, wooden furnishings, garments, and as a representation of purity through the presence of white flowers. Nevertheless, it is indisputable that white is not the preferred color in relation to coral reefs. In essence, the white hue exhibited by coral serves as an indication of the depletion of vital nutrients and the eventual mortality of coral.

Bleaching has raised significant apprehension among scientists and the general populace (Chow, 2023). More considerable worry is that the coral bleaching occurring in Florida represents only a small component of a larger-scale global phenomenon of coral bleaching. Based on research conducted by the National Oceanic and Atmospheric Administration (NOAA), it has been observed that a significant proportion of the coral reefs in the Caribbean region are presently undergoing a process known as coral bleaching, resulting in a loss of coloration. Bleaching event is so serious that it can be simply stated as follows. Suppose someone sees a random white spot in the Caribbean and then investigates under the ocean. That person will see with their own eyes the bleached coral reefs. This fact also means that the coral system faces severe environmental stress, leading to mass "starvation."

The potential demise of coral reefs poses significant ramifications for both human livelihoods and the long-term sustainability of the marine economy. Coral reefs are recognized as one of the most diverse and ecologically significant ecosystems on the planet. Coral reefs possess the remarkable ability to sustain an exceptionally high concentration of species within a given unit area beyond that of any other ecosystem. Coral reef ecosystems are home to a diverse array of animals, including over 4,000 fish species, 800 coral species, and many other organisms numbering in the millions (EPA, 2023). The coral reef system's biological variety is of paramount importance in the identification and exploration of essential medications in the 21st century. Various novel pharmaceuticals are now derived from the wide range of animal and plant species inhabiting coral reefs. These pharmaceutical compounds exhibit potential therapeutic applications in treating various diseases, including but not limited to cancer, asthma, and infections. The coastal economies derive substantial annual revenue from several sectors, such as fishing, tourism and recreation, and dining establishments, which are directly reliant on the coral reef ecosystems. According to available data, coral reefs' projected yearly economic value had reached nearly $30 billion by 2003 (Cesar et al., 2003).

Coastal regions are becoming ever more susceptible to the swift expansion and intensifying environmental perils stemming from climate change. Hence, the significance of coral reefs in ameliorating these adverse effects is becoming prominent. Coral reefs possess a substantial physical framework that serves as a protective barrier against the harmful impacts of oceanic waves, storms, and floods. This formidable structure has the capacity to mitigate as much as 97% of the potentially destructive energy emanating from the sea (Ferrario et al., 2014). The demise of coral reefs necessitates that both human populations and coastal ecosystems face a substantial rise in the occurrence of natural disasters.

Climate change as the predominant cause of coral "starvation"

The continuous existence of coral reefs is persistently jeopardized by human economic activities, with climate change, particularly the increase in sea temperatures, being the predominant factor (Eakin et al., 2019). Coral bleaching is attributed to the occurrence of heightened sea temperatures, which induces significant stress on the coral organisms. The period spanning from 2014 to 2017 is widely recognized as the most severe documented occurrence of mass coral bleaching to date. This event was mainly attributed to elevated sea temperatures stemming from climate change, which inflicted significant harm on around 75% of the iconic Great Barrier Reef located in Queensland, Australia. Coral bleaching is a phenomenon that arises when elevated temperatures induce thermal stress, leading to the disturbance and breakdown of the mutualistic association between corals and the endosymbiotic algae residing within their tissues. The coral polyps, which serve as the primary constructors of the calcium carbonate skeleton of the coral, are considered the hosts within this particular system.

Although coral may first give the impression of being hard like stone, a more detailed examination reveals that it is actually composed of delicate living tissues loaded with polyps and tentacles. The coral reef system is sustained by a substantial assemblage of live polyps. Each polyp is linked to its base by the calcium carbonate skeleton, generated by layers of CaCO3 contributed by polyps-past. The formation of the calcium skeleton occurs gradually and incrementally across multiple generations of coral. Every individual polyp within the organism is characterized by a sac-like structure enveloped by a circular band encircling its oral aperture, via which the polyp's digestive tract is accessible. The pigmentation of coral tissue is attributed to the presence of coral pigments, as well as a combination of brown and red algae residing within the cellular structure of the coral (McDermott, 2020).

The symbiotic relationship between algae and coral provides a suitable habitat for algae, brings color to coral reefs, and supplies vital nutrients to both organisms concurrently. The study conducted by Frankowiak et al. (2016) shows that the symbiotic relationship with algae allowed corals to thrive in nutrient-poor waters and form coral reefs in the tropics more than 210 million years ago (during the Late Triassic period).

Algae reside symbiotically within coral polyps and play a crucial role in fulfilling the metabolic requirements of coral by supplying a significant portion of the necessary energy. Coral reefs establish symbiotic relationships with endosymbiotic dinoflagellates of the genus *Symbiodinium*. Like other photosynthetic organisms, *Symbiodinium* must effectively manage the absorption and utilization of sunlight through photosynthesis to sustain a high level of primary productivity while avoiding any detrimental effects. The carbon that Symbiodinium assimilates undergoes conversion into energy to support coral development and calcification. Additionally, oxygen is generated as a byproduct of the photosynthetic process, hence enhancing coral calcification rates to their full potential. In reciprocation, corals provide their endosymbiotic algae with essential nutrients and a safe, sunny habitat in the nutrient-poor ocean. Due to the nutrient-recycling and -conversion mechanism driven by the coral-algae symbiotic relationship, coral populations can thrive in tropical nutrient-deficient oceans (Roth, 2014).

Nevertheless, extended durations of elevated water temperatures induce a transformation in these mutually beneficial algae, rendering them detrimental to corals, hence prompting the corals to expel them from their tissues. Thus, coral bleaching can be described as the disruption of the symbiotic relationship between coral and algae, leaving the corals bleached and vulnerable. Primary factors influencing the duration and severity of coral bleaching are the extent and duration of temperature anomalies, light intensity, other environmental variables, and the thermal history of the coral reef (Baker et al., 2008; Middlebrook et al., 2008; Strong et al., 2011). The phenomenon of coral bleaching can result in the mortality of coral colonies due to prolonged deprivation of essential nutrients in cases where the affected corals are unable to restore their normal metabolic processes and the associated algae fail to re-establish symbiotic relationships. Even when the algae return and the symbiotic process is restored, the coral's growth, regeneration, and general health are also diminished and more susceptible to bleaching in the future (Roth, 2014).

At what point do algae establish a harmful symbiotic relationship with coral? The occurrence arises when extended periods of elevated temperatures disturb the photosynthetic apparatus of the algae. During this period, the algae exhibit reduced efficiency in light processing and generating reactive oxygen and nitrogen species, including hydrogen peroxide (H_2O_2), which harms coral well-being. When coral is exposed to hydrogen peroxide (H_2O_2), the proteins within the coral can be damaged. In order to protect themselves, coral polyps engage in the process of expelling or eliminating algae from their bodies. This can be achieved by either digestion of algae within coral cells or by pushing them back into the gut and expelling them through the mouth (Figueiredo et al., 2022; McDermott, 2020; Raj et al., 2020).

The impact of global warming on coral reefs is evident since it is causing significant disruption, including elevated mortality rates among coral polyp larvae and reduced lifespan. As temperatures warm by 2°C, larval dispersal patterns change, causing the average larval dispersal distance to decrease by 7% and the number of connections to each coral reef to decrease by 8%. Overall, a 2°C increase in temperature will reduce inter-habitat connectivity between coral reefs, hindering recovery after disturbances. Furthermore, it has been observed that increasing temperatures reduce the ability of polyps to acquire genetic traits that facilitate adaptation to elevated temperatures (Figueiredo et al., 2022). Algal blooms can cause temporary oxygen shortages, contributing to mass coral mortality. However, these occurrences are not as commonly documented. During the period spanning from September to October 2019, a notable amount of coral in the Gulf of Mannar, located in southeast India, experienced mortality as a result of algal blooms. During the blooms, the concentrations of dissolved oxygen experienced a decline below 2 mg/l, resulting in temporary shortages of oxygen and a coral mortality rate surpassing 71%. It is anticipated that there will be a heightened occurrence and expanded magnitude of algal blooms in the future as a result of global climate change. Hence, shallow-water coral reefs will be affected more frequently by hypoxic conditions caused by algal blooms (Raj et al., 2020).

Financial concerns about sustainable conservation

The occurrence of extensive coral bleaching resulting from catastrophic climate events is not limited to 2023 alone. Significant devastation transpired in the previous years, specifically from 2014 to 2017 (Eakin et al., 2019). Throughout this period, there was a persistent increase in the Earth's temperature, resulting in several record-breaking years and subsequently causing extensive mortality among coral populations. As the circumstances keep intensifying, the financial burden of upholding Marine Protected Areas (MPAs) on a large scale can drastically increase. According to a recent estimate, the projected expenses associated with establishing and maintaining a worldwide MPA system encompassing 10-30% of the Earth's oceans between 2020 and 2050 will vary between 311 and 835 billion USD, contingent upon the particular implementation scenario (Brander et al., 2020). Although the author also shows that the benefits of expanding MPAs exceed their costs by a factor of 1.4–2.7 depending on location and extent of expansion, it must be noted that these economic estimates are based on several marine ecosystem services, such as the provision of food and materials, tourism and recreation, coastal protection, biodiversity, and carbon sequestration. The majority of these qualities presently lack mechanisms that can convert them into economic value and support the financing of conservation endeavors (Nguyen & Jones, 2022; Vuong, 2021).

Simultaneously, the feasibility and effectiveness of sustainable conservation have experienced a notable decline, heightening the challenges associated with achieving this objective (Eakin et al., 2019; Nguyen & Jones, 2022). The limited efficacy and inadequate long-term viability of MPAs can be attributed to their capacity only to address certain adverse local environmental stresses while offering minimal protection against global influences, like global warming and carbon dioxide levels. For example, the situation in 2023 summer was so dire that many conservationists and scientists in Florida had to pull corals out of the ocean and let them live in climate-controlled environments. After the seawater temperature stabilized, they returned the corals to the sea. The method may be comprehended as a viable option under critical situations wherein abrupt increases in temperature result in widespread coral bleaching. However, its long-term viability is hindered by two primary factors (Vuong, 2018).

First, it is essential to note that the transplanting and maintenance procedure requires significant resources and labor. While not fully precise, the cost of coral reef restoration might serve as a useful point of reference. According to Bayraktarov et al. (2019), the average expenditure for restoring a single hectare of coral reef is estimated to be approximately 400,000 USD. This financial commitment is tremendous, even for developed countries. In addition, even if replanting is successful, the ability of corals to withstand increased environmental stress is still a crucial inquiry because the adaptation abilities of biological systems protected under safe conditions will be impaired. In previous coral restoration projects, the average recorded survival rate of coral after being planted in the sea was only 60.9% (Bayraktarov et al., 2019).

In summary, based on the facts provided above, it can be shown that the demise of coral reefs in 2023 due to bleaching, coinciding with a peak in CO_2 emissions, is not an exceptional occurrence. The current state of the environment can be seen as a continuation of historical events characterized by the detrimental effects of climate change and human actions. Additionally, it serves as a link to various instances of ecological loss, including the mass mortality of crabs, whales, penguins, seagrasses, dolphins, and other organisms. These occurrences collectively serve as an S.O.S. signal of severe prolonged climate extremes (Vuong, 2023).

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