Effect of anomalies in sea surface temperature on coral symbiosis and marine biodiversity resilience

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Received: 13 February 2025; Revised: 18 March 2025; Accepted: 03 April 2025; Published: 20 May 2025

Abstract

Symbiotic partnerships facilitate the flourishing and survival of partners in environments where they might otherwise struggle or fail to exist without such interdependence. The Coral Reef (CR) ecosystem, along with its vast biodiversity, depends on the symbiotic relationships between cnidarians (such as scleractinian CR, octocorals, marine anemones, and jellyfish) and other creatures, including dinoflagellate algae, bivalves, lobsters, squid, and fish. The article examines the implications if CR cnidarian symbiosis is obligatory, necessitating the presence of more than one partner for survival, or facultative. The research explores the ramifications of cnidarian symbioses, demonstrating partner adaptability or faithfulness. Fidelity, wherein a symbiotic partnership can participate in symbiosis only with a select group of mates, is absolute or contextually dependent. Contemporary study indicates that numerous cnidarian symbioses are predominantly obligate and seem to display complete fidelity. Thus, the survival of several CR cnidarian symbionts under shifting circumstances will rely on the resilience and potential adaptability of the current host-symbiont pair. Adverse circumstances impacting even a single element of this symbiotic consortium trigger a cascade effect, resulting in the collapse of the entire relationship. Symbiosis is fundamental to the CR ecology, its survival, and its extensive biodiversity. Global warming precipitates the extinction of specific cnidarian symbioses, resulting in a subsequent decline in CR's biodiversity.

Keywords: Temperature, Coral, Symbiosis, Biodiversity, Marine

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DOI: 10.70102/IJARES/V5I1/5-1-07

Introduction

Research characterized symbiosis as the "coexistence of creatures of different species." Coexistence can enable species to inhabit environments where they might not last without symbiosis, hence enhancing biodiversity in that ecosystem (Wang *et al.*, 2025). "Coexistence" can potentially generate new organisms in a group of creatures. When symbionts reside within (endosymbionts) or on (ectosymbionts) the host's tissue, the host-symbiont organism, known as the holobiont, displays unique physiological and ecological characteristics (Becks, Gaedke and Klauschies, 2025).

Despite some contention over the evolutionary importance of this word, certain holobiont traits diverge from the features of the organisms in solitude (Kerfouf *et al.*, 2023). Host-symbiont genotypic pairings produce varied holobionts that exhibit distinct physical and ecological characteristics. Various symbiotic relationships and holobionts can enhance variation within and across host organisms, thereby adding to total biodiversity in an ecosystem (Sharipov *et al.*, 2024).

Symbioses are prevalent in terrestrial and aquatic settings, ranging from the tube-oxidizing bacterium in deep-sea hydrothermal vents to the algal symbiosis in arctic mosses (Benítez-Burraco, Ferretti and Progovac, 2021). In specific settings, symbiotic relationships are essential for the survival of entire ecosystems, as exemplified by Coral Reefs (CR) (Vasquez and Mendoza, 2024). The article examines the symbiotic relationships between species of the phylum Cnidaria (e.g., scleractinian CR, octocorals, sea anemones, jellies) and their microorganisms. These symbiotic relationships influence biodiversity on CR; however, warming temperatures jeopardize these crucial interactions, resulting in a decline in biodiversity (Petrou *et al.*, 2021). The geometric intricacy of CR diminishes, adversely impacting other creatures within the environment. The extent of dependence on companions in cnidarian symbiosis and their loyalty ultimately result in their extinction.

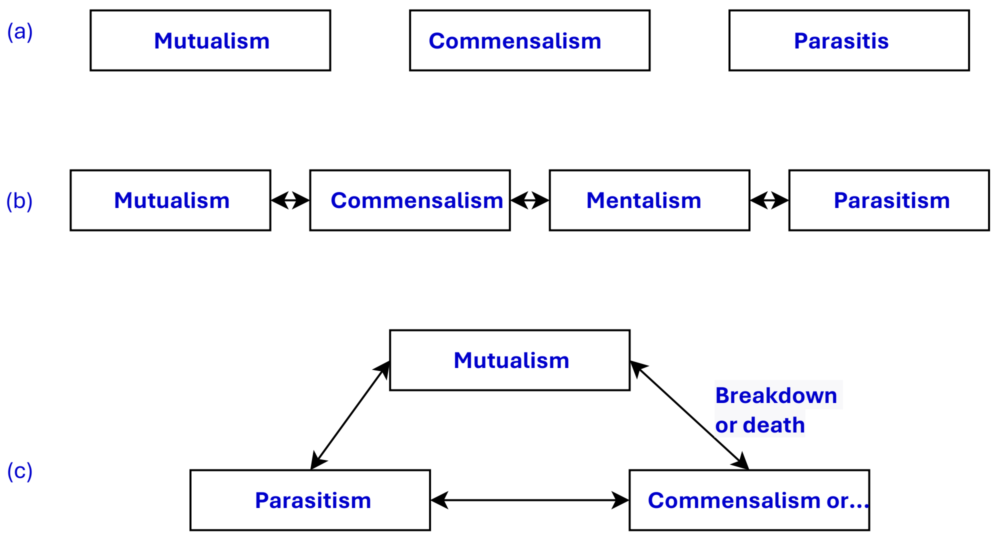

Figure 1: (a) Symbiosis states, (b) Continuum, (c). Oscillation between states.

The concept of symbiosis delineates phenomena rather than their implications. Attributes were allocated to symbiotic relationships according to their advantages and disadvantages, ranging from cooperation (both collaborators benefit), commensalism (one collaborate advantages while the other is unaffected), infection (one partner advantages at the expense of the other), to the newly introduced amensalism (one collaborate suffers while the other remains unaffected) (Figure 1). The research follows the classifications of symbiosis rather than equating symbiosis with mutualism (Rappaport and Oliverio, 2024). The depiction of symbiotic content as distinct categories or a sliding continuity fails to encapsulate the intricacies of symbiosis; the former approach presupposes that a symbiotic relationship is limited to a single classification, while the latter suggests that mutualism must evolve into commercialization or amensalism before transitioning into parasitic behavior, and vice versa (Naseer and Devi, 2019). Symbiotic phases fluctuate between one another depending on the context. Alterations in the outside environment, frequently associated with global warming, catalyze such symbiotic transitions. If the symbiotic individuals rely on a specific symbiotic condition, ecological alterations result in the dissolution of symbiosis and potentially the demise of one or both individuals (Iyer and Verma, 2023).

Acclimatization to Thermal Pressure

Numerous investigations have established a direct correlation between heat preconditioning and sensitivity to bleaching (Zhu *et al.,* 2021). Following short-term heat preconditioned trials, only the prepared CR exhibited no bleaching during a heat-stress test, while preserving their Symbiodiniaceae and bacterial ecology (Veres *et al.,* 2022). Other research has contrasted CR response during the initial significant mass bleaching occurrence with subsequent, more severe bleaching occurrences. The study examined identical sites. Following a more intense bleaching episode in 2012, characterized by Double-Degree Heating Weeks (DHW) and a 16% increase in solar irradiation, CR acclimatized and showed less bleaching (Grottoli *et al.,* 2021).

The research revealed that bleaching of CR was less severe following the 2015 extensive bleaching events in Southeast Asia at sites that had experienced significant bleaching (Singapore and Malaysia) and showed more considerable historical temperature variability and lower heating rates. CR in Indonesia experienced no bleaching in 1998; they exhibited significant mortality. As a result, CR that had acclimatized to prior thermal stress episodes and those residing in locations with substantial temperature variability exhibited greater tolerance.

The study revealed 'long-term ecological memory' after the 2015 bleaching catastrophe. The CR colonies underwent a 180° rotation in a controlled study. In the 2015 bleaching incident, the exteriors of colonies subjected to elevated sun radiation before rotating in the 2000 study maintained fourfold more symbionts than those exposed to diminished sunlight, despite enduring higher radiation levels for a decade (Kang, 2024). These investigations demonstrate that prolonged acclimatization to the area improves thermal resistance during bleaching occurrences. The research provided evidence of acclimatization to warmer oceans by duplicating a bleaching experiment conducted in 1980 at the same site in 2020. Due to a consistent rise in Sea-Surface Temperatures (SST) of 1.4 °C over the past forty years, the researchers artificially elevated the surroundings by 2.4°C. In 2020, CR exhibited elevated calcification costs, postponed bleaching, and increased mortality relative to CR in 1980. Regrettably, despite enhanced resistance to temperature in local CR, Hawaii experienced significant CR death (35%) throughout the global whitening event. This indicates that acclimatization to elevated temperatures is not happening rapidly enough to alleviate future bleaching processes' anticipated duration and severity.

Effects on Marine Environments and Biodiversity

Global warming and ocean acidification will escalate swiftly due to human activities impacting fisheries and marine environments, including environmental degradation, excessive fishing, invasive species, excessive nutrient amounts, contamination, and thermal impacts. These effects manifest right away, through elevated temperatures and reduced pH levels affecting specific organisms, and informally, through alterations to the ecosystems that provide both nourishment and habitat. Ocean acidification adversely affects bivalves (clams, mussels, oysters) and many aquatic flora and fauna, including top and deep-water CR, marine microorganisms, pteropods (marine slugs), mollusks, and crustaceans such as copepods, crabs, shrimps, and lobsters. Climate change impacts oceanic waters and the trends of aquatic production. Small, photosynthesis-producing organisms such as microalgae and aquatic plants thrive in the well-lit upper layers of the ocean, performing a crucial part in food chains and the food web. The proliferation of phytoplankton depends on temperatures and the accessibility of nutrients such as phosphorus, nitrogen, iron, and silica. The generation and dispersion of phytoplankton in the sea are influenced by ocean waves and rising waters, which are most pronounced at the Equator, in moderate and polar northern latitudes, and along the westernmost point of countries. Global warming is expected to impact nutrient cycling, hence diminishing the biological efficiency of the ocean and seas.

Phytoplankton saw a reduction in both the subtropics and the tropics throughout warm periods of the El Niño-Southern Oscillation (ENSO), characterized by elevated sea surface temperature and stratified ocean. The number and distribution of specific plankton species are vulnerable to rising sea surface temperatures and altered ocean circulation, affecting their general productivity. Many climate-related fluctuations affect fishery environments and fishing-dependent economies, including extreme weather events, storms, droughts, alterations in the marine environment's efficiency, and shifts in fish stock trends and availability. Intense ENSO episodes significantly affect phytoplankton, aquaculture, and aquatic mammals, serving as notable instances of climatic effects on oceanic biology. Marine CO2 levels of absorption fluctuate widely based on wind intensity and temperature. More chilly waters can hold more significant amounts of dissolved carbon dioxide than warmer waters and are hence more susceptible to acidification. Rising ocean temperatures and alterations in the cycle of temperatures will disturb the predator-prey dynamics, impacting the ability to survive of young fish that typically hatch at specific times of the year and rely on an immediate, plentiful supply of prey. Variations in temperatures will modify the dissemination of illnesses and parasites across natural environments and marine fishing (Figure 2). Acidifying the oceans and warming temperatures are expected to impact commercially significant varieties of fish and the tourism industry.

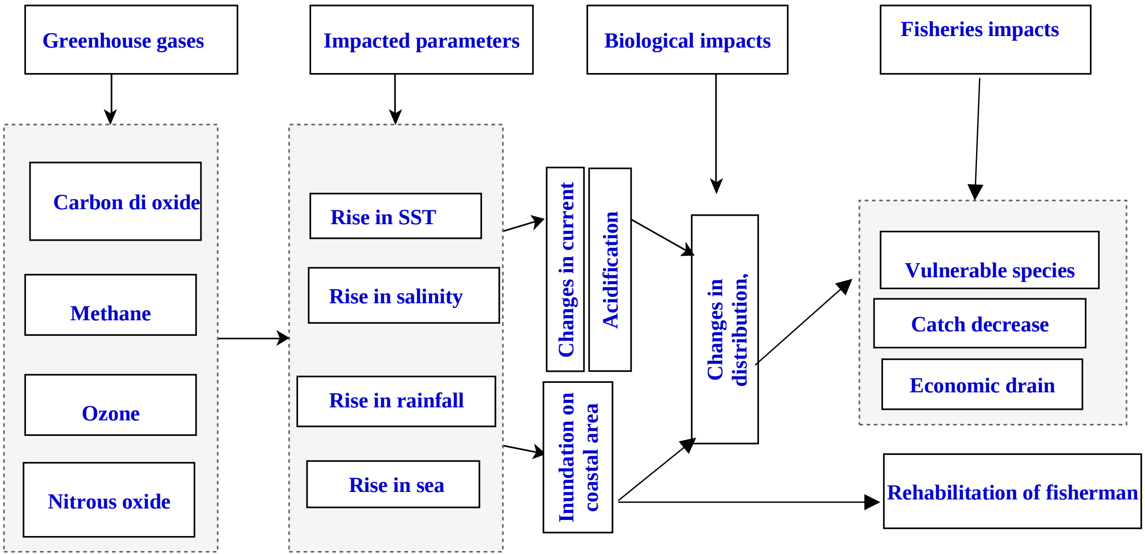

Figure 2: Climatic change of the marine fisheries effect.

Variations in water temperatures and rainfall influence the movement of ocean waves, river flow, and the extent of wetland coverage. This will impact ecosystem functioning and structure, as well as the distribution and productivity of fish stocks. The rising frequency of severe weather, including hurricanes, droughts, and floods, will compromise the safety and efficacy of commercial fishing while exacerbating harm and interruption to coastal and riparian residences, services, and infrastructures. The diverse elements of global warming are anticipated to impact all levels of aquatic biodiversity, ranging from individual organisms to entire biomes. Global warming can diminish genetic variation within groups due to selective pressure and fast migration, potentially impacting ecosystems.

Impacts on the Life Cycle of Marine Organisms

Marine species inhabiting coastal regions would be adversely affected by the decline of near-shore larval habitats, including mangrove forests, CR, seagrass beds, mudflats, swamps, waterways, and saline waters, due to the persistent rise in sea levels, pollution, and ecosystem loss. Alterations in precipitation and flow of rivers will modify coastal freshwater waves, influencing the movement of eggs and larvae of aquatic organisms. Significant fisheries globally, such as those off Peru and the western coast of Africa, arise from wind-induced coastal rising waters, vulnerable to warming temperatures. Rising sea surface temperatures will diminish gas solubility, heightening the likelihood of oxygen shortages or anoxic episodes already observed in particular estuary and coastal areas, such as those off the banks of the Mississippi.

The persistent increase in surface water temperatures significantly jeopardizes the migration of aquatic fish, mammals, and seagulls. This results in elevated mortality rates, the loss of breeding habitats, and extensive relocations as species seek favorable conditions. Elevated temperatures influence marine living things' survival, development, hatching, and embryonic metabolism, while causing oxidative damage in the eggs of the keystone invertebrate, Loligo vulgaris. Pelagic and marine intertidal living things exhibit complex physiological reactions to thermal stress, probably resulting in adverse effects on growth and maturation, altering population structure and ecological processes. Metabolic metabolism in fish escalates by 12% for each 1 °C elevation in aquatic temperatures, necessitating a 12% boost in oxygen consumption for each 1 °C rise.

Future Outlook

The global decline of CR will result in catastrophic repercussions due to human impact, prompting the exploration of techniques to reduce damage and enhance CR tolerance to heat. Aided settlement, movement, and gene flow involve the translocation of colonies or larvae of identical species residing at varying latitudes.

Warm-adapted CR are relocated to high-latitude regions, where similar species inhabiting cooler settings are susceptible to heat stress. Aided evolution can enhance thermal stress acceptance in CR via several methods: preconditioning acclimatization, trans-generational acclimatization, alterations in microbial populations, selective breeding, mutations, and applying gene editing technological advances. The consideration of utilizing 'strong CR naturally acclimated to harsh temperatures, such as those from the Persian Gulf or Red Sea, as potential seedlings for repopulating regions wherein CR have vanished is underway. Regrettably, none of these methods can match the current velocity of global warming, as the interval between successive bleaching events is diminishing, preventing the complete regeneration of reef ecosystems. Notwithstanding recent advancements in research methodologies and technological advances, like transcriptomics, economic and logistical constraints persist in their implementation, particularly on an extensive basis, and the safe deployment of new technology requires many years following social and political examination.

Additional conservation strategies being evaluated involve the design of improved Marine Protected Areas (MPAs) or networks of MPAs, accounting for larval dispersal, connectivity, and distribution patterns in regions with thermally resilient CR, as well as incorporating 'refugia' in locations where CR have demonstrated resilience to climate change. This mitigates the "protection paradox" in MPAs, where vulnerable species are shielded from local threats, such as fishing; when these species recuperate, they become increasingly susceptible to global threats, such as bleaching incidents. Adequately safeguarded reefs under MPAs are not immune to heat stress. This was proven for MPA and remote, inaccessible reefs with less direct human impact following the most recent bleaching occurrence.

Incorporating aided selection into CR rehabilitation efforts to enhance the durability of compromised ecosystems is an approach that has demonstrated success. The research utilized organically thermal-tolerant reefs from the Solomon Islands to demonstrate that resistant CR endure several bleaching events, offering the initial evidence that ecosystem design for conservation serves as a significant resilience restoration tool in the climate-altered future. Data from inversely implanted CR copies across sites with varying thermal history demonstrate how single communities of CR can alter their heat thresholds and tolerance.

Many varieties of CR are acclimatizing and adjusting to rapid climatic changes, with processes varying among species and locations. Based on current greenhouse gas emission forecasts, CR globally is expected to transform novel topologies with distinct species groupings. These shifts are occurring rapidly, with the prime illustration. Following the huge bleaching events, even more ‘pristine’ regions of the northern Great Barrier Reef saw significant mortality, irrespective of the individual management conditions on the reefs, demonstrating that existing management methods cannot safeguard CR environments from warming temperatures. The Paris Agreement was a first effort to address the climate catastrophe; no significant developed nation is fulfilling its commitments to regulate and diminish greenhouse gas emissions. Society must fundamentally alter its reliance on fossil fuels to tackle the basic causes of the changing climate.

Conclusion

Coexisting in symbiosis allows organisms to thrive where they could not survive independently. Obligate and high-fidelity symbioses enhance biodiversity within an ecosystem due to the numerous intra- and interrelated host-symbiont genotypic pairings. CR exemplifies ecosystems driven by cnidarian symbiosis. When the surroundings alter, mutualism shifts to parasitic behavior, a symbiosis is forsaken, the current host-symbiont genetic mix endures the disturbance, or the entire symbiotic relationship disintegrates. The obligation and faithfulness of numerous cnidarian symbioses render symbiotic transfers highly improbable. A particular obligatory symbiosis’s robustness ultimately results in a decline in intra- and interrelated biodiversity. Comprehending the characteristics of cnidarian symbiosis (from obligate to voluntary, fidelity versus flexibility), the symbiotic consortia, and the environmental impacts of these symbioses would enhance the comprehension of the current and potential biodiversity of cnidarian symbiosis in CR.

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