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Research progress on coral reef growth factors and their ecosystem restoration

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Abstract:

Healthy coral reef ecosystems have various functions such as reef-building, reef protection, reef stabilization, wave protection, shore protection, and the prevention of land erosion. Additionally, coral reef ecosystems are characterized by high biodiversity, often dubbed the "rainforest" of the ocean, as one of the most crucial ecosystems on Earth. In recent decades, global coral reefs have been significantly affected or damaged to varying degrees by climate change and human activities, posing threats to marine ecology and reef safety. This paper outlines the factors influencing coral reef growth, including global warming, ocean acidification, eutrophication, suspended solids, and tourism activities. It also discusses the status of coral reefs and viable restoration methods. Finally, this paper proposes an updated strategy for coral reef conservation, offering fresh insights into coral reef restoration efforts.

Keywords: coral reef;coral reef growth;ecological restoration.

1. Introduction

Globally, coral reefs are mainly between 30°S and 30°N, concentrated in the Indo-Pacific and Atlantic-Caribbean sea regions. Although coral reefs occupy just 0.2% of the world's ocean area, they harbor 34% of marine life, earning them the moniker "rainforests of the ocean". Coral reefs serve as critical habitats for marine organisms, offering spaces for spawning, reproduction, dwelling, and protection from predators. They also furnish human society with fisheries, tourism opportunities, and coastal ecological services [1]. Over recent decades, coral reefs worldwide have endured considerable degradation, Wilkinsonet et al. reported a 19% decline in global coral reefs, with 15% in critical condition, 20% under threat, and only 46% relatively healthy.[2]. Bruno and Selig et al. demonstrated that between 1997 and 2003, coral cover decreased by roughly 2% annually on Indo-Pacific coral reefs, amounting to a yearly loss of 3168 km², with an average coral cover of 22.1% in 2003 [3]. In the Caribbean, coral cover plummeted from around 50% in 1977 to approximately 10% by 2001 [4].

Coral reefs are complex three-dimensional ecological structures with high productivity and biodiversity, dominated by reef-building corals. They represent the largest marine ecosystems on Earth and are of immense importance in the evolution of global marine ecosystems. Coral reef ecosystems hold tremendous ecological, economic, and cultural values, characterized by high primary productivity and biodiversity. They serve as breeding grounds for marine organisms, maintain marine ecological balance, promote the circulation of marine matter and energy, offer wave protection, prevent land erosion, and fulfill other critical functions [5]. It's estimated that approximately 500 million people reside within 100km2 of coral reef ecosystems [1]. However, coral reefs are notably sensitive and fragile ecosystems, vulnerable to the natural elements and human interference, especially human high-intensity disturbances resulting in ecological harm on land and at sea, leading to severe damage to coral reef ecosystems that may be challenging to recover from [6, 7]. With the rapid development of society and the economy, human activities have an increasingly significant impact on the marine environment, requiring a more favorable environment for the growth and development of reef-building corals. When the environmental pressure exceeds the coral's tolerance level, corals may expel their symbiotic algae or zooxanthellae, leading to coral bleaching or fatalities, consequently resulting in coral reef deterioration. This paper summarizes the main factors affecting coral reef growth and the principal methods of coral reef ecological restoration, offering valuable insights for coral reef preservation efforts.

2. Factors affecting coral growth

2.1 Global warming

The coral growth environment has strict requirements.

Generally, suitable water temperature for coral growth ranges from 18 to 30 °C, with optimal water temperature falling between 25 to 29°C or 25 to 30°C. monthly average temperature for coral growth is about 13°C, while the maximum sits at around 31°C. The anomalous rise in sea surface temperature (SST) caused by climate change has caused widespread occurrences of mass bleaching and mortality amongst corals (Scleractinia) in low-latitude waters globally. Consequently, coral reef ecosystems are rapidly deteriorating. [8-10] The warming of seawater due to global warming is widely recognized as the primary driver behind coral bleaching on a worldwide scale.[8]. Elevated seawater temperatures not only impact coral calcification processes, reducing the rate of coral calcification, but also destroy the photosystem II (PSII) of Cnidaria, affecting their photosynthesis. This disturbance diminishes or eliminates their capacity to provide nutrients and energy to host corals, disrupting the symbiotic relationship between corals and Cnidaria. This breakdown can result in the loss of Cnidaria and, in severe cases, coral bleaching. Over the past 30 years, coral reefs in numerous regions worldwide have faced increasingly severe bleaching events [11]. The powerful El Niño event in 1997-1998 led to an abnormal seawater warming, destroying about 16% of the world's coral reefs, with the mortality rate of coral reefs in some reef areas exceeding 90%. Muller et al revealed a positive linear correlation between the prevalence of coral, and changes in water temperature [12]. Additionally, bleached corals exhibited a higher tissue loss rate compared to unblanched corals, suggesting that coral bleaching caused by unusual seawater warming diminishes the resilience of corals against environmental stressors. With global warming intensifying, coral bleaching incidents are projected to become more prevalent in the ensuing decades. There is a looming expectation that coral reefs might be the first ecosystem to vanish due to global warming by the century's end [13].

2.2 Ocean acidification

Ocean acidification occurs when seawater absorbs excess carbon dioxide from the air, resulting in a decrease in pH. Seawater should be weakly alkaline, with a pH of about 8.2, and the oceans become acidified when excess carbon dioxide from the air enters them. Studies have shown that as of 2012 the pH of the surface layer of seawater has decreased by 0.1 due to anthropogenic CO2 emissions, indicating a 30% increase in the acidity of seawater. Reef-building corals are important calcifying organisms in coral reef ecosystems and sustain coral reefs by producing large amounts of CaCO3. Acidification of seawater directly affects coral calcification. Compared to the pre-industrial revolution, the current calcification rate of reef-building corals is about 20% lower and will decrease by about 50% when seawater pH decreases by 0.2 units [14]. Crustose coralline algae can provide a hard attachment substrate for coral larvae, which is important for the attachment of coral larvae. However, under high CO2 conditions, the growth of chitinous coralline algae is inhibited and affects the attachment and development of coral larvae, which in turn affects the replenishment of coral populations and the growth of coral reefs[15]. Although living corals are resistant to seawater acidification, more pronounced dissolution of aragonite crystal morphology occurs when skeletons of dead corals are left in acidified water for 3 months [16]. Aragonite saturation (Ω arag) of 3.5 is considered to be the limit of coral reef growth [17]. Tropical shallow waters are still saturated, but the Ω arag has declined over the past century from 4.6 to 4.0. As ocean acidification accelerates, the Ω arag will continue to decline, and by the time atmospheric CO2 reaches 809.55 mg/m3, only 8% of the world's coral reefs will be in waters with an Ω arag > 3.5 [18].

2.3 Eutrophication

Eutrophication is a phenomenon of water pollution caused by excessive content of nitrogen, phosphorus, and other plant nutrients. Under natural conditions, with the river-entrained alluvial sediment and aquatic organisms' debris in the bottom of the lake continuing to sedimentation siltation, the lake will from a poor nutrient lake transition to a eutrophic lake and then evolve into a swamp and land, which is an extremely slow process. However, the discharge of industrial wastewater, domestic sewage and agricultural runoff into slow-flowing water bodies as a result of human activities has caused aquatic organisms, especially algae, to proliferate, altering the number of biological populations and disrupting the ecological balance of water bodies. The indicators of eutrophication are generally used: the content of nitrogen in the water body is more than 0.2-0.33 ppm, the phosphorus content is more than 0.01-0.02 ppm, the biochemical oxygen demand is more than 10 ppm, the total number of bacteria in the freshwater of pH 7-9 is more than 100,000 per milliliter, and the content of chlorophyll-a, which characterizes the number of algae, is more than 10 milligrams per liter.

Coral reefs are highly productive areas of the ocean, but coral polyps are suited to live in low-nutrient salt environments. Eutrophication significantly reduces the proportion of corals containing oocytes, decreases the number of coral oocytes reaching mature size, and reduces coral skeletal growth rates. Inputs from land-based sources of runoff, domestic sewage, and aquaculture wastewater discharges may lead to eutrophication in coral reef waters. At ammonium concentrations above 1 μmol/L, coral fecundity, egg size, and fertilization rates are reduced, along with an increase in the number of malformed embryos and a decrease in the coral larval replenishment population [19]. Seawater eutrophication also breaks the competitive balance between corals and macroalgae, making macroalgae bloom and grow in large quantities in the reef area, resulting in the suffocation and death of mature corals; macroalgae will also seize the attachment substrate of coral larvae, hindering the attachment of coral larvae, leading to a decrease in coral cover, or even replacing slow-growing corals as the dominant species, and ultimately altering the community structure of the coral reef ecosystem. The growth rate of corals (Porites porites) exposed to macroalgae decreased by 80%, and the effect disappeared after the isolation of both [20]. In addition, Vossh et al. found that nutrient salt concentration directly affects the rate of black band disease infection in live corals in both in situ and indoor nutrient salt addition experiments, indicating that seawater eutrophication accelerates the rate of coral disease infection and exacerbates the effects of disease on corals [21]Bacterial/analysis/isolation & purification</keyword><keyword>DNA, Ribosomal/analysis</keyword><keyword>*Ecosystem</keyword><keyword>Molecular Sequence Data</keyword><keyword>-Phylogeny</keyword><keyword>Polymerase Chain Reaction</keyword><keyword>RNA, Ribosomal, 16S/genetics</keyword></keywords><dates><year>2007</year><pub-dates><date>Nov</date></pub-dates></dates><isbn>0095-3628 (Print.

2.4 Suspension

The suspended matter is organic and inorganic particles suspended in the water column that cannot pass through 0.45-micron filter paper or filters. Such is difficult to dissolve in water silt, clay, organic matter, algae, and microorganisms. Land runoff and beachfront development, port terminals, bridges, and other marine engineering construction of suspended solids under the action of the sea current will also have an impact on coral reefs. On the one hand, the material and energy needed by corals mainly come from the photosynthesis of the symbiotic zooxanthellae, the increase of suspended solids will reduce the light transmission of the water, affecting the photosynthesis of the zooxanthellae and thus affecting the growth of corals; on the other hand, suspended solids will also form sediment that affects coral respiration, fertilization, adhesion, and survival. In general, the average calcification rate of reef-building corals under light conditions is three times higher than that under no light conditions [22], and the greater sediment content of the water column in the southern Gulf of Mexico leads to lower growth rates of corals [23]. Babcock et al. determined the growth rates of coral larvae under different determining attachment rates and survival rates of coral larvae under different sediment deposition rates, only 71% of the control group, and the survival rate after 8 months was only 39% of the control group [24]. Port excavation in the western and southwestern part of China's Yongxing Island Reef has caused a large number of live coral deaths and a significant decline in coverage. The coral reefs in the Xiaodonghai of Sanya were affected by the dredging process and dumping of dredged material, which resulted in a significant decrease in live coral cover and a significant reduction in coral replenishment [25].

2.5 Tourism activity

The improvement of human living standards led to the development of marine leisure tourism, diving projects are more and more favored by tourists, which makes the coral reefs have another source of pressure. The factors affecting corals in diving tourism are mainly in three aspects. firstly, diving tourists' body parts, diving equipment and coral contact [26] and boat, destructive behaviors such as anchoring of the body can directly cause coral skeleton breakage and tissue abrasion [27, 28]; through underwater tracking and video analysis, researchers have found that the flippers and diving equipment of dive tourists often come into contact with corals, and a few tourists even walk, kneel, stand, and jump on the reefs. Some studies have reported that the probability of coral contact by divers ranges from approximately 71% to 97% [29], and that flipper contact is the most frequent and damaging contact behavior to corals. In the St. Lucia dive area, 81.4% of dive tourists were recorded to have contacted corals with their flippers [30]. Additionally, due to the difficulty of controlling the body balance of dive tourists underwater, from

collision with corals [31]. Continuous human contact can affect the growth of coral communities: on the one hand, excessive contact can cause coral skeleton breakage and tissue wear.

On the one hand, excessive touching can cause coral skeleton breakage and tissue abrasion. Skeletal damage rates of corals in diving areas along the west coast of India increased from 4.83% in 2016 to 11.58% in 2019, with a cumulative 4-year skeletal damage rate of 33.1% [31].

Secondly, Near-shore tourism development has led to the discharge of large quantities of pollutants and an increase in the nutrient salt (mainly ammonium nitrogen) content of seawater, affecting coral growth conditions. Due to the discharge of a large number of pollutants into the ocean as a result of near-shore tourism development, the increase in the concentration of oxidized nitrogen, organic nitrogen, and inorganic nitrogen in the water body will harm coral physiology. Rising levels of oxidized nitrogen (oxidized nitrogen) such as nitrate inhibit coral skeletal growth [32] and reduce coral cover, species diversity, and densities of Botrytis cinerea in the dive area [33, 34]; live coral cover and coral abundance per square meter were lower in the area of higher total organic nitrogen concentrations (0.4 to 0.6 μmol-L-1), higher mortality rates [35]; and elevated dissolved inorganic nitrogen (DIN) concentrations were associated with lower temperature thresholds for coral bleaching in the nearshore of the Great Barrier Reef [36]. Anthropogenic activities can alter the concentration ratios between nutrients in the water column. When the environment contains an excess of dissolved inorganic nitrogen, Wormwood algal cells obtain relatively little phosphate from the outside world, resulting in a nutrient imbalance, at which time the maximum light quantum efficiency (Fv/Fm) of the coral decreases, reflecting an increased sensitivity of the coral to changes in temperature and light [33]. In addition, the continuous elevation of seawater nitrogen and phosphorus levels also promotes the growth of macroalgae [37], which compete with corals for substrate. However, in recent years, the mainstream view that “elevated nutrient levels in the water column are the cause of coral bleaching” has been challenged, and several indoor experiments on nutrient stress have not found any obvious negative effects on coral physiology [38]. affected the growth of corals [39].

Finally, the seafloor sediments are easily stirred with flippers during diving [40], which leads to changes in sediment deposition rate and suspended particulate matter content in the water column; meanwhile, the re-suspension of sediments can be significantly strengthened by the increase of human activities. Tanjung Tuan Dive Tourism Area (Tanjung Tuan, Malaysia) has low live coral cover due to high sediment content [41]. WIELGUS found that the suspended sediment content in the Eilat Intensive Dive Area (EIDA) was twice as much as that of the control area, which had the same offshore distance and depth [35]. The stirred seafloor sediments will cover the coral surface and inhibit the normal respiration of corals on the one hand; on the other hand, it will exacerbate the re-suspension of sediments, resulting in increased turbidity in the water column of the reef area. The increase of suspended particulate matter in the water column will prevent the settlement and replenishment of coral larvae, thus inhibiting coral reproduction and affecting the normal growth of adult coral populations [42]; the presence of a large amount of suspended matter in the water column reduces light transmittance, resulting in a decrease in the photosynthetic capacity of the wormwood zooxanthellae; in addition, corals need to consume a large amount of energy to remove the sediment that has fallen on their surfaces [43], which results in the physiological activities used for growth and reproduction, etc. energy reduction, bleaching and death.

3. Coral reef restoration

Coral reef ecosystems have great ecological significance and economic value. Healthy coral reef ecosystems have the functions of reef-building, reef protection, reef stabilization, wave protection and shore protection, and prevention of land erosion. At the same time, coral reef ecosystems have high biodiversity, known as the “rainforest” in the ocean. It is estimated that the asset value of tropical coral reefs is close to US$1 trillion [44], and the economic value of goods and services generated annually exceeds US$375 billion [45]. In recent years, coral reef ecosystems have been affected or damaged to varying degrees due to global climate change and human activities such as land reclamation, jeopardizing marine ecology and island safety, and the restoration of coral reef ecosystems is crucial.

3.1 Current situation

Coral reef ecosystems have extremely important ecological, economic, and cultural values, with high primary productivity and biodiversity, provide breeding habitats for marine organisms, maintain the marine ecological balance, promote the circulation of marine materials and energy, wave protection, and prevent land erosion [46]. At the same time, coral reefs are also a sensitive and fragile ecosystem, susceptible to the natural environment and anthropogenic interference, especially human high-intensity disturbance on land and sea ecological damage, environmental pollution, resulting in coral reef ecosystems seriously damaged, or even difficulty to recover [47]. The coral reef ecosystems are seriously damaged and even difficult to recover[7, 47]. Research studies show that in recent years, coral reefs around the world have been decreasing at an alarming rate, at least 20% of global coral reefs have been degraded or disappeared, and another 50% are threatened to varying degrees, and it is expected that by 2030, nearly 70% of the world’s coral reefs will undergo bleaching events[48-50]. Although some studies have shown that once environmental pressures subside, ecosystem damage caused by environmental factors can be recovered naturally, it is not possible to predict the future of coral reefs.

Ecosystem damage caused by environmental factors can be recovered naturally once environmental stresses disappear, but it may take up to 20-25 years, or even hundreds of years. Human-induced restoration and rehabilitation can accelerate the process of natural recovery.

The process of natural recovery can be accelerated by human-induced restoration and reconstruction. Therefore, the development and establishment of coral reef ecological restoration techniques and strategies have become a hot research topic in the field of coral reef conservation and sustainable utilization.

3.2 Coral Reef Ecosystem Restoration Strategies

With the continuous degradation of coral reef ecosystems, governments, scientists and social welfare organizations have gradually increased their attention to the protection, restoration, and sustainable use of coral reef ecosystems. Coral reef ecosystem restoration is for damaged or declining ecosystems, the use of its restoration capacity and the necessary artificial aids, to promote its recovery to the original or close to the original state of the structure and function, so that the coral reef ecosystem can be rebuilt process.

According to the degree of damage to coral reefs, coral reef ecological restoration strategies are generally divided into three categories: natural restoration, bioremediation, and ecological reconstruction. For relatively healthy, good reef-building organisms and reef organisms seed replenishment of mildly damaged coral reefs, its self-recovery is only a matter of time, to take appropriate measures to eliminate the pressure, to avoid man-made damage is the most critical restoration strategy; for some moderately damaged coral reef ecosystems, its natural recovery may take up to hundreds of years, man-made interventions can accelerate the process of natural restoration to promote the ecosystem's natural recovery; but for severely damaged coral reef ecosystems, its natural restoration may take several hundred years. For some moderately damaged coral reef ecosystems, natural recovery may take hundreds of years, and human intervention can accelerate the natural restoration process and promote the natural recovery of the ecosystems. Research shows that Active biodiversity protection practices and adequate human interventions could speed up the biological recovery of coral reefs [51]. Effective management of anthropogenic activities and the adoption of certain bioremediation techniques have curbed the degradation of coral reef ecosystems and increased coral cover in some areas [52]. Guzmán used artificial intervention and natural restoration strategies to restore coral reefs along the Pacific coast of Costa Rica, which is a successful case of large-scale ecological restoration of coral reefs, with a total of 110 live coral cuttings transplanted from nearby reefs to damaged reefs, and the coral survival rate reached 79%-83% after 3 years, with growth rates ranging from 41% to 115%.

Bioremediation refers to the restoration and rebuilding of one or more damaged organisms within a coral reef through natural or artificial methods, including artificial transplantation of desired organisms, and suppression or killing of disease and enemy organisms, to optimize the community composition and structure of the degraded area. For less damaged and relatively healthy coral reefs, measures to avoid anthropogenic damage are key restoration strategies, such as the establishment of marine parks and nature reserves to allow coral reefs to recover slowly. The first large-scale ecological restoration of coral reefs was carried out in 1990 in the Indo-Pacific and Red Sea waters [53]. Natural replenishment of corals for restoration is very inefficient, and a comparison of the effects of different sizes of protected areas on coral reef restoration in the Red Sea region revealed that simple isolation of coral reefs by simply designating a small area of protected area would have little effect. Although nature reserves have improved some ecological parameters of coral reefs, they are not sufficient to compensate for the impacts caused by anthropogenic activities. Due to the high cost and long period of coral reef ecological restoration projects, there are not many successfully promoted coral reef restoration cases, among which coral transplantation coral horticulture, and the removal of hostile organisms are the most reported restoration methods.

Reef-building corals are the main framework organisms of coral reef ecosystems, and they are also the key targets for repairing and restructuring damaged coral reef ecosystems. Coral transplantation refers to the transplantation of whole corals, coral fragments, or coral larvae to the damaged area, which is widely used because of its low cost and rapid increase in the number of corals in the damaged area [54]. Kaly tested different methods of coral transplantation in the Great Barrier Reef of Australia and proved the feasibility of transplanting coral fragments on a large scale[55]. Kaly tested different coral transplantation methods on the Great Barrier Reef, Australia, and demonstrated the feasibility of transplanting coral cuttings on a large scale [55]; Shaish et al. increased the coral volume of rose coral (Montipora digitata) by 3.84 times after 15 months of transplantation into a degraded reef area [56]; Zhang et al. carried out a partial experiment on coral transplantation and established a coral cultivation base on Ximaozhou Island, Hainan [57]. Okubo et al. suggested combining coral transplantation with eco-tourism to accelerate the restoration of coral reef ecosystems [58]; Edwards et al. suggested that most of the mortality of transplanted corals occurs in the first 7 months and that the survival rate is related to the area of transplantation, the mortality rate of corals transplanted to the Hawaiian Islands ranged from 5% to 50% after 2 years, and that of corals transplanted to Armoflex Reef was 28 months, and the survival rate of corals transplanted to Armoflex Reef was 28 months, and the survival rate of corals transplanted to Armoflex Reef was 28 months. Corals transplanted to the Armoflex Reef had a 28-month survival rate of about 50%, while corals transplanted to a small area on the Mexican island of Cozumel had a survival rate of 97% within 1 month. In addition, studies have shown that factors such as coral species, size, transplantation protocol, and transplantation environment also affect the survival of transplanted corals [57, 59, 60]. Therefore, it is necessary to carry out investigations and assessments before transplanting corals; blind transplantation not only fails to achieve the expected results, but also may harm the coral donors. When the dominant species in the damaged or degraded area are in the transition from stony corals to soft corals or macroalgae, or the degradation is caused by coral larvae reduction, unstable substrate, but the water quality is suitable for coral growth of the reef, it is suitable for restoration using coral transplantation method.

Coral horticulture refers to the cultivation of coral fragments or larvae in a specific marine area, and then transplanting them to damaged or degraded areas when they grow to a suitable size, which is less damaging to the coral tissues, and the mortality rate of the transplanted corals is lower [61, 62]. The concept of coral aquaculture was first proposed by Rinkevich in 1995 and has been widely applied in the Caribbean Sea, Red Sea, Singapore, Philippines, Japan, etc. [63]. Mbije et al. used coral aquaculture to cultivate corals in Zanzibar and Mafia Islands for the restoration of damaged coral reef ecosystems in Tanzania [64]. Shafir et al. used a suspension coral culture system in the Red Sea to restore the coral reefs in Tanzania. In the Red Sea, Shafir et al. tried to cultivate corals by using a plastic net suspended in the water as a seedbed for corals, and then transplanting the corals when they grew to a suitable size and achieved good restoration results, and the transplanted corals grew faster and had a survival rate of more than 80 % [65]. Oren et al. transplanted corals onto PVC boards fixed on ropes, and the results showed that vertically placed PVC boards were more suitable for the growth of corals than horizontally placed PVC boards [66]. The main reason is that the vertically placed PVC boards have less sediment, less covered algae, and fewer hostile organisms[66]. Rinkevich (2015) further proposed a new commercially viable ecological restoration method based on the concept of coral horticulture that could expand the market for ecological restoration of coral reefs [62].

Seedlings are the basis and prerequisite for coral transplantation and coral horticulture, and how to improve the tolerance and recovery ability of corals and other organisms to the environment is also an important part of coral reef ecological restoration. Studies have shown that domestication and selective breeding of corals can improve the tolerance ability of corals [67, 68]. Van Oppen et al. (2015) transplanted coral larvae from a relatively high-temperature zone to a low-temperature zone of a coral reef for hybridization, which significantly improved the temperature tolerance of newborn corals [69]. In addition, selective inoculation of Xanthophyllum worms [70] and reorganization of coral-symbiotic microbial phyla structure [71] can also change the tolerance ability of corals, but the relevant studies are still in the laboratory stage, how to improve the coral's adaptive ability to the environment from the genetic level, as well as the possible ecological impacts of genetic modification need to be further evaluated and investigated.

Removal of hostile organisms mainly includes controlling the number of coral predators (e.g., crown-of-thorns starfish), removing overgrown macroalgae, etc., but the relevant studies are still relatively few [72]. On some coastal reefs, overgrowth and increased abundance of macroalgae due to eutrophication or reduction of herbivores have caused corals to face great competition. Ceccarelli et al. (2018) summarized the ecological roles of macroalgae in coral reefs evaluated the advantages and disadvantages of macroalgae removal, and concluded that the coral competition with macroalgae can be reduced by increasing herbivorous fish or removing macroalgae by humans. competition between corals and macroalgae provides sufficient space for coral reproduction and may be an effective method for coral reef ecosystem restoration, and the effect of restoration is better by removing macroalgae sequestrators [72].

3.2.1 Ecological reconstruction

Ecological restructuring is mainly for severely damaged coral reefs, including habitat restoration and bioremediation, usually based on habitat restoration, and then biological transplantation. Habitat restoration refers to the construction of artificial reefs and putting them into the damaged coral reefs or artificial repair of existing reefs, reconstructing the coral reef habitat, improving the complexity of the three-dimensional structure of coral reefs, providing a good and stable habitat for marine organisms and reproduction sites, to promote coral and other organisms attached, growth, reproduction, and its population recovery, to accelerate the process of restoration of coral reef ecosystems. When the three-dimensional structure of coral reefs is severely damaged, and the coral reef restoration cannot be completed through traditional coral transplantation, artificial reefs are a good choice.

Artificial reefs have been tested in many countries for coral reef restoration, and the most widely used raw materials for artificial reefs include natural reef rock, concrete blocks, and ceramic blocks [73-75]. Clark et al (1994)

[76] put 360t of cemented reefs in the Maldives and observed more than 500 corals attached to the reefs after 3 to 5 years. Blakeway et al. (2013)[77] deployed artificial reefs and transplanted corals in Parker Point, Australia, and found that the artificial reefs were ideal substrates for coral growth, and the coral cover increased rapidly after transplantation. Li Yuanchao et al. put artificial reefs and transplanted corals in the sea area of Zhaoshu Island for the current situation of coral reef ecosystems in the Xisha Islands, and found that the restoration effect of only putting the reefs is relatively ideal, and it is hypothesized that artificial reefs can promote the restoration of stony coral communities and accelerate the restoration of coral reef ecosystems[78]. Recently, it was reported that a new reef material, microbial-induced calcium carbonate precipitation (MICP), can effectively solidify and cement the coral substrate indoors [78]. However, artificial reefs put into the sea area are easily covered by benthic algae, thus occupying the ecological niche of corals, causing the coral community to algal community succession, and affecting the effect of ecological restoration of coral reefs, while some areas can prey on the benthic algae and reduce their coverage, thus promoting coral attachment and growth [79]. Therefore, the use of artificial reefs to restore coral reefs requires attention to the balance between related ecological factors. In contrast, there are fewer cases of coral reef repair, and the common method is to use cement and gypsum to bond the cracked coral reefs to restore the structural integrity of the reefs, and then use transplantation to repair the coral reef ecosystems and restore the coral populations [80, 81]. In addition, reducing environmental pressure, improving the living environment, reducing human activities such as reducing over-exploitation and utilization, reducing sedimentation brought by the project, managing pollutants, treating wastewater, removing or reducing hostile and competing organisms can also promote coral reef habitat restoration and accelerate the process of ecological restoration of coral reefs.

3.2.2 Monitoring and Assessment

Monitoring and assessment of coral reef ecosystems is one of the key links in coral reef ecosystem restoration, through regular assessment of the restoration effect, it can provide recommendations for the next ecological restoration. Currently, there are few indicators commonly used to evaluate the effectiveness of restoration, mainly two: coral growth and survival rate [82, 83]. A few studies have used these two indicators in combination with a limited number of other ecological factors. Hein et al. summarized 83 papers on coral reef ecosystem restoration and found that most of the evaluations of restoration effects have focused on short-term experiments, with fewer long-term monitoring and evaluation [84]. 53% of the studies monitored the state of restored coral reefs for only one year or less, and only 5% monitored the condition of the reefs for more than 5 years after restoration.

Firstly, compared with the wide distribution of coral reefs around the world, the number and area of coral reefs under study are too small; there is a lack of long-term and continuous monitoring of coral reefs as well as appropriate evaluation criteria for ecological restoration, making it difficult to evaluate the restoration effect clearly and quantitatively; and there are fewer studies on the restoration of the ecological structure and function of coral reefs during the process of restoration, such as insufficient research on the diversity of species, the relationship between organisms, and the material basis of the ecosystems.

Secondly, in terms of the scale of ecological restoration, most of the restoration remains on a small scale, within the local area, or focusing on the restoration of a single community or species. However, the coral reef ecosystem is a complex system with high biodiversity, and all kinds of organisms within it are closely and dynamically linked together, and the interrelationship is very complicated. Coral reef restoration and rehabilitation should gradually shift from ecological restoration of specific species or individual ecosystems to large-scale ecological restoration, requiring comprehensive and effective restoration of ecosystem structure, function, biodiversity, and sustainability. Although there are successful cases of multi-dimensional ecological restoration technology and demonstration based on systematic thinking and key function restoration, the systematic restoration theory, technical system, and application promotion need to be further explored and improved.

Thirdly, lack of comprehensive cost and benefit assessment. Studies have shown that ecological restoration of coral reefs can not only bring significant economic benefits to the local and marine industries but also affect the local socio-cultural values [85-87]. Abelson et al. combined ecological restoration of coral reefs and fisheries management and concluded that stocking herbivorous fish is one of the effective ways to restore degraded coral reefs. Increasing fish biomass can not only increase fishery production but also reduce damage to coral reefs and improve the compliance of residents with fishery policies[88]. However, most of the existing studies still focus on the ecological significance of restoration, and few of them address the social, economic, and cultural values of restoration and comprehensive cost estimation [89]. Therefore, it is necessary to comprehensively analyze and evaluate the value of coral reef ecological restoration.

4. Conclusion

Coral reefs are formed by the continuous accumulation and compaction of a large number of coral polyps' skeletons over thousands of years, which is of great importance in maintaining marine biodiversity. Research results show that 60% of coral reefs will disappear globally by 2030 [8]. Therefore, given the ecological problems faced by coral reef ecosystems, the ecological restoration master plan should be prepared with coral reef ecosystems as the regulatory unit, to restore the marine ecological service function, improve the marine ecological environment, and construct the coral reef ecological landscape, focusing on the coral reef ecosystem monitoring and assessment, coral reef ecosystems and key functions of the biological breeding technology and the protection and restoration of multi-dimensional coral reef ecosystems. First, a sound coral reef protection system should be established, reasonable and effective administrative practices should be formulated for coral reef ecosystems in different regions, and publicity for coral reef protection should be increased. Second, carry out long-term field surveys and indoor simulation experiments to investigate the mechanics of coral reef deterioration caused by climate change and anthropogenic duress. Third, we will increase the investment in coral reef ecological restoration research, explore ecological restoration measures in depth, and actively promote the protection and restoration of multi-dimensional coral reef ecosystems. Fourth, strengthening long-term systematic observation of coral reef ecosystems, establishing an ecological restoration assessment mechanism, and continuing to carry out tracking and monitoring of coral reef ecological restoration and assessment of its effects. Coral reef ecological restoration should adhere to the combination of demand-oriented, goal-oriented, and problem-oriented, adhere to the concept of ecological priority, "natural protection and natural restoration as the main, artificial intervention as a supplement" as the principle, from the economic, social, cultural and other perspectives, comprehensive analysis of coral reef ecological restoration of the cost and value, to build ecosystem-based coral reefs. The ecosystem-based coral reef ecological restoration costs and values should be analyzed from economic, social, cultural and other perspectives, and an ecosystem-based coral reef comprehensive management framework and regulatory strategy system should be built.

References

[1] Reaka-Kudla, M.L., Known and unknown biodiversity, risk of extinction and conservation strategy in the sea, in Waters in peril. 2001, Springer. p. 19-33.

[2] Chin, A., et al., Status of coral reefs of the Pacific and outlook: 2011. 2011: Global coral reef monitoring network.

[3] Freckleton, R., J.F. Bruno, and E.R. Selig, Regional Decline of Coral Cover in the Indo-Pacific: Timing, Extent, and Subregional Comparisons. PLoS ONE, 2007. 2(8).

[4] Gardner, T.A., et al., Long-term region-wide declines in Caribbean corals. Science, 2003. 301(5635): p. 958-60.

[5] Albright, R., et al., Ocean acidification: Linking science to management solutions using the Great Barrier Reef as a case study. (1095-8630 (Electronic)).

[6] De'ath, G., et al., The 27–year decline of coral cover on the Great Barrier Reef and its causes. Proceedings of the National Academy of Sciences, 2012. 109(44): p. 17995-17999.

[7] Ferse, S.C.A., et al., Human, Oceanographic and Habitat Drivers of Central and Western Pacific Coral Reef Fish Assemblages. Plos One, 2015. 10(4).

[8] Hughes, T.P., et al., Climate change, human impacts, and the resilience of coral reefs. (1095-9203 (Electronic)).

[9] Hoegh-Guldberg, O., et al., Coral reefs under rapid climate change and ocean acidification. (1095-9203 (Electronic)).

[10] Pandolfi, J.M., et al., Projecting coral reef futures under global warming and ocean acidification. Science, 2011. 333(6041): p. 418-22.

[11] Hughes, T.A.-O., et al., Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. (1095-9203 (Electronic)).

[12] Muller, E.M., E. Bartels, and I.B. Baums, Bleaching causes loss of disease resistance within the threatened coral species Acropora cervicornis. eLife, 2018. 7.

[13] Wilkinson, C., et al., Status of Caribbean coral reefs in seven countries in 1986. (1879-3363 (Electronic)).

[14] Schneider, K., et al., Carbon cycling in a zero-discharge mariculture system. Water Res, 2011. 45(7): p. 2375-82.

[15] Webster, N.S., et al., Ocean acidification reduces induction of coral settlement by crustose coralline algae. Global Change Biology, 2012. 19(1): p. 303-315.

[16] Goncalves, P., et al., Rapid transcriptional acclimation following transgenerational exposure of oysters to ocean acidification. Mol Ecol, 2016. 25(19): p. 4836-49.

[17] Pfister, C.A., et al., Historical baselines and the future of shell calcification for a foundation species in a changing ocean. Proceedings of the Royal Society B: Biological Sciences, 2016. 283(1832).

[18] Cao, L., et al., Importance of carbon dioxide physiological forcing to future climate change. Proceedings of the National Academy of Sciences, 2010. 107(21): p. 9513-9518.

[19] Koop, K., et al., ENCORE: the effect of nutrient enrichment on coral reefs. Synthesis of results and conclusions. Mar Pollut Bull, 2001. 42(2): p. 91-120.

[20] River, G.F. and P.J. Edmunds, Mechanisms of interaction between macroalgae and scleractinians on a coral reef in Jamaica. J Exp Mar Biol Ecol, 2001. 261(2): p. 159-172.

[21] Voss, J.D., et al., Black band disease microbial community

variation on corals in three regions of the wider Caribbean. Microb Ecol, 2007. 54(4): p. 730-9.

[22] Gattuso, J.P., M. Frankignoulle, and S.V. Smith, Measurement of community metabolism and significance in the coral reef CO2 source-sink debate. Proc Natl Acad Sci U S A, 1999. 96(23): p. 13017-22.

[23] Carriquiry, J.D. and G. Horta-Puga, The Ba/Ca record of corals from the Southern Gulf of Mexico: contributions from land-use changes, fluvial discharge and oil-drilling muds. Mar Pollut Bull, 2010. 60(9): p. 1625-30.

[24] Flores, F., et al., Chronic exposure of corals to fine sediments: lethal and sub-lethal impacts. PLoS One, 2012. 7(5): p. e37795.

[25] Li, X., et al., Coral community changes in response to a high sedimentation event: A case study in southern Hainan Island. Chinese Science Bulletin, 2012. 58(9): p. 1028-1037.

[26] Richards, K., et al., Sharks and people: insight into the global practices of tourism operators and their attitudes to shark behaviour. Mar Pollut Bull, 2015. 91(1): p. 200-10.

[27] Krieger, J.R. and N.E. Chadwick, Recreational diving impacts and the use of pre-dive briefings as a management strategy on Florida coral reefs. Journal of Coastal Conservation, 2013. 17(1): p. 179-189.

[28] Rouphael, T., The temporal and spatial patterns of impact caused by SCUBA diving in coral reefs, and the human and site specific characteristics that influence these patterns. 1997: James Cook University of North Queensland.

[29] Roche, R.C., et al., Recreational Diving Impacts on Coral Reefs and the Adoption of Environmentally Responsible Practices within the SCUBA Diving Industry. Environmental Management, 2016. 58(1): p. 107-116.

[30] Barker, N.H.L. and C.M. Roberts, Scuba diver behaviour and the management of diving impacts on coral reefs. Biological Conservation, 2004. 120(4): p. 481-489.

[31] De, K., et al., Coral damage by recreational diving activities in a Marine Protected Area of India: Unaccountability leading to â€˜tragedy of the not so commonsâ€™. Marine Pollution Bulletin, 2020. 155: p. 111190.

[32] Hughes, T.P., et al., Climate Change, Human Impacts, and the Resilience of Coral Reefs. Science, 2003. 301(5635): p. 929-933.

[33] Wiedenmann, J.r., et al., Nutrient enrichment can increase the susceptibility of reef corals to bleaching. Nature Climate Change, 2013. 3(2): p. 160-164.

[34] Vago, R., et al., A non-destructive method for monitoring coral growth affected by anthropogenic and natural long term changes. Bulletin of marine science, 1994. 55(1): p. 126-132.

[35] Wielgus, J., N.E. Chadwick-Furman, and Z. Dubinsky, Coral cover and partial mortality on anthropogenically impacted coral reefs at Eilat, northern Red Sea. Marine Pollution Bulletin, 2004. 48(3): p. 248-253.

[36] Wooldridge, S.A., Water quality and coral bleaching thresholds: Formalising the linkage for the inshore reefs of the Great Barrier Reef, Australia. Marine Pollution Bulletin, 2009. 58(5): p. 745-751.

[37] Smith, J.E., et al., Indirect effects of algae on coral: algaeâ€□mediated, microbeâ€□induced coral mortality. Ecology letters, 2006. 9(7): p. 835-845.

[38] Lucia, B., et al., Survival, growth and gonad development of two hermatypic corals subjected to in situ fish-farm nutrient enrichment. Marine Ecology Progress Series, 2003. 253: p. 137-144.

[39] McCook, L., J. Jompa, and G. Diaz-Pulido, Competition between corals and algae on coral reefs: a review of evidence and mechanisms. Coral Reefs, 2001. 19(4): p. 400-417.

[40] Zakai, D. and N.E. Chadwick-Furman, Impacts of intensive recreational diving on reef corals at Eilat, northern Red Sea. Biological Conservation, 2002. 105(2): p. 179-187.

[41] Crehan, O., et al., Effect of Tourism and Sedimentation on Coral Cover and Community Structure. Tropical Life Sciences Research, 2019. 30(2): p. 149-165.

[42] Riegl, B., Effects of sand deposition on scleractinian and alcyonacean corals. Marine Biology, 1995. 121(3): p. 517-526.

[43] Philipp, E. and K. Fabricius, Photophysiological stress in scleractinian corals in response to short-term sedimentation. Journal of Experimental Marine Biology and Ecology, 2003. 287(1): p. 57-78.

[44] Hoegh-Guldberg, O., et al., Reviving the Ocean Economy: the case for action-2015. WWF International. Gland, Switzerland, Geneva, 2015.

[45] Burke, L., et al., Reefs at risk revisited: technical notes on modeling threats to the worldâ€™s coral reefs. Washington, DC: World Resources Institute, 2011.

[46] BRANDER, L.M., et al., THE ECONOMIC IMPACT OF OCEAN ACIDIFICATION ON CORAL REEFS. Climate Change Economics, 2012. 03(01): p. 1250002.

[47] Deâ€™ath, G., et al., The 27â€“year decline of coral cover on the Great Barrier Reef and its causes. Proceedings of the National Academy of Sciences, 2012. 109(44): p. 17995-17999.

[48] Benayas, J.M.R., et al., Enhancement of Biodiversity and Ecosystem Services by Ecological Restoration: A Meta-Analysis. Science, 2009. 325(5944): p. 1121-1124.

[49] Jaleel, A., The status of the coral reefs and the management approaches: The case of the Maldives. Ocean & Coastal Management, 2013. 82: p. 104-118.

[50] Maynard, J., et al., Improving marine disease surveillance through sea temperature monitoring, outlooks and projections. Philosophical Transactions of the Royal Society B: Biological Sciences, 2016. 371(1689): p. 20150208.

[51] Rinkevich, B., Conservation of Coral Reefs through Active Restoration Measures:â€‰ Recent Approaches and Last Decade Progress. Environmental Science & Technology, 2005. 39(12): p. 4333-4342.

[52] Guzmán, H.M., Restoration of coral reefs in Pacific Costa

Rica. Conservation Biology, 1991. 5(2): p. 189-194.

[53] Richmond, R.H. and C.L. Hunter, Reproduction and recruitment of corals: comparisons among the Caribbean, the tropical Pacific, and the Red Sea. Marine ecology progress series. Oldendorf, 1990. 60(1): p. 185-203.

[54] Edwards, A.J. and S. Clark, Coral Transplantation: A Useful Management Tool or Misguided Meddling? Marine Pollution Bulletin, 1999. 37(8): p. 474-487.

[55] Kaly, U.L., Experimental test of the effects of methods of attachment and handling on the rapid transplantation of corals. 1995: CRC Reef Research Centre.

[56] Shaish, L., et al., Employing a highly fragmented, weedy coral species in reef restoration. Ecological Engineering, 2010. 36(10): p. 1424-1432.

[57] Zhang, Y., et al., The effects of four transplantation methods on five coral species at the Sanya Bay. Acta Oceanologica Sinica, 2016. 35(10): p. 88-95.

[58] Okubo, N. and A. Onuma, An economic and ecological consideration of commercial coral transplantation to restore the marine ecosystem in Okinawa, Japan. Ecosystem Services, 2015. 11: p. 39-44.

[59] Cabaitan, P.C., H.T. Yap, and E.D. Gomez, Performance of single versus mixed coral species for transplantation to restore degraded reefs. Restoration Ecology, 2015. 23(4): p. 349-356.

[60] Martinez, A., et al., Species-specific calcification response of Caribbean corals after 2-year transplantation to a low aragonite saturation submarine spring. Proceedings of the Royal Society B, 2019. 286(1905): p. 20190572.

[61] Rinkevich, B., Rebuilding coral reefs: does active reef restoration lead to sustainable reefs? Current Opinion in Environmental Sustainability, 2014. 7: p. 28-36.

[62] Rinkevich, B., Novel tradable instruments in the conservation of coral reefs, based on the coral gardening concept for reef restoration. Journal of Environmental Management, 2015. 162: p. 199-205.

[63] Rinkevich, B., Restoration strategies for coral reefs damaged by recreational activities: the use of sexual and asexual recruits. Restoration Ecology, 1995. 3(4): p. 241-251.

[64] Mbije, N.E.J., E. Spanier, and B. Rinkevich, Testing the first phase of the ‘gardening concept’ as an applicable tool in restoring denuded reefs in Tanzania. Ecological Engineering, 2010. 36(5): p. 713-721.

[65] Shafir, S., J. Van Rijn, and B. Rinkevich, Nubbing of Coral Colonies: A Novel Approach for the Development of Inland Broodstocks. Aquarium Sciences and Conservation, 2001. 3(1): p. 183-190.

[66] Oren, U. and Y. Benayahu, Transplantation of juvenile corals: a new approach for enhancing colonization of artificial reefs. Marine Biology, 1997. 127(3): p. 499-505.

[67] Barshis, D.J., et al., Genomic basis for coral resilience to climate change. Proceedings of the National Academy of Sciences, 2013. 110(4): p. 1387-1392.

[68] Chan, W.Y., L.M. Peplow, and M.J.H. van Oppen, Interspecific gamete compatibility and hybrid larval fitness in reef-building corals: Implications for coral reef restoration. Scientific Reports, 2019. 9(1): p. 4757.

[69] Van Oppen, M.J., et al., Building coral reef resilience through assisted evolution. Proceedings of the National Academy of Sciences, 2015. 112(8): p. 2307-2313.

[70] Silverstein, R.N., A.M. Correa, and A.C. Baker, Specificity is rarely absolute in coral–algal symbiosis: implications for coral response to climate change. Proceedings of the Royal Society B: Biological Sciences, 2012. 279(1738): p. 2609-2618.

[71] Brown, T., D. Bourne, and M. Rodriguez-Lanetty, Transcriptional activation of c3 and hsp70 as part of the immune response of Acropora millepora to bacterial challenges. PLoS One, 2013. 8(7): p. e67246.

[72] Ceccarelli, D.M., et al., Rehabilitation of coral reefs through removal of macroalgae: state of knowledge and considerations for management and implementation. Restoration Ecology, 2018. 26(5): p. 827-838.

[73] Keller, K., et al., Multispecies presence and connectivity around a designed artificial reef. Marine and Freshwater Research, 2017. 68(8): p. 1489-1500.

[74] Silva, R., et al., An artificial reef improves coastal protection and provides a base for coral recovery. Journal of Coastal Research, 2016(75): p. 467-471.

[75] Ng, C.S.L., T.C. Toh, and L.M. Chou, Artificial reefs as a reef restoration strategy in sediment-affected environments: Insights from long-term monitoring. Aquatic Conservation: Marine and Freshwater Ecosystems, 2017. 27(5): p. 976-985.

[76] Clark, S. and A.J. Edwards, Use of artificial reef structures to rehabilitate reef flats degraded by coral mining in the Maldives. Bulletin of Marine Science, 1994. 55(2-3): p. 724-744.

[77] Blakeway, D., et al., Coral colonisation of an artificial reef in a turbid nearshore environment, Dampier Harbour, western Australia. PLoS One, 2013. 8(9): p. e75281.

[78] Li, Y., et al., Preliminary assessment of the coral reef restoration in areas of Zhaoshu Island, Xiasha Islands. Journal of Applied Oceanography, 2014. 33(3): p. 348-353.

[79] Bruno, J.F., How do coral reefs recover? Science, 2014. 345(6199): p. 879-880.

[80] Jaap, W.C., Coral reef restoration. Ecological Engineering, 2000. 15(3): p. 345-364.

[81] Shafir, S., J. Van Rijn, and B. Rinkevich, Steps in the construction of underwater coral nursery, an essential component in reef restoration acts. Marine Biology, 2006. 149(3): p. 679-687.

[82] Guest, J.R., et al., How quickly do fragments of coral “self-attach” after transplantation? Restoration Ecology, 2011. 19(2): p. 234-242.

[83] Bayraktarov, E., et al., The cost and feasibility of marine coastal restoration. Ecological applications, 2016. 26(4): p.

1055-1074.
[84] Hein, M.Y., et al., The need for broader ecological and socioeconomic tools to evaluate the effectiveness of coral restoration programs. Restoration ecology, 2017. 25(6): p. 873-883.
[85] Rogers, A., et al., Anticipative management for coral reef ecosystem services in the 21st century. Global Change Biology, 2015. 21(2): p. 504-514.
[86] Kittinger, J.N., et al., Restoring ecosystems, restoring community: socioeconomic and cultural dimensions of a community-based coral reef restoration project. Regional Environmental Change, 2016. 16(2): p. 301-313.
[87] Pascal, N., et al., Economic valuation of coral reef ecosystem service of coastal protection: A pragmatic approach. Ecosystem Services, 2016. 21: p. 72-80.
[88] Abelson, A., et al., Restocking herbivorous fish populations as a social-ecological restoration tool in coral reefs. Frontiers in Marine Science, 2016. 3: p. 138.
[89] De Groot, R.S., et al., Benefits of investing in ecosystem restoration. Conservation Biology, 2013. 27(6): p. 1286-1293.