Coral Reef Restoration: An Ecological Imperative for The Blue Economy

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Abstract

Ecological restoration is defined by the Society for Ecological Restoration as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed". This research paper reveals practices of restoration of coral reefs in several terrestrial ecosystems, yet it remains a comparatively emerging subject in the marine environment. Both conceptual and empirical scientific evidence increasingly supports importance of coral reef restoration, a comprehensive field that includes active intervention strategies designed to enhance the resilience of reef structure, function, and diversity in response to stress, thereby ensuring the continued provision of ecosystem services. The field has had considerable progress in recent years, enhancing the scope of spatial activity and ecological complexity. Initial research suggests that coral transplantation serves as a restorative technique to enhance natural ecosystems. This research presents a unique analysis of the value, costs, and advantages associated with the coral reef economy, highlighting that shifting the trajectory of coral reef health from continuous decline to a resilient state might provide tens of billions of dollars in additional value. The results suggest that this transition can primarily be achieved through strategic interventions employing existing techniques and methodologies, indicating that the goal of reconciling the anticipated benefits of a healthy reef with the current trend of coral reef decline is feasible. While the private sector would retain a substantial share of the financial gains, these advantages might also empower governments to establish programs that redistribute part of this money to persons adversely affected by changes in reef management, including local fishing businesses. Furthermore, the social co-benefits of ecosystem restoration focused on fostering healthy reefs may exceed private profits, including improvements in municipal sanitation, more sustainable local fisheries, reduced soil erosion, and enhanced cultural heritage values.

***Keywords**: Coral reefs, Techniques of restoration, Benefits, Fishing, Eco System, Blue economy*

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1. Coral Reef Restoration Methods, Strategies, & Approaches

Methods of coral restoration can be grouped into three categories:

Asexual propagation methods

Sexual propagation methods

Substrate enhancement

1.1. Asexual propagation methods

Asexual propagation denotes any coral restoration method that involves the transplantation of coral colonies (fragments adorned with living coral polyps) from a healthy reef or coral farming initiative to a compromised reef. These approaches often do not utilise any aspects of the natural coral spawning process. This approach does not address the necessity of preserving genetic diversity within each species, which is crucial for enhancing the likelihood that some transplanted corals will endure disease outbreaks, rising temperatures, or other threats, unless it is integrated with additional strategies. For instance, the necessity for enhanced genetic diversity can be addressed by establishing colonies of each coral species derived from a range of "donors" [1].

1.1.1. Direct Transplantation

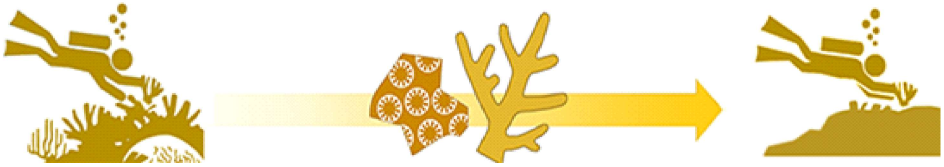

Figure 1: Direct transplantation method of coral reefs [1]

The direct transplantation of coral colonies from healthy reefs to degraded sections or entirely new environments is one of the oldest, simplest, and most common procedures utilised to combat coral reef degradation [Figure 1 & 2]. This approach involves the removal of live coral from a mature reef, which can significantly jeopardise the donor reef if an excessive quantity of coral is harvested from a limited area in a short period. Occasionally, unexpected events such as vessel groundings on reefs, severe storms, or other factors physically displace fragments of coral colonies, resulting in "corals of opportunity" that are already damaged and can be transplanted to other reefs without necessitating the removal of additional healthy coral. The efficacy of transplantation is contingent upon numerous factors, including the dimensions and vitality of coral fragments, the method of conveyance to the designated site, aquatic conditions (turbidity, illumination), species diversity, density of "outplanted" coral, the robustness of attachment to a substrate, and the presence of algae and predatory fish that consume coral. In a compromised reef with significant algal proliferation, algae will rapidly overgrow and smother transplanted corals without ongoing human intervention to control algae growth [2].

Figure 2: Picture of direct transplantation of coral reefs [2].

1.1.2. Coral Cultivation

Coral farming is the development of coral colonies from small fragments of live coral in nurseries, and thereafter out planting these colonies onto a damaged reef once they have reached a size adequate for independent survival. A portion of the cultivated coral may be conserved and divided into smaller segments to begin the next cycle of coral cultivation. This obviates the need for the continual extraction of coral from flourishing reefs to support restoration efforts elsewhere. Coral fragments can be developed in underwater nurseries (in situ) utilising natural conditions, or propagated in terrestrial facilities (ex situ) equipped with arrays of tanks including rigorously regulated water quality management systems [3].

1.1.3. Conventional methods

i) Coral farming

It has been initiated by scientific institutions as well as the aquarium, tourist, and hospitality sectors. Traditionally, coral farming operations entail the cultivation of tiny fragments of donor coral, which are nurtured in nurseries until they attain sufficient size to thrive independently, without much human involvement. The coral cultivars can be positioned on racks, cement bases, frames, or midwater structures made of metal or PVC pipes. Farm-cultivated coral is then out planted to deteriorated reefs or to new sites with circumstances conducive to coral development [Figure 3].

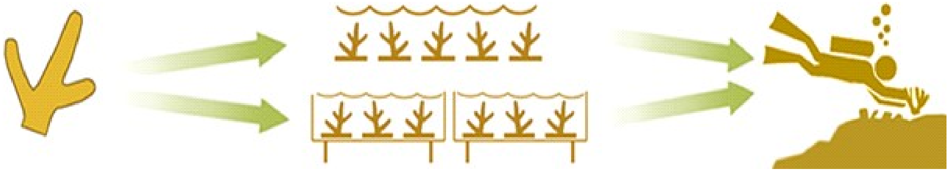

Figure 3: Coral farming method [3]

Traditional coral farming predominantly encompasses species that exhibit rapid growth and healing, as well as those that reproduce both asexually (by budding or fragmentation) and sexually (via spawning) in their natural habitats. This guarantees an acceptable survival rate and quantifiable outcomes within a very short timeframe. The Report noted that comparing the success rates of direct transplantation with coral farming is challenging due to the death rates associated with each stage of the latter, whereas direct transplantation entails hazards just during the transit and transplantation stages. Moreover, the authors observed that several coral farming organisations fail to consistently monitor coral survival and development beyond the initial one or two years, complicating the assessment and comparison of the long-term results of various operations.

ii) Microfragmentation

The process involves cutting larger fragments of live coral into micro-sized pieces (1 cm square or less) using a diamond-coated saw blade and attaching them to small tiles or concrete "pucks," on which they will grow until they are large enough to be outplanted to a reef. The micro-fragments and their bases are cultured in shallow tanks of seawater, known as raceways. The approach resulted from an inadvertent discovery. In 2006, during the extraction of a live elkhorn coral fragment from a saltwater tank at the Mote facility, Dr. Vaughan saw that a portion of the fragment had inadvertently fractured, resulting in the retention of two or three coral polyps. After many weeks, Dr. Vaughan examined the tank where the fracture had occurred and saw that the remaining polyps had proliferated, more than tripling the colony size and the number of polyps—an extraordinary occurrence, considering the sluggish growth rate of coral in the wild. The reduction to a diminutive scale elicited an expedited growth response in the corals, prompting rapid reproduction to restore their size. (In this context, corals reproduce asexually by budding, producing new "buds" that develop into distinct, genetically identical polyps) [Figure 4].

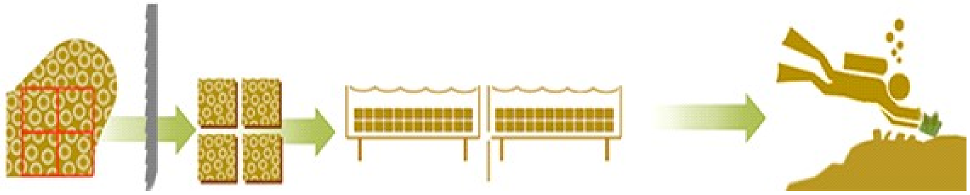

Figure 4: Microfragmentation method [4].

1.1.4 Challenges and solutions

During the initial stages of optimising the micro-fragmentation process, Dr. Vaughn and his team of researchers and volunteers faced a significant obstacle:

parrotfish and other coralivorous species favoured the farm-cultivated corals over those naturally residing in the reefs, resulting in a near-complete loss of the transplanted corals. A solution was created that included an extra step—an initial acclimatisation phase near the transplant site, whereby the farmed corals are secured in underwater tents to shield them from predators. Following a time of acclimatisation, the corals transitioned from their vibrant green hue, observed in terrestrial tanks and seemingly appealing to parrotfish, to the more subdued colouration characteristic of the same coral species on the reef. The absence of genetic variety is a limitation of coral farming methods, such as micro-fragmentation. Elevated genetic variety within a singular species significantly enhances the likelihood that some cultured corals will endure disease outbreaks or adapt to altered environments, such as increased water temperatures. This can be resolved by integrating tank-based growing techniques, which produce genetically identical clones, with strategies that utilise the sexual spawning process.

1.2. Sexual Propagation Methods

Sexual propagation encompasses strategies to rehabilitate coral reefs by employing methods that harness the natural coral spawning process, with the objective of enhancing recruitment—the mechanism through which certain coral larvae settle on the seabed and adhere to a stable substrate, facilitating their development into coral polyps. Successful recruitment of hard coral larvae results in the formation of a colony that develops calciferous skeletons fused to the substrate upon which they settle. Coral colonies reproduce annually by simultaneously releasing millions of gametes (eggs and sperm) into the water, resulting in an undersea "blizzard" of spawn that ascends to the surface, where the eggs and sperm intermingle in the water column. The circumstances influencing the time of this extraordinary synchronous occurrence are inadequately comprehended. An egg and a sperm gamete unite to form an embryo, which subsequently grows into a coral larva known as a planula. Planulae float at the surface for days or weeks, depending upon the species, until they are prepared to adhere to a firm substrate on the reef bottom. Upon completion of this developmental period, they drop to the substrate and—if successful—secure themselves permanently to an appropriate surface, initiating the growth of a new coral colony in nature, a significant fraction of larvae fail to transition to sedentary adults, since they are carried away by currents, consumed by predators, or unable to find suitable substrates. Moreover, fertilisation of coral in the water column may be impeded by asynchronous spawning, wherein coral eggs and sperm are released at disparate periods. These issues are intensified by anthropogenic hazards that disrupt typical spawning circumstances. By utilising the capacity of corals to produce millions of gametes (eggs and sperm) and significantly decreasing the mortality rate of coral spawn, which persists even in optimal reef conditions, larval (sexual) propagation seeks to mitigate the increasingly detrimental conditions that obstruct natural propagation [4,5].

1.2.1. Ex Situ Larval Enhancement Methods

This method of larval propagation entails the ex-situ cultivation or collection of coral gametes, rearing them through the larval phase, and subsequently permitting their settlement on artificial substrates within terrestrial saltwater tanks [Figure 5]. This method allows for enhanced control over the recruitment of coral polyps (substrate attachment) compared to natural conditions (in situ), where ocean currents and predators diminish success rates. Once the polyps have transitioned to their sedentary life-cycle phase, they can be out planted on deteriorated or artificial reefs.

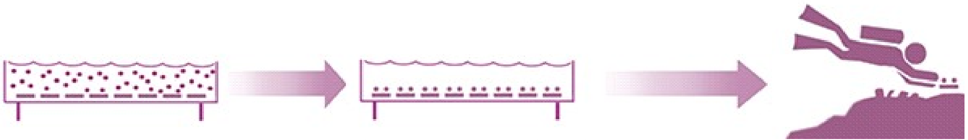

Figure 5. Ex situ larval cultivation method [6].

1.2.2. In Situ larval Enhancements

In situ larval enhancement techniques commence with the collection of coral gametes from coral reefs during spawning episodes. The collecting time must be impeccable, as the chance arises once annually [Figure 6]. The gametes and fertilised embryos are contained in saltwater pens or booms until they develop into planulae, which are prepared for the settlement phase. Upon readiness for settlement, the embryos are guided into a floorless mesh tent or an enclosed curtain over the designated reef restoration site. The planulae descend to the area of the reef bottom within the tent's edge. The cages may be relocated to other sites, releasing only a fraction of the planulae at each designated place [6].

Figure 6: In situ larval cultivation method [6]

1.3. Substrate Enhancement

This group's reef restoration strategies seek to create optimal circumstances for coral recruitment without cultivating or propagating coral colonies, but the transplantation of coral pieces is frequently conducted alongside substrate enhancement initiatives.

1.3.1. Artificial Reef

The construction of artificial reefs entails the deployment of anthropogenic structures on the seabed to replicate the architectural features (projections, overhangs, and shelters) of a natural coral reef, thereby attracting marine organisms, including corals and various other species typical of a thriving coral ecosystem [7, 8]. Artificial reefs have been constructed from submerged vessels, concrete pipes, cubes, hollow spheres (such as Reef Balls), and blocks; modular configurations of steel rods and pipes; as well as granite, porcelain, and various other materials. Corals of opportunity, such as pieces salvaged from vessel groundings or storms, or corals sourced from farming operations, are frequently employed to initiate colonisation of the artificial reef. Natural reefs include intricate ecosystems with vast quantities of fish species, hard corals, soft corals (corals lacking calciferous skeletons, such as sea whips and sea fans), and innumerable other marine invertebrates. The simple transplanting of a restricted number of coral species onto manmade structures does not guarantee the subsequent colonisation of a varied array of other species on the reef, unless other procedures are implemented [9].

1.3.2. Stabilization Of Substrate

Restoration initiatives focused on the strengthening and stabilisation of substrates are crucial in regions where prior coral formations have suffered significant damage from storms or ship groundings, leading to a seafloor comprised of unstable pieces and debris. Given that the majority of corals require a stable substrate for growth, the seabed is reinforced with mesh or netting, substantial boulders are placed on unstable surfaces, or spikes are inserted into accumulations of loose debris. Substrate stabilisation alone does not promote the recovery of healthy coral. It is frequently integrated with artificial reef construction and coral transplantation initiatives.

2. Key Economic Role of Coral Reefs in The Blue Economy

Coral reefs, sometimes referred to as the “rainforests of the sea,” sustain an exceptional variety of marine organisms and offer vital advantages to human populations throughout. In addition to their stunning beauty and biological importance, coral reefs constitute a vital economic resource that generates billions of dollars each year for the world economy. The acceleration of climate change, pollution, and other threats to coral reefs leads to significant deterioration, with economic repercussions that transcend environmental issues, impacting industries, livelihoods, and national economies worldwide [10].

2.1. Tourism Industry

The Great Barrier Reef in Australia produces roughly $6.4 billion per year and sustains over 64,000 employments in the tourism industry. Recent studies indicate that after significant coral bleaching occurrences, visitor numbers declined by 10-20%, leading to economic losses of over $1 billion. Tourism providers indicate that the mere idea of reef damage might compel visitors to seek alternative sites.

a) The annual worldwide tourist value directly associated with coral reefs is estimated to be over $10 billion.
b) The economic value of the entire tourism ecosystem supported by reefs, including hotels, restaurants, and transportation, surpasses $36 billion annually.
c) Reef-oriented tourism sustains nearly 1 million employment opportunities globally.

2.2. Breeding ground for fisheries and other food products

Coral reefs function as vital breeding grounds, nurseries, and habitats for over 25% of all marine species, including several economically significant fish. Coral reef ecosystems furnish protein, income, and livelihoods for hundreds of millions globally.

Global reef fisheries are valued at $6.8 billion annually.

Over 500 million people depend on reef fisheries for food security and income.

Small-scale reef fisheries support approximately 6 million fishers across developing countries.

2.3. Coastal and Infrastructure Protector

Studies in Florida indicate that coral reefs diminish wave energy by more than 90% during storm occurrences. Research conducted by the U.S. Geological Survey revealed that a singular bleaching event might elevate flood risk and anticipated economic losses by 25-30%. In South Florida, the absence of reef protection may elevate damage expenses by $1.6 billion during a centenary storm event. Commercial real estate valuations are now indicative of this heightened risk, with assets in reef-protected zones fetching prices 16% more than comparable properties lacking adequate reef protection.

Healthy coral reefs function as natural breakwaters, absorbing up to 97% of wave energy before it reaches the shorelines. This physical barrier offers essential protection from storms, erosion, and flooding for coastal towns globally.

a) Coral reefs avert around $94 billion in coastal damage each year.
b) More than 100 million individuals benefit from the coastal protection afforded by reefs.

c) The global replacement cost of manmade coastal defences would surpass $2 trillion [7,8].

2.4. Saviour of the essential Ecosystem

Beyond tourism, fisheries, and coastal protection, coral reefs provide numerous additional ecosystem services that support economic activities and human well-being.

a) The yearly value of water filtering and waste absorption is around $3.9 billion.
b) Annual sand output for tourism-supporting beaches is estimated at $2.1 billion [7,11]
c) Carbon sequestration services that aid in climate regulation

Research in the Caribbean indicates that coral destruction has diminished water filtering capacity, leading to worse nearshore water quality. Tourist locations are compelled to provide $25-50 million each site for water treatment facilities, while beaches face heightened erosion necessitating sand replenishment initiatives costing $5-10 million per mile of shoreline. These supplementary costs directly affect the profitability of tourist enterprises and the economic viability of coastal towns or biodiversity in linked marine environments.

2.5. Role in Biotechnology and Pharmaceutical fields

Compounds obtained from coral reef organisms have resulted in innovative therapies, such as AZT (utilised in HIV therapy), Prialt (for chronic pain management), and Halaven (for breast cancer treatment). The aggregate annual worth of these therapies surpasses $3 billion. Researchers project that the decline in coral reef biodiversity may preclude the identification of 50-70% of prospective marine pharmaceuticals, signifying tens of billions in unactualized economic worth.

2.6. Cascading Economic Effects on Local and Global Economies

The combined impacts of coral reef loss create ripple effects throughout local and global economies, affecting everything from government revenues to social stability. In Indonesia, which possesses the largest coral reef system globally, reef-associated industries generate over $3 billion per year for the national economy and sustain more than 1 million employments. Research indicates that ongoing reef deterioration may diminish this income by as much as 75%, jeopardising economic stability in coastal areas with few alternative options. Government estimates suggest that preserving reef health would yield economic advantages 15-20 times above the expenses of conservation efforts.

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