Coral Reef Restoration in Tamil Nadu, India

Guidelines for Practitioners

Tamil Nadu Forest Department
Gulf of Mannar Marine National Park
Tamil Nadu Coastal Restoration Mission
In partnership with
Suganthi Devadason Marine Research Institute

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Tamil Nadu
Coastal Restoration Mission

SDMRI

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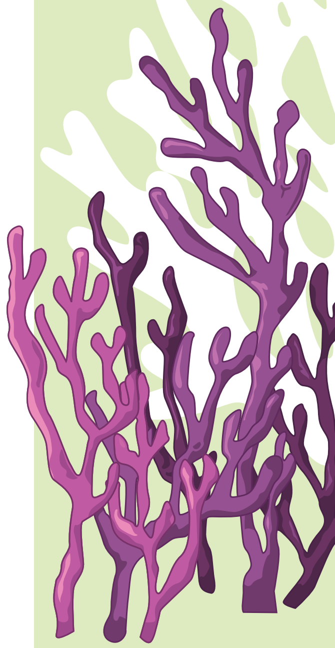

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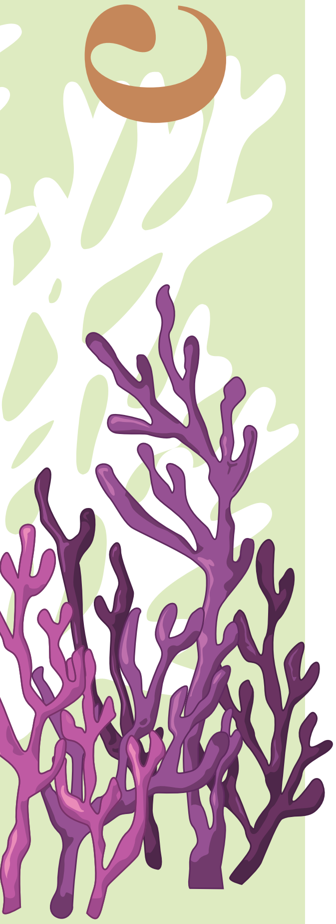
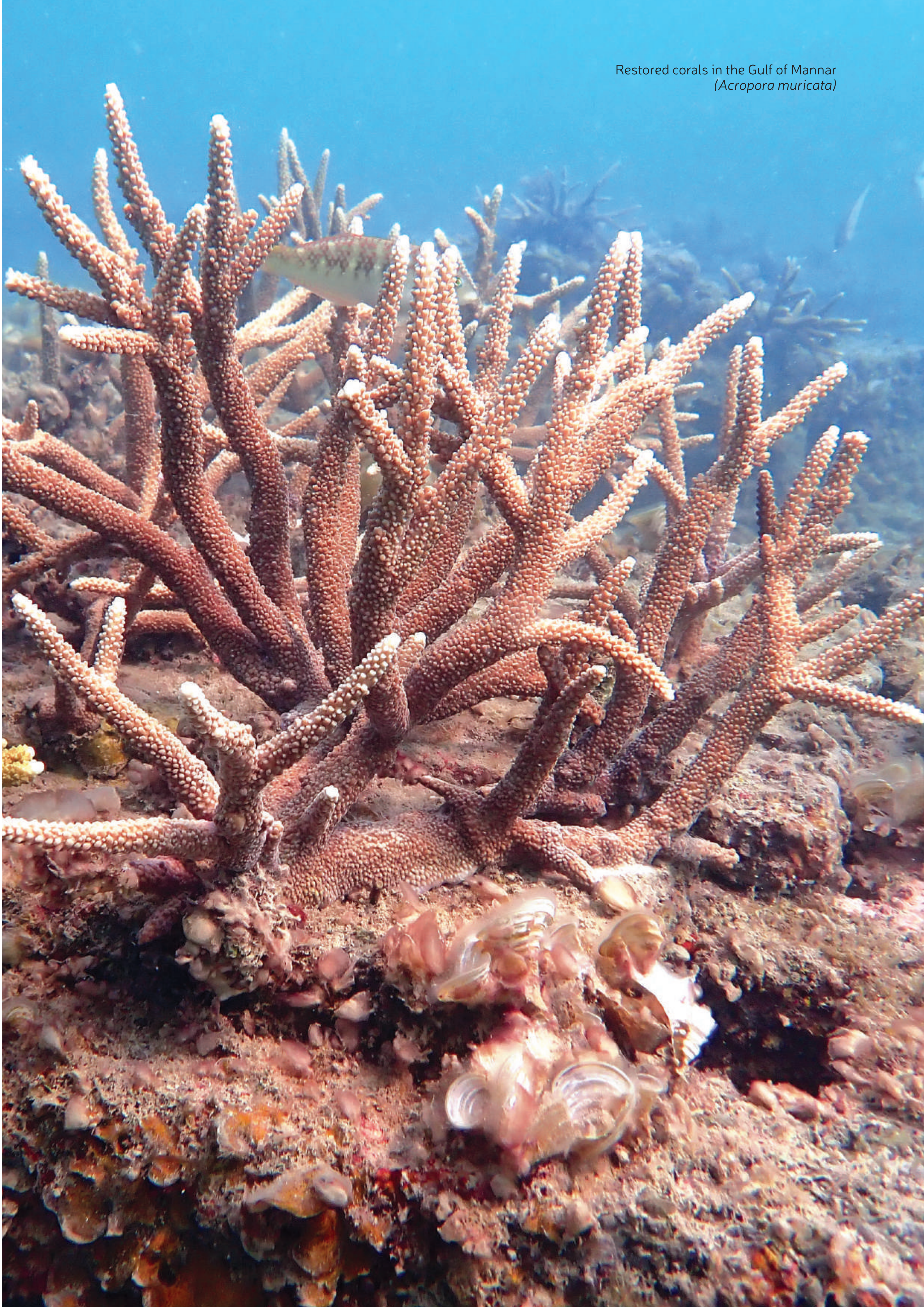




Restored corals in the Gulf of Mannar
(Acropora muricata)

Executive summary

Coral reefs are dynamic marine ecosystems that offer various ecological and economic benefits including but not limited to biodiversity support, fishery production and coastal protection. Positioned in the tropical realm, India has a significant extent of coral reefs, primarily in the island groups of Lakshadweep and Andaman & Nicobar apart from the vast extents in the mainland states of Tamil Nadu and Gujarat. Among the Indian mainland reef regions, the Gulf of Mannar and Palk Bay in Tamil Nadu have the most diverse, abundant and healthy coral reefs. Thousands of coastal people depend on the reefs in Tamil Nadu for their livelihood and for coastal protection: while the reefs protect the coast, the reef-associated fishery protects the livelihood of the people, who very much depend on those resources.

Coral reefs around the world including the reefs in Tamil Nadu have declined over the years primarily due to climate change mediated mass coral bleaching events followed by other natural and human-induced factors. The loss of coral reefs means the loss of all the associated ecological and economic benefits. Hence, the measures of conservation and restoration of coral reefs have gained a lot of global attention during the past few decades. Coral restoration is an evolving science as, globally, several coral restoration technologies have been tested and improved, and many are in experimental stages. The rates of their success, differing from one technology to another, rely on several factors including species involved, environmental conditions, proper execution and maintenance, prevailing threats and more. Hence, understanding the regional feasibility is very important while opting for restoration technology to be used in a local reef.

Restored corals in the Gulf of Mannar *(Acropora robusta)*

Coral restoration effort in India was first initiated in the reef areas of Tamil Nadu by Suganthi Devadason Marine Research Institute (SDMRI) in the early 2000s in association with Tamil Nadu Forest Department. After several initial experimentations, direct transplantation using artificial substrates was found to be the feasible method for restoring the degraded reef areas of Tamil Nadu. The method has been standardized to suit the local conditions and logistics. Using this low-cost and low-tech method, several coral restoration projects have been implemented in Tamil Nadu with a significant success rate. Over the past two decades, restoration protocols have been improved based on experience, and they are still being evaluated for

further improvement. Based on more than two decades of experience and expertise, guidelines have been prepared for carrying out coral restoration with maximum outcomes in the degraded reef areas of Tamil Nadu.

The first step in a successful restoration effort is to select proper restoration and donor sites, which is very important for the best expected outcome. Degraded reef areas are selected as restoration sites while healthy nearby natural reef sites are selected as donor sites; these selections are based on several ecological and biological parameters. Coral restoration is carried out only with native coral species and predominantly with fast growing species such as *Acropora* and *Montipora* in Tamil Nadu. Concrete frames made of ferro-cement (dimensions: 1 m X 1 m X 25 cm; weight: 100–120 kg) along with cement slabs (20 cm X 15 cm) are used as artificial substrates for direct transplantation. The concrete frames built at a construction site are transported to the seashore, then to the restoration site, and deployed there. Coral fragments collected from healthy donor colonies are tied carefully to cement slabs, and the slabs with fragments are then placed on the already deployed concrete frames. Then the transplants are maintained and monitored for a minimum period of three years. Being delicate animals, corals need to be handled carefully in every step in order not to harm them while carrying out restoration activities. Hence, the entire process of coral restoration needs to be carried out by scientific scuba divers with ample knowledge about coral ecology and biology.

Post-restoration maintenance and monitoring are of high importance to enhance the success rate. Maintenance consists of important steps like getting rid of benthic space competitors, removal of discarded fishing nets, if any, found on the substrates, and replacement of damaged substrates and dead fragments. Monitoring of survival, growth, reproduction, recruitment of corals, other associated organisms, and environmental parameters is also important to evaluate the success of restoration, while it is also essential to monitor adverse issues like bleaching, disease outbreaks, and algal bloom impacts for the proper management of restoration sites.

Coral restoration in Tamil Nadu during the past two decades has brought about several positive impacts including the enhancement of coral cover, boosting of coral sexual reproduction and recruitment, improvement in reef-associated biodiversity, livelihood sustenance for coastal communities, job and awareness creation, capacity building among the enforcement staff and assistance in climate adaptation and mitigation. However, the restoration efforts face several challenges including the requirement of skilled manpower and proper facilities, lack of awareness among the coastal communities, recurrent bleaching events and other biological phenomena, funding and rough weather.

In spite of these challenges, coral restoration has been highly successful in Tamil Nadu and the effort has emerged as a model for other reef areas of the country to emulate. More research and evaluation are in place to enhance the restoration efficiency in order to conserve corals. More wide-scale restoration efforts should be made in the reef areas of Tamil Nadu to keep the coral biomass intact considering the magnitude of loss. Conservation and restoration of coral reefs is intertwined with the livelihood of the coastal communities. As protocols have been established, they can be reproduced in any degraded reef area in Tamil Nadu to sustain and enhance the coral-associated ecological and economic benefits.

Reef area in Tamil Nadu

1 Introduction


Favites sp.

1. Introduction

1.1. Marine and coastal ecosystems

The oceans occupy more than 70% of our planet's surface and offer space for more than 95% of the biosphere, making them fundamental to life on Earth. Marine and coastal ecosystems are particularly important for humanity, as they provide essential ecosystem services such as food provision, oxygen production, water filtration, and climate regulation (McLean et al. 2001). As a result, human societies have developed in close connection with the oceans. Today, about 2 billion people around the world live within 50 km and1 billion within 10 km from the shoreline (Cosby et al. 2024) of which many people are dependent on orbenefitedby the resources of the oceans. This coastal population has increased at an unprecedented rate over the past few decades, further intensifying human dependence on marine resources.

Marine organisms that live in the vast oceans play key ecological roles while also providing economic benefits. However, despite their importance, global marine biodiversity remains poorly understood due to the limited accessibility and challenges associated with their exploration. According to current estimations, only between 11 and

78% of the global marine biodiversity has been discovered and described suggesting substantial knowledge gaps (Luypaert et al. 2020).

Marine and coastal ecosystems support a great multitude of marine organisms, and these ecosystems are to a large extent formed by the species living in them. Intertidal habitats, mudflats, mangrove forests, estuaries, salt marshes, kelp forests, seagrass meadows, coral reefs, oyster reefs and seaweed stretches are some of the most important marine and coastal ecosystems. Apart from offering direct socio-economic benefits to the coastal human populations, these ecosystems contribute significantly to poverty eradication, sustained economic growth, food security and the mitigation of the impacts of climate change (Munang et al. 2011). Fishery production, coastal protection, biological productivity, carbon sequestration, supply of food and medicines and provision of recreational space are some of the important ecosystem services offered by marine ecosystems (Vierros et al. 2017).

1.2. Coral reefs

Among the many marine ecosystems, coral reefs are considered the most dynamic, being ecologically complex and providing a number of socio-economic benefits.Coral reefs occupy only 0.1% of the ocean floor butfunction as shelter for approximately 25% of all known marine species (Hoegh-Guldberg et al. 2017). In view of their rich biodiversity, coral reefs are often called the rain forests of the sea. Hard corals, belonging to the phylum Cnidaria, are among the foundation species of coral reefs. Corals are colonial animals formed of tiny, soft-bodied organisms called coral polyps that extract calcium carbonate from seawater to build a hard, durable skeleton. The majority of these reef-building organisms depend for their survival on their symbiotic relationship with microscopic algae called zooxanthellae, which provide nutrition to the corals through photosynthesis. Coral reefs are primarily distributed in shallow, warm tropical and subtropical waters, roughly between 30°N and 30°S latitude.There are coral species living in the colder waters of deep seas and higher latitudes too, and, although some of these species are reef building, they are mostly ahermatypic (not reef building). Global coral reefs cover about 250,000 km^2 with the Indo-Pacific region having the most abundant and diverse coral species (Woodroffe and Webster 2014).

A coral colony with polyps exposed

1.2.1. Importance

Coral reefs constitute the framework that supports thousands of commercially and ecologically important marine species. They provide the living environment- for innumerable flora and fauna, which directly or indirectly benefit millions of people around the world. The number of speciesassociated with coral reef has been estimated to be around 830,000 (Fisher et al. 2015) makingcoral reefs about 70 times more economically valuable per hectare per year than tropical forests (Fezzi et al. 2023). About 850 million people around the world live within 100 km and about 275 million live within 30 km from coral reefs and many of them are benefited by these precious marine ecosystems (Burke et al. 2011). The economic benefits of coral reefs in terms of ecological services can range in annual value between US$ 100,000 to 600,000 per sq. km (UNEP-WCMC, 2006). About 30% of the described marine fish species inhabit coral reefs (Hixon and Randall 2019), providing livelihood to thousands of coastal communities. According to an estimate, one sq.km of coral reefs can yield 5 to 10 tons of fish annually (Burke et al. 2011) and reef fisheries have been estimated to garner US$ 6.8 billion per year, making a significant contribution to the global economy (Spalding et al. 2016). Further, people in reef nations consume an average of 29 kg of seafood each year, and as much as 77% of the animal protein in their diet is derived from this (Burke et al. 2011). Food is directly taken from reef waters and it feeds millions of people in developing and island nations.

Due to their physical build-up, coral reefs function as natural barriers against waves, storms, and even tsunamis and thus provide coastal protection, mitigate erosion and prevent property damage along the coast (Ferrario et al. 2014). Coastal protection offered by coral reefs is very effective as they perform a function similar to immersed concrete structures along the coast. Some island countries would be sub-

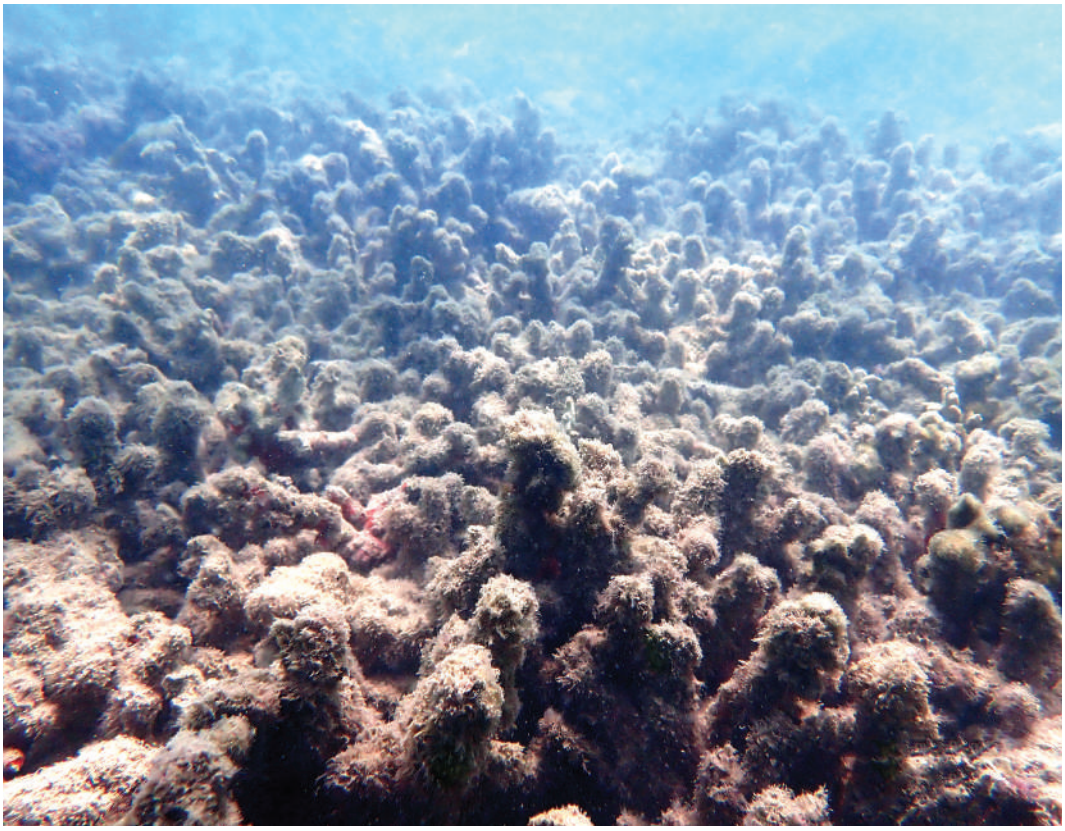
Reef area in Tamil Nadu

merged without this coastal protection by coral reefs (Yamamoto and Esteban 2010). Reefs also dissipate the wave energy to provide calm environmental conditions for other near-shore marine ecosystems such as seagrass meadows and mangrove forests. More than 150,000 km of shoreline in 100 different countries is protected by coral reefs, safeguarding thousands of human lives and their properties (Burke et al. 2011). According to an estimate, the economic value of this protection is about US$94 billion annually. Coral reefs also lay the basis for the formation of islands by supplying very large expanses of sand.

Coral reefs attract scuba divers, recreational travelers and beach-lovers, and thus support a significantpart of the economy of countries that have well-managed coral reefs. Coral reef-associated tourism provides livelihood to thousands of coastal people in at least 94 countries, and in 23 countries among them tourism accounts for more than 15% of the gross domestic product (GDP). Coral reefs directly contribute about US$10 billion per year to global tourism (Spalding et al. 2017). Extracts from organisms that live in coral reefs are used to develop medicines and drugs for several diseases including cancer. The source of many of marine-derived compounds originates from coral reef-associated organisms (Sang et al. 2019).

1.2.2. Threats and decline

Worldwide coral reefs are facing a severe decline over the past few decades due to various natural and human-induced factors. Climate change-induced coral bleaching, ocean acidification, and ocean deoxygenation are primary threats to the very existence of global coral reefs (Hughes et al. 2018). Corals, like all living organisms, respond to deviations in the environmental parameters, especially to temperature anomalies. Zooxanthellae are primary producers and provide energy to the coral through a symbiotic relationship. Thermal stress driven by global climate



A degraded reef

change causes the symbiotic zooxanthellae to leave the coral, making it starve and lose colour. Permanent loss of zooxanthellae, due to the continuous exposure to stressors, would eventually lead to coral death. Coral bleaching mayoccur when corals experience increased sea surface temperatures of just 1 to 2°C, and they may recover if the normal temperature returns within a short period, but, if the temperature stress continues for the long term, corals will eventually die (Hughes et al. 2017).

Globally, corals have been affected by several severe and widespread bleaching episodes. Some such events happened in 1998, 2010, 2014-17, and 2023-24. During the third and longest global coral bleaching event (2014-17), about 51% of global corals were affected (Eakin et al. 2026), and the fourth event (2023-24) has been reported to be even more severe (Reimer et al. 2024). Apart from coral bleaching and the consequent mortality, climate change-mediated ocean acidification and ocean de-oxygenation are also impacting global coral reefs severely. Benthic space competition, disease outbreaks, bioinvasion, storm events, and sedimentation are some of the other threats to coral reefs. Human actions such as coral collection, over-exploitation, destructive fishing activities, tourism, coastal development, and pollution are also contributing significantly to the decline of global coral reef ecosystems and the consequent economic loss (Hughes et al. 2017). The ever-increasing coastal population has aggravated these anthropogenic threats to corals, especially in developing countries.

Reef area in Tamil Nadu

2

Need for coral restoration

Mass coral bleaching in Tamil Nadu

The decline of coral reefs will affect all the associated ecological and economic benefits, depleting food security and decreasing the protection of the reef-associated coastal communities globally. It has been reported that by the year 2100, climate-related loss of coral reef ecosystem services will total around US$ 500 billion or more per year (Gattuso et al. 2015; Hoegh-Guldberg 2015; Heron et al. 2017). The loss of global coral reef ecosystems has caused a decline of at least 63% in reef-associated biodiversity and a decrease of 60% in reef-associated fishes since 1950 (Eddy et al. 2021). Further, degraded reefs have caused an estimated loss of 80-90% of tourist visits globally (Brander et al. 2012), which will severely impact the economy of several countries that thrive on reef-based tourism. Coastal protection has also been compromised in many countries due to the decline of reefs. The loss of corals will reduce the efficiency of the reefs in dissipating wave energy due to the reduction in structural complexity (Harris et al. 2018). Sea level rise coupled with coral loss will seriously affect many coastal countries and island nations. Thus, the continuous degradation of coral reefs will cause damage to people, properties and economy, and these damages are often irreversible. In

many reef areas, the status of the reef has reached a critical point of reduced resilience. Hence, it is imperative to sustain the integrity of the remaining reef ecosystems and restore the lost coral biomass.

In order to compensate for coral loss and sustain the associated benefits, a number of initiatives are taken worldwide to protect and seek to secure the future of coral reefs globally and locally (Hein et al. 2021). Some of the initiatives are establishing marine protected areas, creating awareness among the stakeholders, reducing human impacts such as pollution, overfishing, destructive fishing activities, and tourism impacts, removing/controlling predators and space competitors, and carrying out coral restoration. After degradation, corals are capable of natural recruitment and recovery (Edwards and Clark 1999), but the rate of natural recovery is very slow, and the process can take several years. Moreover, frequent bleaching events make this natural recovery impossible in many reef regions. Hence, among all the conservation initiatives, coral restoration efforts have received more serious consideration than ever before over the past decades (Pessoa 2025). Coral restoration may not be the sole solution to tackle global reef degradation, but restoration efforts are inevitable as a proactive mea-

A reef dominated by *Turbinaria* corals

sure in the context of global climate change (Mulà et al. 2025). Coral restoration efforts provide us with a chance to sustain the reef integrity and associated benefits. Corals have been evolving and been in existence for millions of years and coral restoration is an effective method to keep these animals intact so that they can naturally develop adaptations to the changing climatic conditions.

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A transplanted coral (*Acropora* sp.)

3
Types of coral restoration

Natural coral recruitment on an artificial reef module

Due to the growing concern about coral reef decline around the world, restoration of coral reefs has assumed greater importance in recent years. Restoration of degraded coral reef areas requires a deep understanding of the natural recovery process as well as knowledge of the conditions under which these natural processes succeed or fail.

Different types of coral restoration techniques have been attempted in different parts of the world with varying success rates. Coral restoration is still an evolving science as techniques are attempted and improvised continuously. Experiments on coral restoration using advanced technologies are conducted worldwide to identify the methodology that is cost-effective for wide-scale restoration efforts and provides long-term benefits. In a recent review, Boström-Einarsson et al. (2020) explained the different types of restoration techniques used around the world, which include direct transplantation, coral gardening, micro-fragmentation, taking advantage of genetic diversity in sexual propagation, larval enhancement, substratum enhancement with electricity, substratum stabilization and deployment of artificial reefs. Among them, direct transplantation and

coral gardening are the most commonly adopted practices accounting for about 70% of the total global efforts (Boström-Einarsson et al. 2020) due to their high success rates and replicability.

3.1. Direct transplantation

When a fragment that breaks off a coral colony finds suitable substrate and environmental conditions, it can grow and form a new colony. This is a kind of asexual reproduction of corals called fragmentation. The method of direct transplantation of corals, based on fragmentation, involves the collection of coral fragments from a healthy donor colony, or already broken off, and directly transplanting them in a degraded site that needs restoration. This method enables the fragments to grow into separate colonies in a degraded reef to increase the coral cover (Oren and Benayahu, 1997; Guzman, 1999). The survival rate in this method has been reported to be as high as 90% (Boström-Einarsson et al. 2020). However, finding suitable natural substrate for direct transplantation is a challenge, as degraded reefs often have an unstable bottom. Hence, artificial substrates of different materials and designs are used for direct transplantation around the world because the survival of transplants depends primarily on suitable

Restored corals in the Gulf of Mannar (*Acropora intermedia* and *Acropora muricata*) substrate (Lindahl 2003; Fox et al., 2003). Though direct transplantation is the earliest restoration initiative (e.g. Guzman 1991, 1993; Yap et al. 1992; Clark and Edwards 1995; Bowden-Kerby 1997), it is still being continued due to its high success rate.

3.2. Coral gardening

Coral gardening is another successful method (Boström-Einarsson et al. 2020; Rinkevich 2021), in which the collected coral fragments are kept in intermediate in-situ or ex-situ nurseries before transplanting on restoration sites. Though nurseries are successful, this method is suitable only for calm and sheltered environments. Also, the maintenance of ex-situ nurseries requires very expensive infrastructure. Selection of substrate, site and species and the management of nurseries are of critical importance for success in coral gardening (Reyes et al. 2017).

3.3. Micro-fragmentation

Recently, a new restoration technique called micro-fragmentation has been developed to accelerate the growth of massive coral transplants (Page 2013; Page and Vaughan 2014; Page et al. 2018). When a coral colony suffers partial mortality or is fragmented mechanically, the isolated segments will reconnect if they grow in contact with one another (Hildemanet al. 1975; Hidaka, 1985). This capacity of corals to reconnect after fragmentation is the basic concept for micro-fragmentation. In this method, corals are cut using a diamond blade into small fragments (1 cm^2) and mounted on tiles, which are then transplanted. This is a very good method for restoring slow-growing massive corals, but it is comparatively expensive.

3.4. Sexual propagation

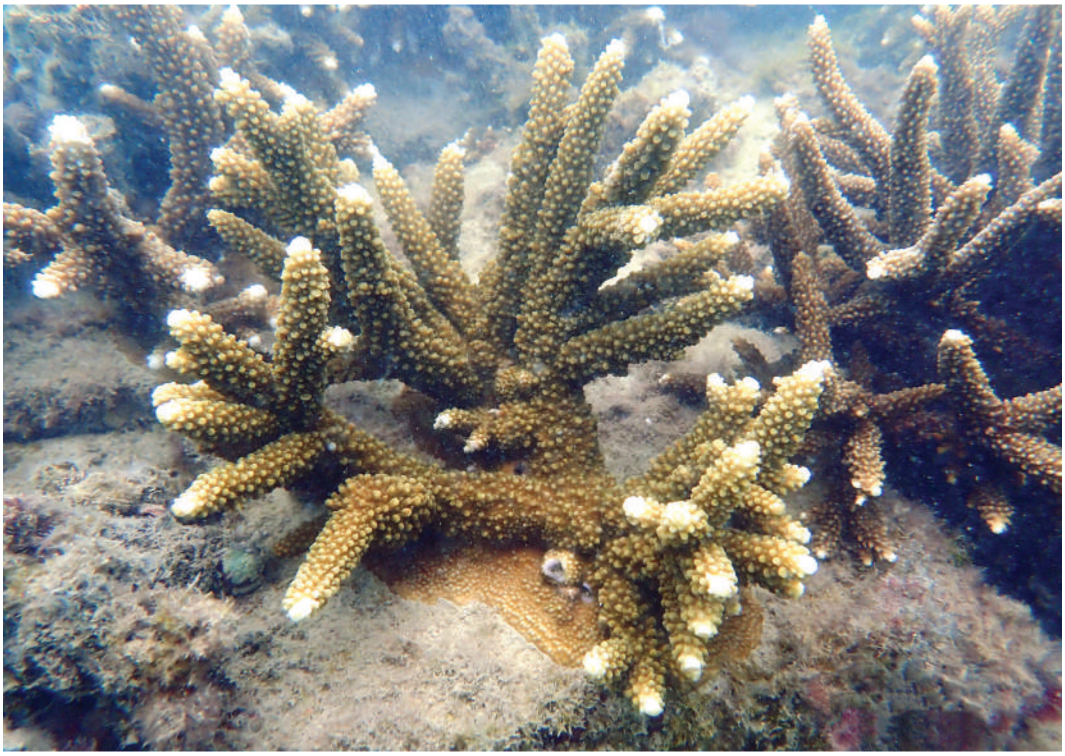
In this advanced method, assisted fertilization or the creation of nursery stocks from the larvae of sexually mature corals is carried out to maintain genetic diversity in coral gardeningfor the long-term survival, adaptation, and resilience. As most of the current restoration projects involve acroporid corals, this method is helpful inincreasing the diversity of genera and species. Additionally, it potentially increases the restoration success providing a larger range of genetic diversity for the future coral reefs. However, this method is still in the experimental stage and requires expensive infrastructure and entails associated cost (Boström-Einarsson et al. 2020).

3.5. Larval enhancement

For reef systems with limited natural larval supply, the larval enhancement method is suitable to recover the natural cover and function of the reef. In this method, coral gametes are harvested, reared ex situ and are then settled onto natural or artificial substrates (Boström-Einarsson et al. 2020). This method can be successfully used for restoring populations of coral species with different life-history traits, and also in degraded reef areas to catalyse the reversal of declining coral populations (Dela Cruz and Harrison 2020). This method is also in its experimental stage and requires large infrastructure development along with associated cost.

3.6. Substratum enhancement with electricity (Biorock)

Biorock Technology is an innovative restoration technique that uses mild electrical current to cause dissolved minerals in the water to crystallize on structures and grow into limestone. Through this method, faster calcification takes place, boosting colony growth and resilience to stressors (Goreau and Prong 2017). This is an expensive method demanding specialized infrastructure development with high maintenance cost (Boström-Einarsson et al. 2020). Though it has been successful in experimental attempts, wide-scale restoration through this method is a challenge.



Restored corals in the Gulf of Mannar (*Acropora muricata*)

3.7. Substrate stabilization

Natural coral recovery in a degraded reef often fails due to unstable substratum and unconsolidated coral rubble. Stabilization of these unsuitable substrata helps the coral recruits to survive. Several methods are used to stabilize the substratum, such as using mesh to stabilise rubble, removing the rubble to reveal hard substrate, and deploying rocks or other hard substrates (Ceccarelli et al. 2020; Boström-Einarsson et al. 2020). This method is often very expensive and is not suitable for wide-scale restoration.

3.8. Artificial reefs

Deployment of artificial structures to assist the natural coral recruitment process has been a common and successful practice in many degraded reefs. Artificial reefs can protect the biodiversity by acting as surrogates for degraded natural reefs (Clark and Edwards 1994). Coral transplantation onto artificial reefs is also applied in several reefs around the world.

Artificial reefs assist in natural fish biomass recovery process and provide substrates for coral recruitment over long time. Several studies have reported the success of artificial reefs in assisting natural coral recovery (Raj et al. 2020; Mathews et al. 2021). However, the method faces a few challenges with regard to developing proper design, costing and logistics.

4

Coral reefs of Tamil Nadu

Reef area in Tamil Nadu

Positioned in the tropical realm between latitudes 37°N and 8°N approximately, the coastal waters of India hold a substantial extent of coral reefs, particularly in the four major coral reef areas, namely the Gulf of Mannar (GoM) and Palk Bay in Tamil Nadu, the Gulf of Kachchh in Gujarat, the Lakshadweep Archipelago, and the Andaman and Nicobar Islands. Apart from these major reef areas, coral reef patches are observed along the west coast of India in Kerala, Karnataka, Goa and Maharashtra. With more than 400 recorded coral species, the Indian coral reefs support a wide range of biodiversity including but not limited to 1,284 species of fishes, 3,271 species of mollusks, 765 species of echinoderms, 519 species of sponges, 607 species of crustaceans, and 624 species of marine algae (De et al. 2017). The coral reef regions of India provide livelihood to thousands of people and contribute significantly to the country's economy. Corals in India are protected under Schedule I of the Wildlife Protection Act (1972), Govt. of India, by which corals get the highest level of protection because under this Act collection and trading of live and dead corals are banned and offenders get harsh penalties.

Among the four major coral reef areas

of the country, two are isolated island groups (Andamans and Lakshadweep) with significant extent of corals, where human population, urbanization and pollution are relatively less. Among the two states that have major reef areas (Tamil Nadu and Gujarat), Tamil Nadu is endowed with comparatively more abundant, more diverse and healthier coral reefs. In Tamil Nadu, coral reefs have developed in the Gulf of Mannar and Palk Bay covering four coastal districts namely Ramanathapuram, Thoothukudi, Tirunelveli and Kanniyakumari. The Gulf of Mannar is located between Rameswaram and Kanniyakumari in the southern part of Tamil Nadu, while Palk Bay is situated off central Tamil Nadu bordering the Cauvery deltaic region between Point Calimere and Rameswaram. Palk Bay and the Gulf of Mannar are connected by a narrow passage called Pamban Pass and also at Adams Bridge. Both Gulf of Mannar and Palk Bay share boundaries with neighboring Sri Lanka and hence are strategically important. Adams Bridge or Ram Sethu is religiously important as thousands of devotees visit Rameswaram and Dhanushkodi every year. The area also has archeological significance due to the early records of commerce between India and Sri Lanka via Dhanushkodi (Kumaraguru et al. 2008).

Reef area in the Gulf of Mannar

People living along the coast of the Gulf of Mannar and Palk Bay depend largely on reef-associated fishery resources for their livelihood. This thick coastal population lives in small hamlets as well as in big cities. The number of fishermen families along the coast was 98,457 in 2005, which increased to 110,667 in 2016, an increase of about 12% (CMFRI-DoF, 2020). Obviously, the population has further increased since then. Due to modernization and increased demand for fishery resources, the share of motorized fishing crafts used in this coastal belt increased significantly from 50.3% in 2005 to 94.8% in 2016 (CMFRI-DoF, 2020). Growing coastal population and escalating fishing pressure put tremendous stress on coral reefs and associated species in Tamil Nadu. Any threat to coral reefs can directly affect the livelihood of the dependent people.

4.1. Corals of the Gulf of Mannar

The Gulf of Mannar with a total area of 10,500 sq.km was declared as Gulf of Mannar Biosphere Reserve (GOMBR) in 1989 by the Government of India and the GOMBR was declared as a Ramsar site in 2022. There are 21 uninhabited coral islands in the Gulf of Mannar lying in a stretch between Rameswaram and Tuticorin, where major coral reefs have developed. The island system in the Gulf of Mannar is the product of complex physical and biological processes, starting from the interglacial period. The islands vary significantly in terms of size, shape, elevation, and geomorphic features (Asir et al. 2020). In 1986 the Government of Tamil Nadu declared the 21 islands and the surrounding waters as the Gulf of Mannar Marine National Park (GOMMNP) with an area covering 560 sq.km, which is a 'no go' and 'no take' zone. Coral reefs of the fringing type are observed around these islands and patch reefs are also observed throughout the Gulf of Mannar. A total of 132 coral species has been reported in the Gulf of Mannar (Edward et al. 2023), and the comparatively higher total biodiversity of 4,223 species reported so far in the Gulf of Mannar (Balaji et al. 2012) can be attributed almost exclusively to the availability of coral reefs. The total reef area cover of the island reefs of the Gulf of Mannar is 66.28 sq.km and the patch reefs cover an area of 44.28 sq.km.

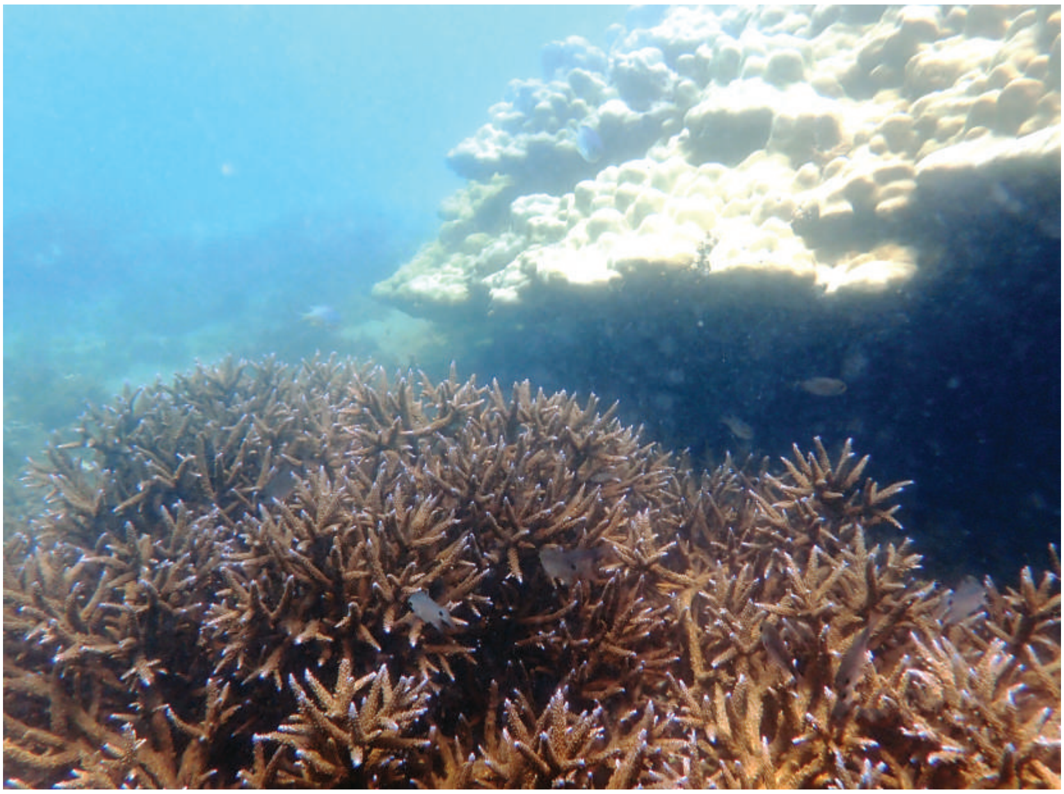
4.2. Coral reefs of Palk Bay

Unlike the Gulf of Mannar, the Palk Bay does not have any island ecosystem with reefs. Reefs in Palk Bay are found at its southern part between Vedhalai and Rameswaram along the coast. These mainland reefs occur from the inter-tidal zone upto a depth of 6 m. A total of 63 coral species has been reported from Palk Bay (Pillai 1969) and the total reported biodiversity of the Bay is 3,289 (Kumaraguru et al. 2008). The reef areas of Palk Bay, estimated to be 20.5 sq. km, are not protected under law asthose of the Gulf of Mannar. Hence, active fishing takes place in these areas and thousands of people rely on them for their livelihood.

4.3. Threats

4.3.1. Direct human-induced threats

Corals of Tamil Nadu have encountered several climatic and non-climatic threats during the past few decades and as a result have declined over the years (Raj et al. 2021; Edward et al. 2023). Corals were included in Schedule I of the Wildlife Protection Act 1972 in 2001 through

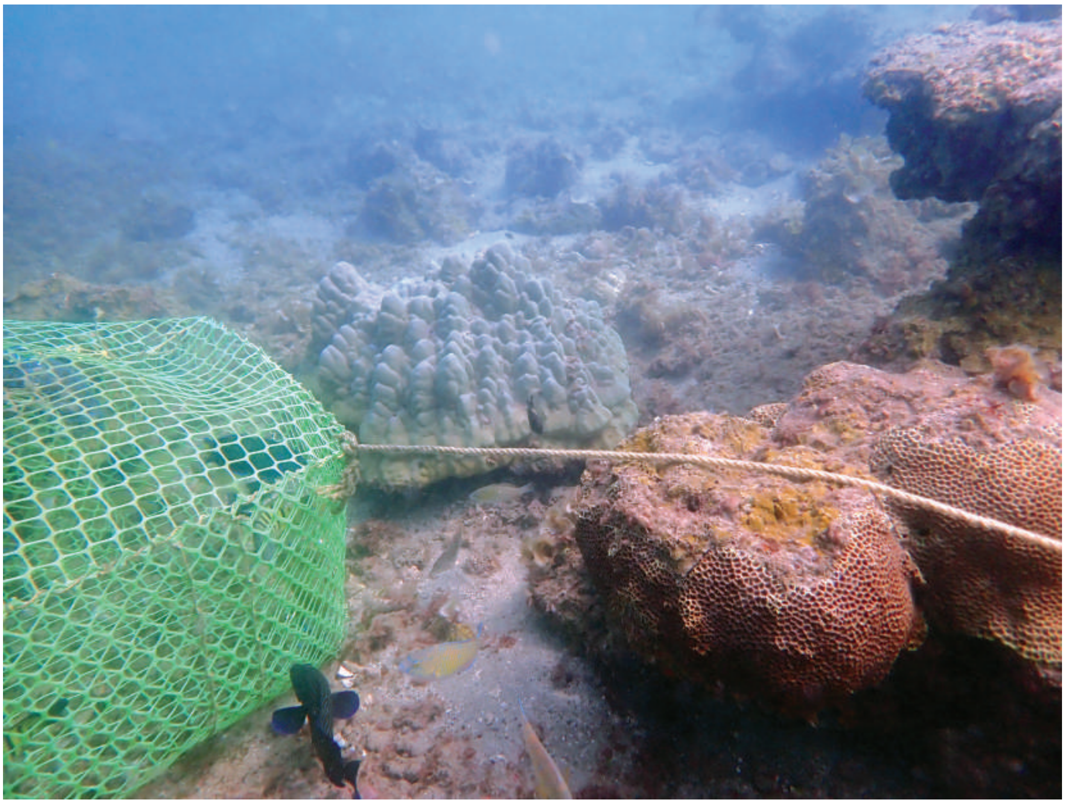


Reef area in Palk Bay

an amendment. Earlier, mining corals for building materials and for lime factories was severe in the Gulf of Mannar and Palk Bay, with the quantity of mined corals reaching 25,000 tons per year (Mahadevan and Nayar, 1972). Strict enforcement of law and awareness creation led to the halting of coral mining, and particularly after the 2004 Indian Ocean tsunami, coral mining is completely absent (Edward et al. 2012). However, destructive fishing practice has been a persistent problem for the corals of Tamil Nadu for many decades. Certain destructive fishing activities such as poison fishing and dynamite fishing have been discontinued, but other activities like bottom trawling, trap fishing and bottom gill netting are still continued (Edward et al. 2012, 2023; Raj et al. 2017). Overfishing is still a problem. Recently, deployment of fish traps has increased and 'spear-fishing' using surface-supplied diving has emerged as a new threat (Edward et al. 2012, 2023; Raj et al. 2015, 2021). Collection of seaweed, ornamental fish and corals for ornamental purposes (Raj et al. 2023a) affects the corals of Tamil Nadu. Recreational and religious activities along the coast of the Gulf of Mannar and Palk Bay remain an important factor in the degradation of corals in Gulf of Mannar (Edward et al. 2023). Pollution from domestic, industrial, fishing and recreational sources also contributes to the coral decline (Edward et al. 2023).

4.3.2. Climatic threats

During the past two decades, climate change has become the primary threat to the corals of Tamil Nadu. The coral loss observed due to climate change is much higher than in the case of human-induced factors. Coral bleaching is an annual phenomenon among the corals of Tamil Nadu during summer months when the temperature levels vary between 31 and 33.5° C though corals tend to recover when temperatures return to normal levels within a short period (Edward et al. 2008). After



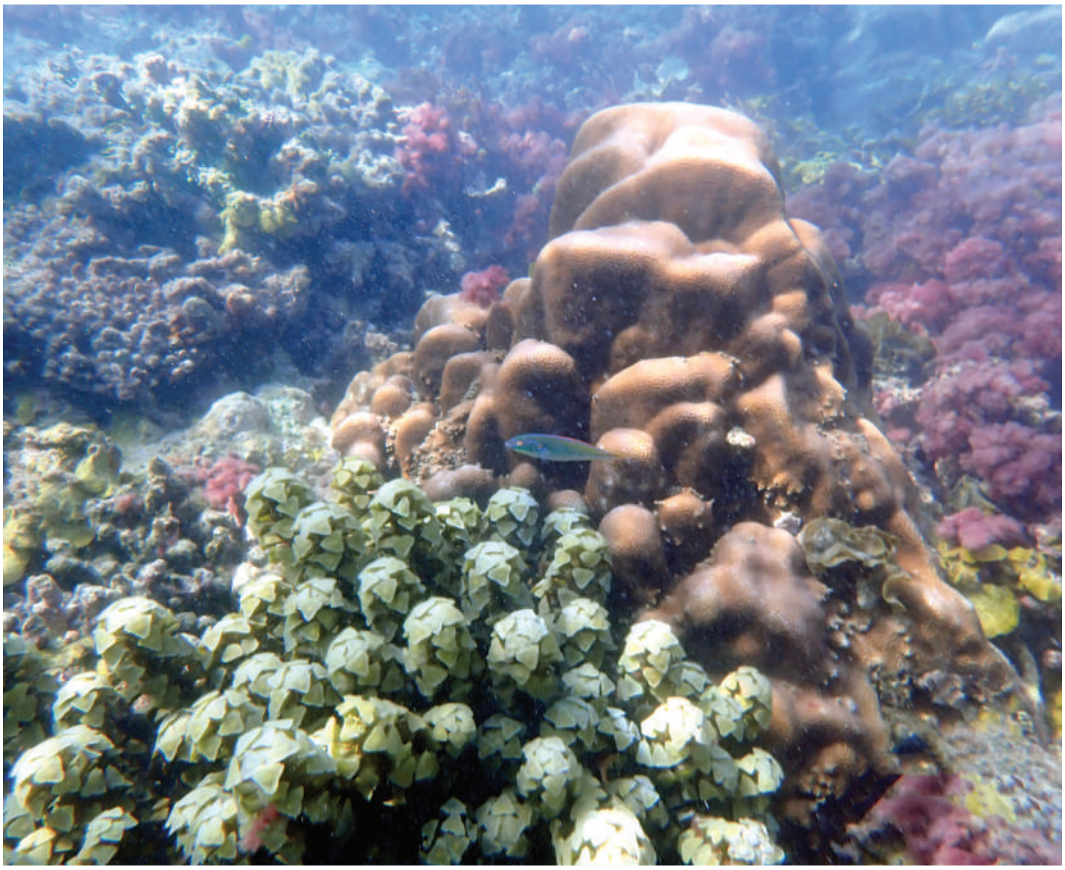
Trap fishing in reef areas

Uprooted corals along the coast

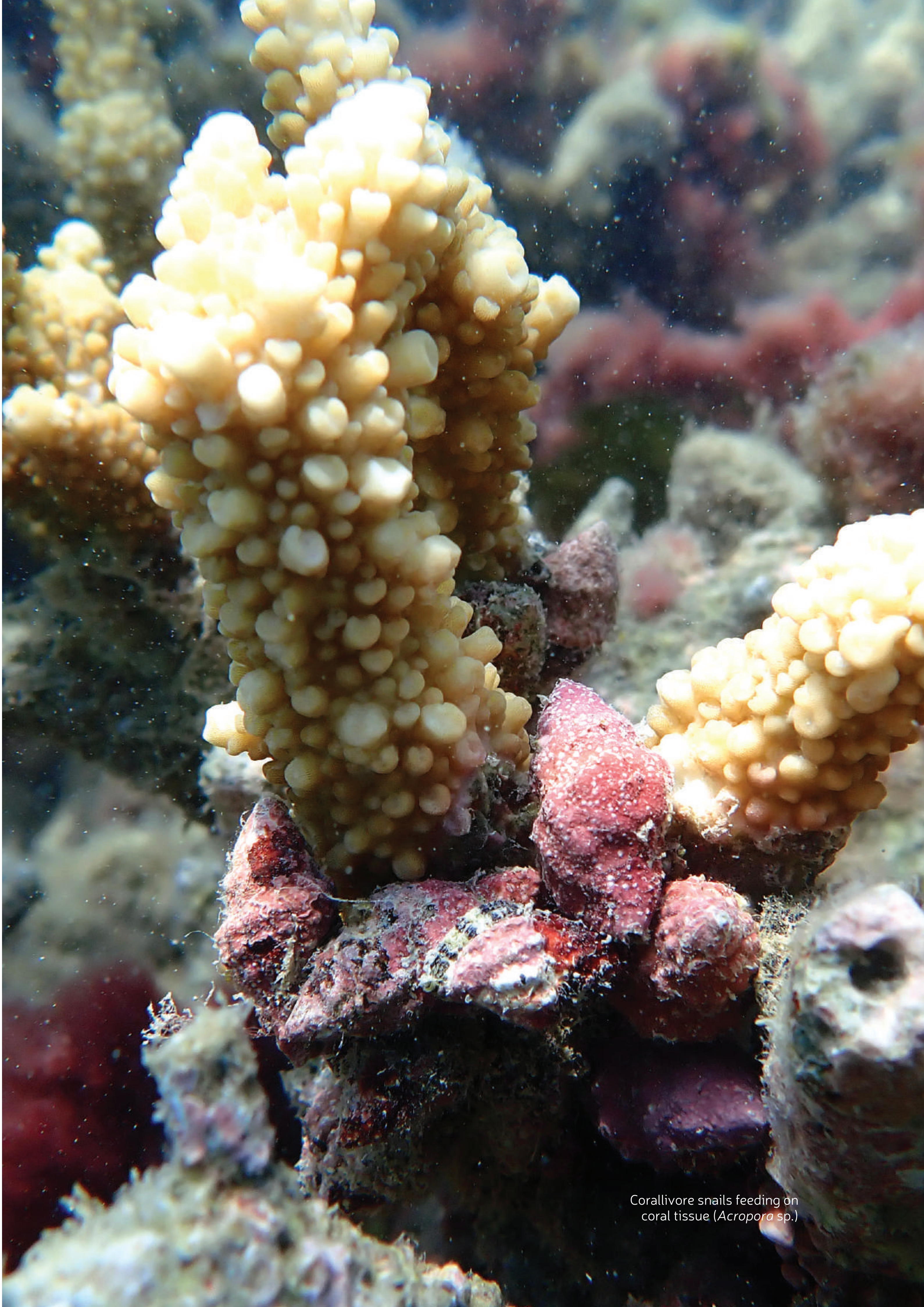
2010, climate change has triggered mass coral bleaching events and the consequent mass coral mortalities have been significant in Tamil Nadu, especially in 2010, 2016 (Raj et al. 2021; Edward et al. 2012, 2023) and 2024. Mass coral mortalities caused by bleaching not only affect coral communities but also reduce the associated fishery resources and endanger the livelihood of the coastal populations that depend on coral reefs. The growth rates and reproductive efficiency of corals are reduced when susceptibility to diseases increases due to bleaching events. Hence, changes in coral community composition sets in (Edward et al. 2023) affecting the biodiversity and fishery production. Based on the frequency and intensity of coral bleaching events, it has been predicted that corals in Gulf of Mannar would experience annual severe bleaching (ASB) under a high emissions scenario (RCP8.5) before the year 2070 and bleaching twice per decade prior to 2060 (Raj et al. 2021). The reduced emissions scenario RCP4.5 has ameliorating effects and the majority of the islands would not experience ASB between now and 2070 (Raj et al. 2021).

Heat-stressed corals in Tamil Nadu are overpowered by other benthic organisms such as macroalgae, sponges, octocorals, and zoanthids (Raj et al. 2022, 2023b; Edward et al. 2023). Modelling studies on the covers of corals and algae in Gulf of Mannar show that the algal cover increased following bleaching events in 2010 and 2016 (Raj et al. 2021). Recent reports indicate that sponge overgrowth has become a serious threat in Gulf of Mannar as sponges can tolerate high temperature levels and dirty waters (Ashok et al. 2018; Raj et al. 2022, 2023b; Emmett et al. 2021). Apart from the mass mortalities caused by coral bleaching, temporary hypoxic conditions caused by algal blooms can trigger mass coral mortalities. Climate change has increased the sea surface temperature levels and warmer

A bleached coral (*Platygyra* sp.)



Macroalgae overgrowth (*Goniastrea* sp.)



Corallivore snails feeding on coral tissue (*Acropora* sp.)

temperatures benefit algal blooms. Since 2019, blooms of *Noctiluca scintillans* have been observed to kill corals (Raj et al. 2021), apart from killing a multitude of marine species. Every year, the intensity and geographical range of this bloom is increasing indicating the severity of climate change. Ocean acidification is also affecting the corals of Tamil Nadu though detailed studies on this phenomenon are yet to be made.

4.3.3. Natural threats

The other threats like disease outbreaks, corallivory, bioinvasion, and sedimentation have also contributed significantly to the decline of corals in Tamil Nadu. Coral disease outbreaks and the consequent coral mortalities have become more frequent among the corals of the Gulf of Mannar and Palk Bay (Thinesh et al. 2013, 2014; Raj et al. 2016 a, b; Bharath et al. 2020). Corallivorous animals are attracted to the eroding tissue of corals affected by coral bleaching or disease outbreaks. Fishes, snails, and starfishes have been reported to feed on coral tissue in the reef areas of Tamil Nadu causing disturbances (Raj et al. 2016a, 2018; Emmett et al. 2021). Bioinvasion of an exotic alga has also caused significant damage to corals and associated organisms in the Gulf of Mannar (Arasamuthu et al. 2023). Other natural factors such as sedimentation, turbidity, storms, freshwater runoff, etc. also contribute to the coral degradation in Tamil Nadu.

Coral colonies infected by white syndrome disease (*Acropora* spp.)

Restored corals in the Gulf of Mannar (*Acropora* spp.)

5

Coral reef restoration in Tamil Nadu

Restored corals in the Gulf of Mannar (*Acropora muricata*)

Owing to all the above-mentioned threats, especially to the bleaching events, coral cover in Tamil Nadu has decreased significantly over the years. In the Gulf of Mannar, a decline of coral cover from 37.0 to 19.7% between 2005 and 2024 has been recorded with a relative decrease of -46.8% (Edward et al. 2023; SDMRI Database). While coral restoration in India was initiated in 2002, efforts were enhanced after the 2004 Indian Ocean tsunami. The decrease in coral cover has been massive during the past two decades as almost half of the ecological services offered by corals have presumably been reduced. The livelihood of thousands of coastal fisher folk along the coast of the Gulf of Mannar and Palk Bay depends on reef-associated fishery resources and thus the decline of coral reefs has significantly impacted their economy. In order to seek to keep the coral biomass intact to sustain the associated advantages, coral restoration using a viable technology is inevitable in Tamil Nadu. Also, considering the continuous decline of corals in the face of climate change, wide-scale restoration efforts backed by effective maintenance and monitoring are warranted.

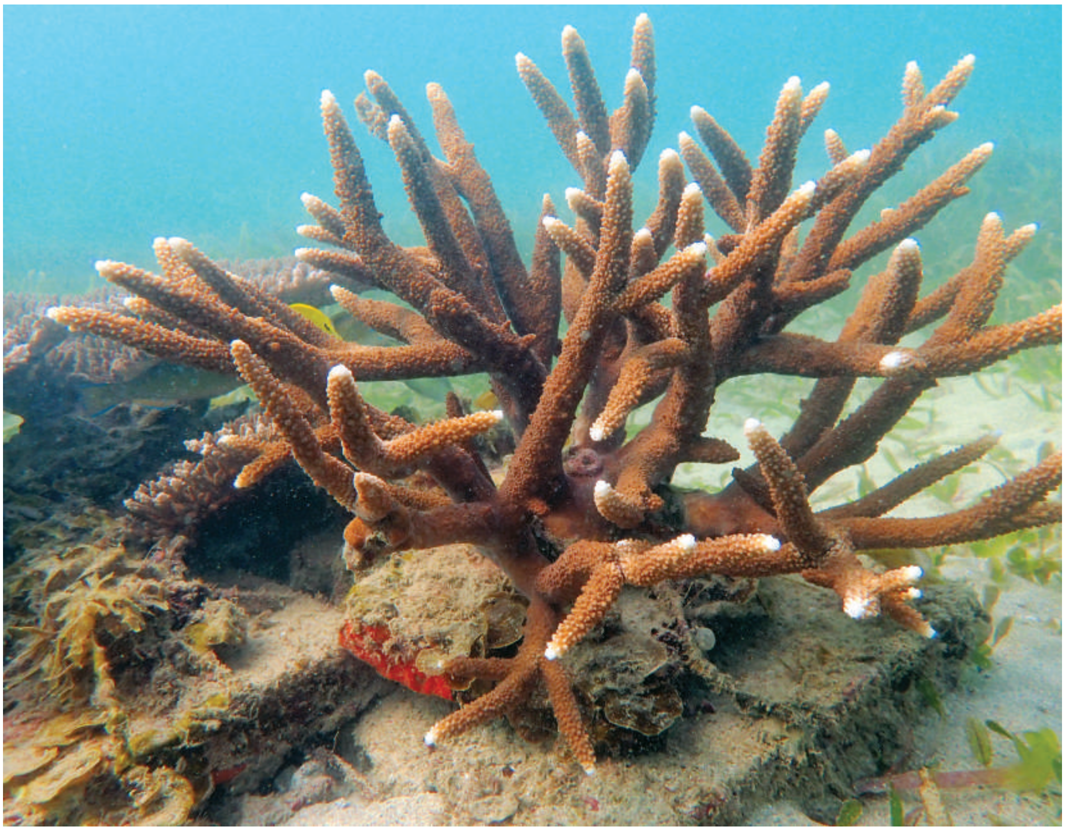
5.1. Selection of suitable coral restoration techniques

The parameters of coral distribution and diversity are region-specific based on geographic and hydrodynamic conditions and hence restoration technology should

also be region-specific. Though several coral restoration technologies have been attempted and carried out around the world, identification of a regionally suitable method for Tamil Nadu is very important. Most of the reef areas in Tamil Nadu are very shallow ranging around a depth of 5 m (Raj et al. 2021) and so the restoration technique should be planned accordingly. Shallow waters are susceptible to high water temperatures, strong wave action and human-induced threats. As not all the species are suitable for coral transplantation, the diversity and dominance of native coral species should be considered. The past and existing threats to the corals of Tamil Nadu should also be taken into account when planning for restoration. Accessibility of maintenance and monitoring is another important thing to be considered.

5.1.1. Evaluation of available coral restoration techniques

Decades of coral mining activities have damaged the bottom integrity of the reef areas in Tamil Nadu and hence substrate stabilization seems to be a good option. However, this method is very expensive and is not suitable for wide-scale restoration in Tamil Nadu as the state's reef area cover is vast. Substratum enhancement with electricity (Biorock) is another expensive method not suitable for regional demands. Provision of continuous electrical supply is almost impossible as the state's coral reef areas are remote. Using



Restored corals in the Gulf of Mannar (*Acropora intermedia*)

solar panels for electrical supply needs heavy infrastructure and is very expensive. Moreover, maintenance cost for the solar based units is very high; the surface of the solar panels needs to be cleaned once in two days to remove bird poop and salt deposition in order to maintain effectiveness; wires and connections need to be checked and adjusted every 10 days; and solar panels need to be replaced once in six months. Above all, maintenance failure will eventually cause coral mortality. During cyclones and rough weather seasons, there is a high likelihood of the collapse or disorganization of the solar units leading to coral mortality. Further, certain species of fish and other organisms move away from the biorock units due to the electrical supply. Advanced restoration technologies such as utilizing genetic diversity in sexual propagation and larval enhancement are still in the experimental stages and are very expensive too. These technologies require heavy land-based infrastructure that needs expertise. Moreover, these methods entail keeping corals in captivity.

Deployment of artificial structures to enhance the natural reef recovery is a good option for the reef areas of Tamil Nadu and this method has been proved to yield good results (Raj et al. 2020; Mathews et al. 2021). Natural recovery, however, takes time where the continuous supply of coral larvae is very important. Micro-fragmentation is a very good option for restoring slow growing massive corals but the technique needs to be tested for the corals of Tamil Nadu. Coral gardening has been successful in many areas but it requires expensive ex-situ laboratory or calm confined water environment for in-situ nursery structures, which is not possible along the coasts of the Gulf of Mannar and Palk Bay. Furthermore, maintenance of nursery is expensive due to the remote location, and environmental conditions may not be suitable for transplanting nursery-grown corals in the restoration area.

Direct transplantation is one of the most used methods around the world and the survival of corals is very high (Boström-Einarsson et al. 2020). The high success rate of this approach is primarily due to the fact that direct transplantation concentrate mortality into a single step (collection to transplantation), whereas nursery-based methods experience mortality across two steps (collection to nursery and nursery to transplantation in the restoration site). In the case of Tamil Nadu, the use of nursery is not ideal for restoration due to the remoteness of the site, and therefore maintenance of the nurseries will also be difficult. Thus, direct transplantation is the most suitable choice. Direct transplantation involves fragmentation of corals, which is an asexual mode of reproduction that has been highly successful due to the corals' effective regenerative capacity. As there is no laboratory-established infrastructurehere in Tamil Nadu for growing corals, transplanting coral fragments directly to the degraded area within a short time would be the best option. Direct transplantation can be carried out easily in the field without bringing corals to the laboratory. Suitable substratum is a basic requirement for any transplantation. It should be noted here that the natural substratum in the reef areas of Tamil Nadu is not stable due to decades of coral mining (Mahadevan and Nayar 1972; Edward et al. 2025). Live and dead corals were mined earlier, which has reduced the possible natural substrates for transplantation. Hence, artificial substrates are necessary for direct transplantation of fragments in Tamil Nadu. Based on these conclusions, a low-tech and low-cost direct transplantation technique using artificial substrates has been developed by Suganthi Devadason Marine Research Institute (SDMRI), and applied in Tamil Nadu as the first coral restoration effort in the country.

5.1.2. Standardization of coral restoration techniques

5.1.2.1. Breakthrough projects on coral restoration

SDMRI has been involved in coral reef research since the early 2000s.The institute surveyed the reef areas of Tamil Nadu during 2003-05 and developed benchmark baseline information on coral status and diversity. Annual surveys have been conducted since then to update the status (Edward et al. 2023). The Ministry of Environment, Forests and Climate Change (MoEF&CC), Government of India awarded SDMRI a research project titled "Coral culturing and rehabilitation of degraded coral reef through transplantation of staghorn corals, *Acropora formosa,* in Tuticorin (2002–05)". Simultaneously, another project titled "Pilot-scale community-based reef restoration and capacity building in Tuticorin coast of Gulf of Mannar, Southeast coast of India (2002–06)" was awarded to SDMRI by Coastal Ocean Research and Development in Indian Ocean (CORDIO). Through these breakthrough projects, SDMRI pioneered in developing the coral restoration technology for the reef areas of Tamil Nadu. This method has been experimented, improved and found suitable to restore degraded reefs areas of Tamil Nadu.

Through the above-mentioned projects, the reef research team (RRT) of SDMRI with professional scuba diving capacity and scientific expertise on coral ecology developed a direct transplantation method using artificial substrates, which has been used in several wide-scale restoration projects in Tamil Nadu (Edward et al. 2005a,b, 2006; Edward 2018; Mathews 2009). From 2002 to 2024, a total of 51,183 coral fragments, ranging from 8 to 12 cm in size, encompassing 20 native coral species with

Restored corals in the Gulf of Mannar (*Acropora robusta*)

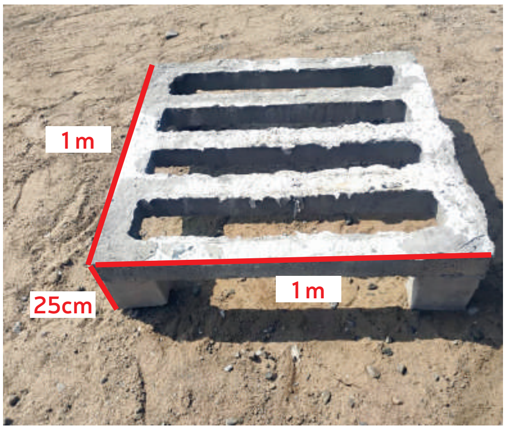
different morphotypes have been used for direct transplantation in the Gulf of Mannar and Palk Bay. Across different locations and species, and also based on the monitoring duration, the average survival of transplants ranged between 55.6 and 79.5% in Tamil Nadu. Growth rates have also been high, in particular for acroporans (Edward et al. 2025).

5.1.2.2. Development of suitable artificial substrates

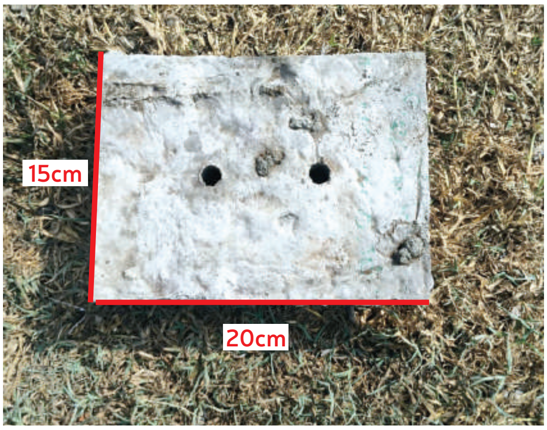
As mentioned above, artificial substrates are inevitable to carry out direct transplantation in the reef areas of Tamil Nadu due to the lack of substratum onto which corals should be transplanted. Identifying and designing proper artificial substrates is a major factor for the success of direct transplantation. Initially, different artificial substrates such as stones, clay pots, ropes, metal structures, cement slabs, fish houses and concrete frames were tested for feasibility in the Gulf of Mannar. The first attempt was made in 2002 in Tuticorin Port area, in which stones, ropes, clay pots and cement slabs were used for direct transplantation of coral fragments. It was found that the rates of survival and growth were good on these substrates, but it was later realized that these substrates were not sturdy and not suitable for long-term sustainability. After the initial success, these substrates were affected severely by high amount of sedimentation due to their fragility, small size and their position close to the bottom. Smaller substrates such as stones, clay pots and ropes were not able to hold the fragments when they grow, and the substrates were found to tilt and fall off. Strong currents and waves also caused dislocation and tilting of substrates leading to reduced survival rate and mortality. Metal substrates were found to corrode over time and could not hold the growing fragments leading to coral mortality. Moreover, these substrates were not able to provide surface for natural coral recruitment and also could not provide shelter to reef-associated organisms. Based on the outcomes of initial experiments through the pilot projects, two types of substrates namely concrete frames and fish houses were finalized during 2003-04.

Artificial concrete structures have been reported to be highly successful in any underwater environment and concrete is generally very durable and stable to the seawater exposure. Concrete frames currently used in Tamil Nadu are made of ferro-cement with a size of 1 m × 1 m and a height of 25 cm weighing about 100–120 kg (Edward, 2018). These are flat square-shaped concrete structures provided with four longitudinal holes that are placed on four corner legs. Height of the frame is increased up to 30 cm at areas with high sedimentation. Along with these fames, cement slabs of 20 cm × 15 cm size are also usedfor attachment of coral fragments (Edward, 2018). Coral fragments are horizontally tied with nylon ropes or cable ties to the cement slabs and these cement slabs laden with fragments are then placed on concrete frames underwater. Earlier, cement slabs were altogether tied to concrete frames with nylon ropes. Later in 2018, a horizontal bulge was made under cement slabs so that they could be locked in the spaces provided in concrete frames to avoid dislodgement. In 2020, an attempt was made to replace nylon ropes with jute twines that are eco-friendly, but jute twine, due to its faster degradation, could not hold the transplants tight until they make firm attachment on substrates. Concrete frames are suitable substrates for newly settling coral larvae too and hence coral recruitment on these substrates is an addition. Gaps and holes in concrete frames enable fish and other organisms to find shelter.

There are several old buildings in Tuticorin that were built exclusively with coral heads, and dead corals can be gathered from these constructions when they are demolished for renovation. Fish houses were indigenously made with mined coral skeletons of massive corals availed from such demolished old residences. In this way, dead corals are brought back to the reef areas where they were mined from. The fish houses are circular in shape with 3–4 holes, a diameter of about 1 m and a height of 0.5 m and weigh 100–120 kg (Edward, 2018). The coral fragments are tied directly onto the surface of fish houses, and the holes are for fish to move in and out. However, the use of fish houses was discontinued in 2015 due to the lack of raw materials as most of the old buildings had already been renovated. Thus, concrete frames remain the only substrate used to restore corals in Tamil Nadu with proven success rate.



Concrete frame



Cement slab

Table 1: Feasibility evaluation of different coral restoration methods to find suitability in Tamil Nadu

Restoration technology	Pros	Cons	Suitability for restoration in Tamil Nadu
Direct transplantation	■ Less expensive ■ Most used method ■ Suitable for wide-scale restoration ■ Survival rate is comparatively high ■ Uses coral's natural asexual mode of regeneration ■ A low-tech method and can be carried out easily ■ Does not require heavy infrastructure	■ Often requires artificial substrates, which increases cost ■ Transplantation of smaller fragments compared to nursery-grown colonies might increase exposure to competition and predation.	As direct transplantation method is low-tech and comparatively low-cost, it is suitable for coral restoration in the degraded reef areas of Tamil Nadu. This method is highly suitable for wide-scale restoration for it does not require the establishment of any infrastructure. However, artificial substrates are required for transplantation of fragments in the reef areas of Tamil Nadu due to the bottom instability. This tested and proven method has been improved during the past two decades in Tamil Nadu.
Coral gardening	■ Suitable for wide-scale restoration ■ Survival rate is comparatively high ■ Evades initial coral mortality ■ Fragment size increased in nurseries cause faster growth rates when transplanted ■ Exposure to competition and predation is reduced with nursery grown corals ■ Uses coral's natural asexual mode of regeneration ■ In-situ nurseries can be cheap	■ Ex-situ nurseries are expensive ■ In-situ nurseries would ideally require calm and clear environment ■ Often requires artificial substrates, which increases cost ■ Potential bottleneck for genotypes/fragment that would survive if directly transplanted. ■ Both in-situ and ex-situ nurseries require continuous maintenance.	Coral gardening has been successful in areas with a calm confined water environment which is not the case in the reef areas of Tamil Nadu. Continuous maintenance of nurseries in the remote islands is not possible. Transplanting nursery-grown corals may not be successful due to high currents, sedimentation and other environmental factors prevailing in the reef areas of Tamil Nadu.
Micro-fragmentation	■ Helps in restoring slow growing massive corals ■ Helps in expediting the growth rate of restored corals	■ Expensive if it involves land-based facility	Micro-fragmentation is a very good method to restore slow growing massive corals in the reef areas of Tamil Nadu. However, the method needs to be experimented for feasibility in Tamil Nadu.
Sexual propagation	■ Helps to preserve the genetic diversity of the future coral reefs	■ Expensive ■ Still in experimental stage ■ Requires heavy infrastructure development	This method is still in the experimental stage and is very expensive. It requires heavy land-based infrastructure and also needs expertise which is currently not available in Tamil Nadu.

Contd...

Table 1: Contd...

Restoration technology	Pros	Cons	Suitability for restoration in Tamil Nadu
Larval enhancement	■ Useful in restoring populations of coral species with different life-history traits ■ Helps in areas with depleted larval supply	■ Expensive ■ Still in experimental stage ■ Requires heavy infrastructure development	This method is still in the experimental stage and is very expensive. It requires heavy land-based infrastructure and also needs expertise which is currently not available in Tamil Nadu. Moreover, larval supply through sexual reproduction is already sufficient in the reef areas of Tamil Nadu.
Substratum enhancement with electricity (Biorock)	■ Helps in faster growth rate	■ Expensive ■ Not suitable for wide-scale restoration ■ Requires frequent maintenance ■ Not suitable for areas with high waves and currents ■ Certain species of fish and other organisms move away from the electrical unit	This method requires advanced infrastructure and is expensive; further, it is not suitable for wide-scale restoration in Tamil Nadu. Provision of continuous electrical supply and regular maintenance are almost impossible as coral reef areas are remote in Tamil Nadu. Maintenance failure will eventually cause coral mortality. During cyclones and rough weather seasons, there is a high likelihood of the collapse of electrical units rendering the entire investment risky.
Substrate stabilization	■ Assists in natural coral recovery in a degraded reef with unstable substrata	■ Expensive ■ Not suitable for wide-scale restoration ■ Affects existing benthic organisms	Though substrate stabilization is required for the degraded reef areas of Tamil Nadu, this method is very expensive and is not suitable for wide-scale restoration in vast extent of degraded areas in Tamil Nadu.
Artificial reefs	■ Assists in natural reef recovery through asexual and sexual reproduction ■ Does not involve collection of natural coral fragments ■ Helps in restoring slow growing massive corals ■ Provides shelter to other organisms including fish	■ Expensive ■ Rate of coral biomass increase is comparatively slow if only dependent on sexual regeneration ■ Requires good larval supply through sexual reproduction	Deployment of artificial structures to enhance the natural reef recovery is a good option for the reef areas of Tamil Nadu; it has been in practice and proved to yield good results. However, the rate of biomass increase is comparatively slower as it depends primarily on the seasonality of coral sexual reproduction and subsequent recruitment. Moreover, this method is expensive.

Note: Information in the table is based on Boström-Einarsson et al. (2020) and on our own experience in the reef areas of Tamil Nadu.

Restored corals in the Gulf of Mannar
(*Acropora robusta*)

A scientific diver collecting coral fragments for transplantation

6

Procedures to execute coral reef restoration in Tamil Nadu

A scientific diver carrying out coral transplantation

Coral restoration is a highly laborious endeavour that requires professional scuba diving skills and scientific understanding of coral ecology and biology. Even though corals are calcareous, they cannot be considered as rocks or stones, for they are living animals and must be treatedas such throughout the entire restoration process. Small miscalculations or mistakes may cause the entire effort to fail. After two decades of experience in restoring corals in Tamil Nadu, several nuances have been understood, mistakes have been corrected and improvements have been made. The following are the guidelines to carry out coral restoration for the best and maximum outcomes in Tamil Nadu.

6.1. Selection of sites

6.1.1. Restoration site

After understanding the degradation drivers and setting clear objectives, the selection of a suitable restoration site is the first step in coral restoration for obtaining the desirable outcomes. While selecting a restoration site, it is important to bear in mind that corals can survive only in areas where environmental conditions are conducive to their growth, as corals, being delicate animals, might negatively respond to even small changes in environmental factors. To ensure such conditions, it is inevitable that the restoration site has a history of coral reefs and environmental conditions as similar as possible to the donor site. Hence,

degraded reef areas are the best to act as restoration sites. The presence of naturallyoccurring live corals at the restoration site indicates that the abiotic conditions required for restoration are suitable. It is not ideal to restore corals in an area where they do not naturally occur. The restoration site should be easily accessible and situated as close as possible to the donor site to reduce the duration of transportation.

Hydrodynamics of the restoration site is very important for the effort to be successful. The restoration area should preferably be protected against strong waves and currents to avoid tilting and dislodgement of substrates and coral fragments and for quicker attachment of transplants. Depth is another crucial factor for restoration. Most of the reef areas in Tamil Nadu are shallow, with a depth of less than 5 m and hence selecting a site within this depth range would enhance the success rate.

Water quality parameters such as salinity, pH, temperature and nutrient concentration must be taken into consideration, and selection should aim to provide an optimum for coral survival. In this context, the presence of reef areas, with healthy, thriving corals serves as natural indicator of suitable environmental parameters. The Tamil Nadu region naturally exhibits these optimal water quality conditions and is therefore ideal for the selection of degraded reefs as restoration site. The vicinity of the

Suitable restoration site

restoration site should be free from freshwater inflow from rivers or other sources, unless a natural reef with thriving corals occurs in the area, especially in the case of Palk Bay. Reef areas in the Gulf of Mannar are predominantly around the 21 islands and are hence naturally protected from such run-offs. If restoration is planned close to urban and/or industrial settlements such as in Tuticorin, the impact of

Table 2: Best practices for selecting a coral restoration site

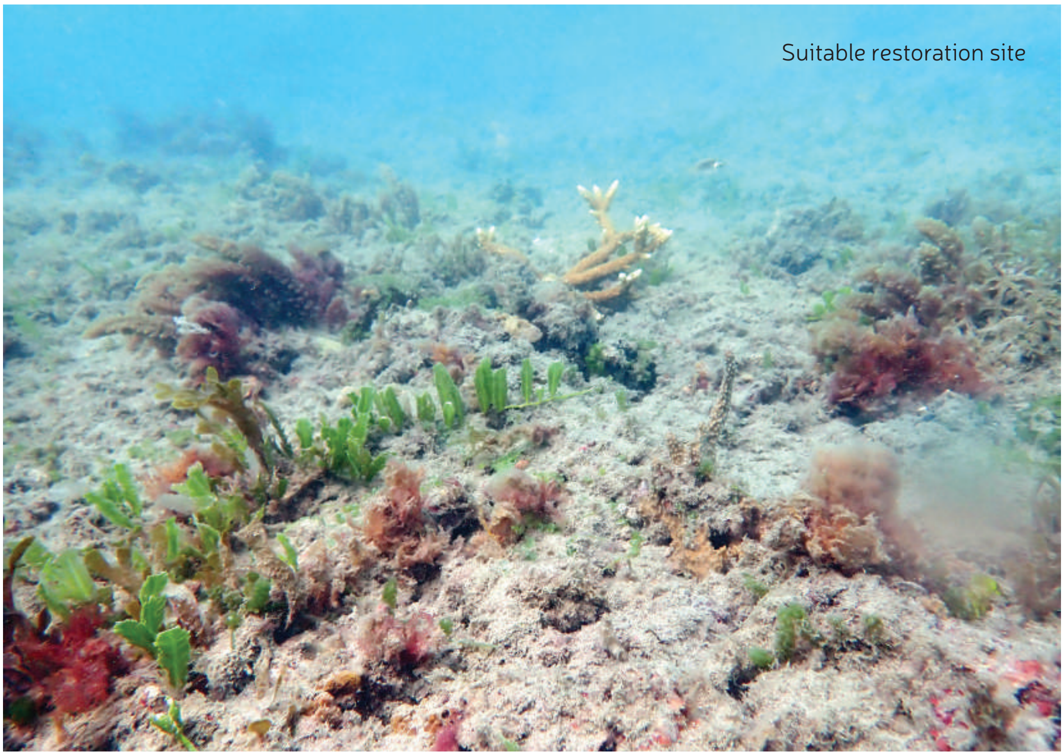
SHOULD DO	SHOULD NOT DO
■ The site should have a coral history ■ The site should have a few live corals ■ The site should be easily accessible ■ The site should be proximate to the donor site ■ The site should have occurrence of natural recruitment ■ The site should have ideal conditions for the successful application of the selected restoration technique ■ The site should have calm and suitable environmental conditions ■ The site should be away from pollution hotspots and freshwater runoffs ■ The site should be free from benthic space-competitors and coral predators ■ The site should be free from active fishing	■ The site should not be far from natural reef area ■ The site should not be far from the donor site ■ The site should not be covered with fleshy macroalgae, sponges or other space-competitors ■ The site should not be near pollution hotspots and freshwater runoffs ■ The site should not have high sedimentation rate and turbidity ■ The site should not be near active fishing area ■ The site should not be exposed to anchoring and other fishing-related mechanical damages

pollution should be assessed before finalizing the restoration site. Pollution hotspots such as areas proximate to sewage and industrial outlets should be avoided. Corals need relatively clear waters and hence sedimentation, turbidity, suspended solids and dissolved matter should also be taken into account before finalizing the site.

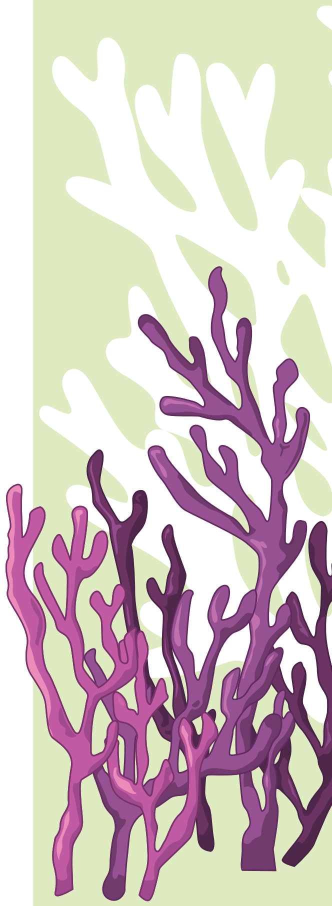
Due to climate change impacts, space competition among sessile benthic organisms is severe in the reef areas of Tamil Nadu. Hence, areas dominated by potent competitors such as fleshy macroalgae, bioeroding sponges and octocorals should be avoided while selecting a restoration site. Corallivorous organisms such as coral feeding fish, mollusks, crustaceans and echinoderms are reported here and hence areas with outbreaks of such organisms should be avoided. Areas with significant fishing activity should also be avoided due to the possibility of mechanical damage to substrates and transplants. Particularly, activities such as bottom set gill netting, bottom trawling, trap fishing and spear fishing can cause severe damage to restored corals. Fragmentation of corals and dislodgement, tilting and burial of substrates can take place due to these fishing activities leading to mortality or reduced survival rate.

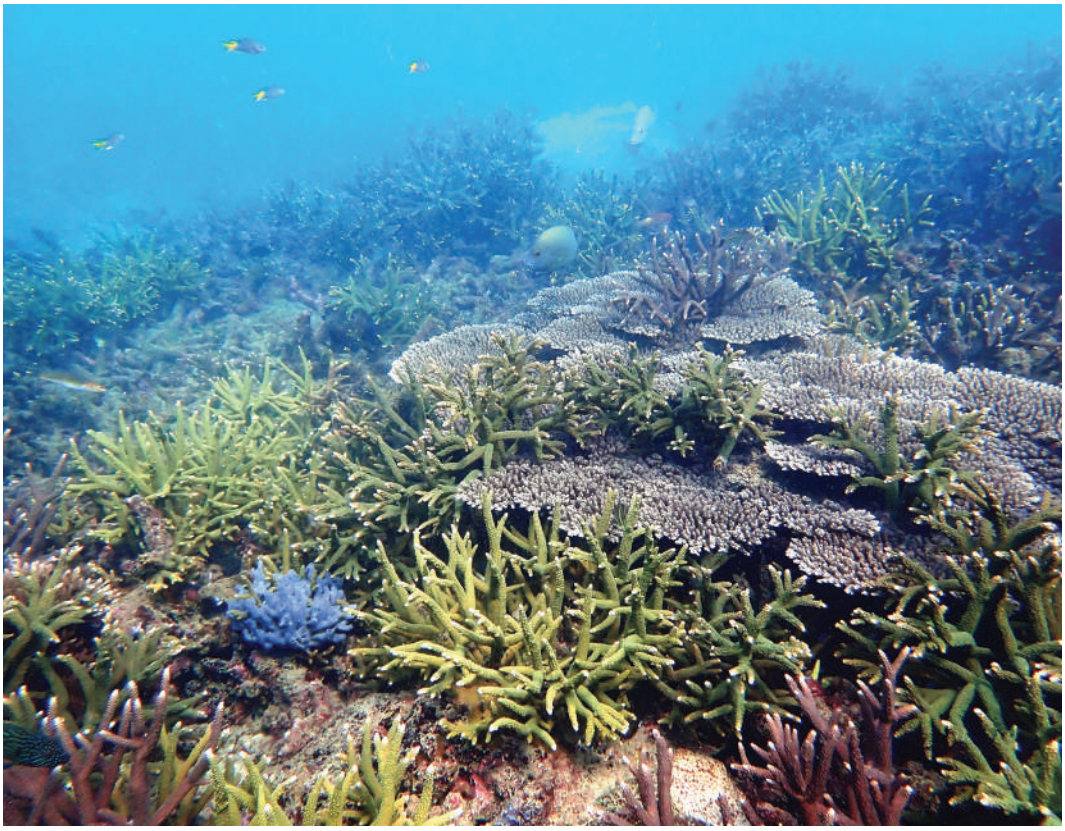
6.1.2. Donor site

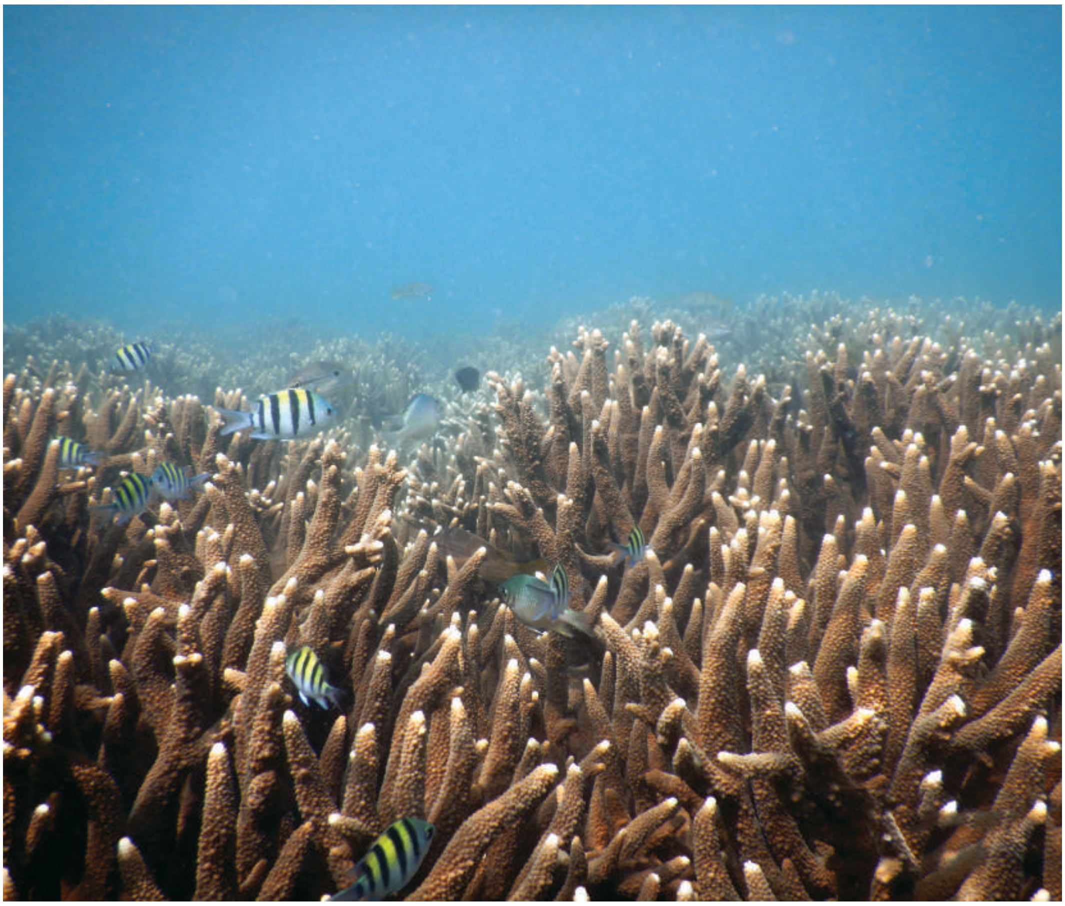
Donor site should ideally be a nearby reef area with relatively healthy corals. As regular underwater assessments and monitoring are currently carried out in the reef areas of Tamil Nadu, such potential donor sites have already been identified by SDMRI. However, an initial underwater inspection should be carried out at potential donor sites to evaluate their status prior to the restoration. A reef with donor potential should be found as close as possible to the proposed transplantation site, not more than 10 nautical miles and should be reached within 30 min by boat to minimize the stress of the coral fragments caused by long transport. Substantial live coral cover is a sign of reef health which is important for the donor site. A minimum of 30% of live coral cover should be available at the



Suitable restoration site







Suitable donor sites

Table 3: Best practices for selecting a donor site

SHOULD DO	SHOULD NOT DO
▪ The site should have healthy corals ▪ A minimum of 30% of live coral cover should be there in the site ▪ The site should have availability of the target species ▪ The site should have availability of corals of opportunity (e.g., naturally broken) ▪ The site should have a high number of adult colonies of the target species for fragment collection ▪ The site should be proximate to the restoration site ▪ The site should be free from bleaching, disease outbreak, benthic space-competition and predator attack	▪ The site should not be far away from the restoration site ▪ The site should not be affected with bleaching, disease outbreak, benthic space-competition and predator attack

donor site in order to supply fragments for restoration. The site should be devoid of any disease outbreak so that no disease is carried to the restoration site. The site should also be devoid of potential predators.

6.1.3. Control and reference sites

To compare and evaluate the success of restoration, a control site and a reference site should be selected in the vicinity of the restoration site. The control site should be fixed in a nearby degraded area where conditions are similar to that of the restoration site but without restoration interventions. This is to understand the difference in the rate of recovery between the site with intervention and the site left as such. It is anticipated that the restoration site will fare better in terms of coral recovery and this will be important to showcase the success of restoration. If the recovery is not fast enough in the restoration site, the underlying factor should be identified and rectified when selecting the site next time. A reference site should also be selected close to the restoration site to get information on species and morphotypes to be targeted and also to understand the pattern of transplantation.

6.1.4. Baseline assessment

Both the restoration site and the donor site should be assessed properly before carrying out any activity. It is important to understand the status of restoration site beforehand to monitor the changes generated by the restoration efforts. Hence, a thorough underwater assessment needs to be carried out before deploying the artificial substrates. Parameters that need to be assessed include benthic cover, coral density, species distribution, recruitment status, availability of associated organisms and environmental characteristics of seawater. Standard international underwater protocols should be followed for all the assessments. All the assessments should be carried out by scientific divers with expertise on underwater monitoring.

Benthic cover of the selected restoration site should be assessed using line intercept transect method that will estimate the covers of prevailing live corals and other benthic categories such as algae, octocorals, crustose coralline algae, abiotic components and others. This is very important as it is anticipated that coral cover in the area will increase considerably after the restoration. The density of coral colonies should be assessed using


Baseline assessment

Table 4: Best practices for baseline assessment

SHOULD DO	SHOULD NOT DO
■ Baseline assessment should be done before the deployment of substrates ■ Parameters needing assessment should include benthic cover, coral density, species distribution, recruitment status, availability of associated organisms and environmental characteristics of sea water ■ Standard international underwater protocols should be followed for all the assessments ■ Scientific divers with experience in underwater protocols should carry out the assessments	■ This is a baseline assessment and hence should not be carried out after the deployment of substrates or after transplantation ■ Assessments should not be carried out by recreational divers or fishermen

belt transect method as it will indicate the increased density after the restoration. Likewise, species distribution should also be assessed as more species will be added through natural recruitment on artificial substrates. Coral recruit density should be assessed using quadrat method as this will also increase in the restoration site through natural sexual recruitment and asexually through fragmentation from restored coral colonies.

Physical, chemical and biological characteristics of seawater should be analysed to understand the impact of coral restoration on water quality of the site. As the coral cover increases in the restoration site, it is anticipated that the abundance of associated organisms will also increase. Hence, fish abundance in the restoration site should be assessed using belt transect method before initiating the restoration. Likewise, the density of benthic macrofauna should also be assessed using quadrat method before the restoration.

6.2. Selection of species

Species selection for coral restoration is also very critical as the species involved should increase the live coral cover in the restoration site to enhance the associated benefits. Species selection is totally a science-based approach and hence should be done by reef researchers. For the restoration effort to be successful and not to be problematic, transplantation should always be carried out using native coral species. Native species are well acclimatized to the local environmental conditions and have the highest chance for survival after transplantation. As restoration and donor sites are selected adjacent to each other, environmental conditions of these sites are also similar and thus fragments collected

Table 5: Best practices for selecting species for coral restoration

SHOULD DO	SHOULD NOT DO
■ Native species should always be selected for restoration ■ Species selection should be carried out by reef researchers who have expertise in coral restoration ■ Species should be selected from the nearby donor site ■ Heterogeneity should be maintained when selecting species ■ Genetic diversity must be prioritized ■ Species that are resistant to bleaching events and disease outbreaks should be preferred ■ Fast growing species such as *Acropora* and *Montipora* should be preferred for better survival and growth	■ Species from far-off places should not be selected ■ Species selection should not be done by recreational divers or fishermen ■ Restoration should not be done with single species ■ Slow growing massive coral species can be added only in small amounts

from native species from the donor site will moreeasily get acclimatized to the conditions of the restoration siteas transplants.

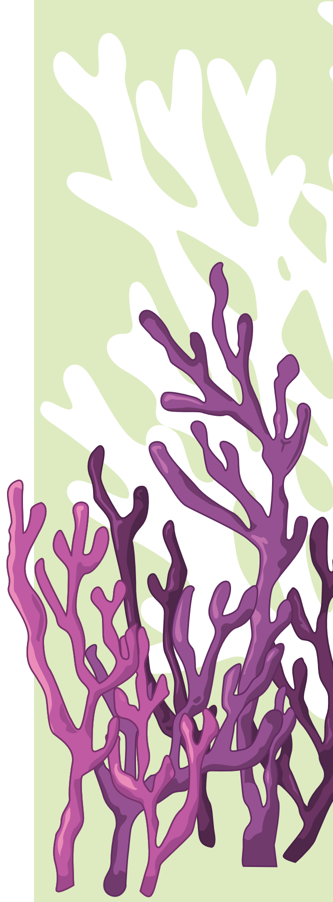
Species from different reef areas may not survive in the restoration sites where prevailing environmental conditions are different. If these transplants survive in the new environment, there is a high likelihood that these species will become weedy and invasive leading to the loss of native species. Thus, cross-transplantation between different reef areas will either cause the restoration effort to fail or will cause the invasion of new species. Hence, this is another reason for using native coral species in any restoration effort in Tamil Nadu.

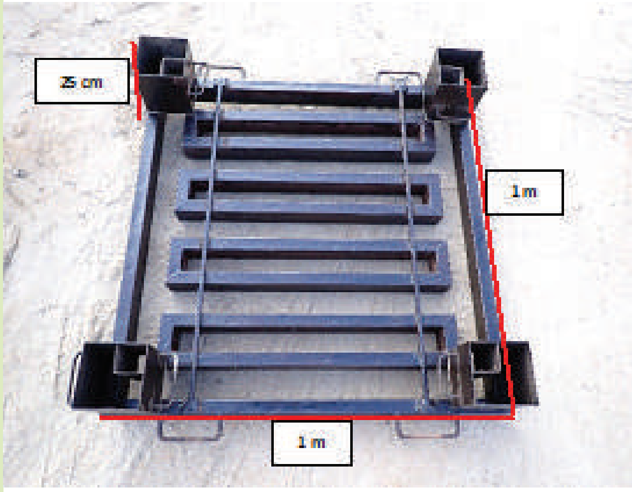
The selected species should be abundant in the donor site so that the biomass of the species in the donor siteis not affected. Restoration should not be carried out with just one species for it may cause monospecific strands leading to the reduction of other species. Heterogeneity should be maintained when selecting species to conserve the integrity of reef environment. In addition, genetic diversity must be prioritized by collecting fragments from colonies spaced apart (e.g., 50 to 100m), or from opposite sides if collection is executed on a monospecific patch. Species that are generally resistant to bleaching events and disease outbreaks should be preferred to achieve maximum results in the long-term.

Different coral species grow with different morphotypes and among them, branching, tabular and digitate growth forms are fast-growing and suitable for asexual regeneration through fragmentation. Thus, fast-growing species such as *Acropora* and *Montipora* are the most preferred coral genera for restoration in the reef areas of Tamil Nadu. This is followed by species with foliose and cup growth forms like *Turbinaria* and *Echinopora*, which can also be transplanted in smaller amounts. Massive corals are generally slow growing and are not suitable for fragment transplantation and hence massive coral species such as *Porites, Dipsastraea, Favites,* etc. can be added in the restoration effort in very small amounts to maintain heterogeneity.

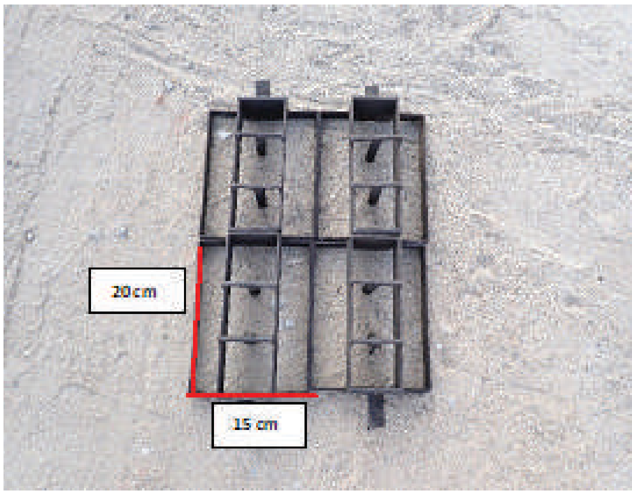
6.3. Construction of artificial substrates

The construction of substrates should be carried out by skilled construction workers in order to achieve strength and durability.





Mould for the construction of concrete frames



Mould for the construction of cement slabs (for four slabs)

Construction of concrete frames

Construction of cement slabs

Table 6: Best practices for the construction of substrates

SHOULD DO	SHOULD NOT DO
■ Construction should be carried out by skilled construction workers ■ The substrates should be constructed using reinforced concrete of M25 grade ■ Reinforcement steel of 8 mm of Fe 500 grade should be used ■ The mix proportion should be 1:1:2 (cement: sand: coarse aggregate) with water for concrete frames ■ The mix proportion should be1:5 (cement: sand) with water for cement slabs ■ Moulds with prescribed dimensions should be prepared beforehand ■ Concrete should be placed properly and carefully ■ Excessive concrete should be removed and the surface should be checked for uniformity ■ Curing should be initiated after the initial setting within 24 hours of placement. ■ Curing with water should be carried out for 28 days	■ Uneven surfaces should not be used to place the moulds ■ The dimensions of moulds should not be compromised ■ Concrete should not be poured from excessive heights ■ Concrete should not be spilled out of the mould area ■ The proportion of materials should not be compromised ■ Curing frequency and length should not be compromised

The construction of concrete frames should be done using reinforced concrete of M25 grade with careful control of materials, placement procedures, and curing practices to ensure adequate strength of 25 MPa, durability, and dimensional stability underwater. Ordinary Portland cementshould be used along with clean, well-graded fine sand and crushed angular coarse aggregate. Freshwater should be used for mixing and curing. Reinforcement steel of 8 mm of Fe 500 grade should be provided as per structural design requirements, which offers essential tensile strength and resistance to ocean currents and wave action. The mix proportion of 1:1:2 (cement: sand: coarse aggregate) should be adopted with water. This proportion ensures sufficient strength while maintaining workability suitable for placing concrete within the confined ribs of the coral frame.

The first thing to do is to prepare a mould using steel as per the dimensions required for the concrete frame. One big mould of 1X1 m with gaps should be constructed and four smaller moulds for legs should also be constructed with steel. Reinforcement bars should be properly tied and placed using appropriate cover blocks within the mould and then the concrete should be placed. Concrete should be mixed using a mechanical mixer to ensure uniformity. Materials required for concrete mixture should be batched accurately, and mixing should be continued for at least 1.5 to 2 minutes after the addition of water until a homogeneous mix with uniform colour and consistency is obtained.

The mould should be properly positioned, aligned, and securely fixed to prevent displacement during concreting. Concrete placing should be carried out immediately after mixing. Care should be taken to prevent leakage of cement slurry, and shuttering oil should be applied uniformly on the contact surfaces to facilitate easy removal after setting. The concrete should be placed gently into the mould in layers to avoid segregation. Placement should begin from one corner and should proceed systematically to ensure that all ribs and cavities of the mould are completely filled.

Care should be taken to avoid dropping the concrete from excessive heights, and no additional water should be added. Compaction should be performed to eliminate entrapped air and achieve dense concrete. After placing the concrete within the bigger mould, leg moulds are placed on respective corners and concrete is placed in them. Excess concrete should be removed and the surface should be checked for uniformity. Curing should be initiated after the initial setting of concrete, typically within 24 hours of placement. The newly constructed concrete frames are watered to retain moisture for 28 days. Placing jute bags over the substrate would help in retaining the moisture for a long time.

Moulds for cement slabs should also be prepared beforehand. Cement slabs should be prepared with a cement mortar of 1:5 (cement: sand) with water. Cement mortar should be prepared using a mechanical mixer to ensure uniformity. The mould should be placed in levelled surface and oil should be applied uniformly on the inner sides of the mould. Then, cement mortar should be placed carefully and the excessive mortar should be removed. Curing should be initiated after the initial setting of cement, typically within 24 hours of placement and continued for 28 days.

6.4. Transportation of substrates

6.4.1. Transportation of substrates from the construction site to the sea shore

As each concrete frame weighs more than 100 kg, transportation is highly laborious. The first part of transportation consists in moving the constructed substrates to the seashore adjacent to the restoration site. Trucks, tractors and any other load vehicles can be used for such transportation. Substrates need to be lifted from the construction site very carefully by sturdy labours or by a crane. In either way, it should be made sure that the constructed substrates are not mechanically damaged. Particularly, the legs of the concrete frames should not be damaged for they are comparatively the weakest part in the substrate.
Therefore, when lifting, the substrates should not be lifted with legs. It is to be made sure that concrete frames are arranged on load vehicles in proper order so that movement and friction are avoided during transportation. Unloading on the seashore should also be carried out carefully with labours or a crane. Placement of substrates should be made on a flat surface on the shore beyond the high tide line. Proper arrangement on the shore is also important so that substrates do not fall

Table 7: Best practices for transporting the substrates from the construction site to the seashore

SHOULD DO	SHOULD NOT DO
■ Heavy vehicles such as trucks and tractors should be used for transportation	■ Care must be taken not to damage the substrates while lifting
■ Sturdy labourers should be employed or a crane should be used for loading and unloading of the substrates	■ Arrangement of substrates on the vehicle should not damage them during transportation
■ Arrangement of substrates on the vehicle should be proper	■ Utmost care should be taken not to damage the legs of substrates during the entire transportation process
■ Transported substrates should be placed on a flat surface on the shore beyond the high tide line	

Transportation of substrates from the construction site to the sea shore off and get damaged mechanically.

6.4.2. Transportation of substrates from the seashore to the restoration site

From the seashore, substrates need to be carried to the restoration site. Again, with the help of labourers, or a crane, substrates should be lifted and placed on a wooden raft or barge or directly onboard a boat. The selection of a conveyance means may be according to availability, geographical setting of the shore and remoteness of the area. For instance, a barge can be used in restoration activities carried out near Tuticorin where it is readily available. In some far-off sites with flatter intertidal areas, a raft made of wooden poles and empty barrels can be used. In sites where the intertidal area is rugose and with a near-shore reef, wider boats can be used for transporting substrates to the restoration site. Dur-

Transportation of substrates from the shore to the restoration site by boat

Transportation of substrates from the shore to the restoration site by barge

Table 8: Best practices for transportingthe substrates from the seashore to the restoration site

SHOULD DO	SHOULD NOT DO
■ A wooden raft or barge or boat should be used for transportation ■ Sturdy labourers should be employed or a crane should be used for loading the substrates ■ Transportation should be carried out during calm weather seasons ■ The shortest possible path to the restoration site should be selected ■ Early morning transportation is suggested to avoid rough weather	■ Care must be taken not to damage the substrates while lifting ■ Transportation should be avoided during rough weather seasons ■ Collision with other boats, entanglement withfishing nets, and grounding at shallow reef areas should be carefully monitored and avoided

ing the loading care should always be taken not to damage the substrates.

Transportation of substrates should generally be carried out during the calm season for rough seas will make the transportation difficult. The shortest possible path to the restoration site should be chosen while transporting the substrates. In the case of barge and raft, a motorized boat should be used to tow them to the site. While sailing, it should be ensured that the substrates are intact and do not fall off. It is always advisable to carry out transportation in the early morning for the sea is generally calm at that time. The people who carry out transportation should be highly vigilant against possible collision with other boats, entanglement with fishing nets, and grounding at shallow reef areas.

6.5. Deployment of substrates

At the restoration site, concrete frames are placed on the sea floor with the help of ropes tied with concrete frames. If sites are wavy and rough, substrates can be pushed down from the raft, barge or boat to carry out the work faster. Before a substrate is pushed into water, it should be tied with a small nylon rope and a buoy in order to find them underwater easily. These buoys can be removed later when the frames are properly arranged underwater. It is always good to deploy the substrates in clusters for it will help the associated organisms to easily find shelter and it will also be easier for post-restoration maintenance and monitoring. The site of each cluster should be marked with a GPS to find them easily. The substrates should not be deployed far from each other, making it difficult to find them underwater.

After deploying the substrates at the restoration site, scuba divers should get into water immediately to check the status of deployed substrates. Some substrates might have fallen upside down, tilted or vertical, which need to be arranged in proper order underwater. There is a possibility of mechanical damage during the deployment such as the breakage of legs of substrates. If one or two legs of a substrate are broken, it is still possible to carry out transplantation on them if they are made to stand horizontally. Frames should be arranged underwater with an interval of 1 to 2 m from each other allowing room for coral growth without congestion and also to provide space for natural asexual reproduction through fragmentation.

After arrangement underwater, the frames can be numbered or tied with each other with ropes for continuous maintenance and monitoring. After the deployment of

Deployment of substrates in the restoration site

Table 9: Best practices for the deployment of substrates in the restoration site

SHOULD DO	SHOULD NOT DO
■ When deploying the substrates, care must be taken not to damage them ■ All substrates should be tied with a rope and buoy to find them easily ■ Substrates should be deployed in clusters ■ Each cluster should be marked with a GPS ■ Scuba divers should go underwater to properly arrange the deployed substrates ■ Substrates that fell upside down, tilted and vertical should be arranged in proper horizontal order ■ Substrates should be arranged underwater with an interval of 1 to 2 m from each other	■ Care must be taken not to damage the substrates while transferring them from the raft / barge / boat ■ All substrates should not be dumped at one place and should also not to be deployed very far from each other ■ Substrates that fell upside down, tilted and vertical should not be left as such

substrates, transplantation can be carried out on a different day when the water is calm and visible.

6.6. Collection of fragments

Coral restoration aims at restoring the degraded reef sites and hence collection of fragments from the donor site should not in any way degrade it. Collection and transportation of collected fragments, tying them onto cement slabs, and placing the slabs on concrete frames all should be carried out within a few hours in order to obtain the best survival rate. Collection of fragments should, therefore, be done in the early morning so that the whole work can be completed before the sea gets rough. If collected fragments are transplanted the next day, the survival rate will be compromised. Collection of fragments should strictly be carried out by scientific divers who have ample knowledge on coral ecology and biology. The scientific diver who collects fragments should be aware of collection protocols, target species and genotypes. Without a basic understanding of coral taxonomy, a diver might possibly damage coral species that are rare or endangered. It is also important to note here

Table 10: Best practices for the collection of fragments for coral transplantation

SHOULD DO	SHOULD NOT DO
■ Collection of fragments should strictly be carried out by scientific divers who have ample knowledge on coral ecology and biology ■ The direction of collection should start opposite to the current direction so that return to the boat with the fragment-filled basket will be easy and safe. ■ Utmost care must be taken during collection not to damage non-target corals or other organisms ■ Collected fragments should be put in plastic baskets or wire meshes in a gentle manner ■ Collected fragments should be brought to the boat as soon as possible	■ Recreational divers or fishermen should not be involved in the collection of fragments ■ Smaller colonies less than 30 cm in diameter should not be collected ■ Uprooting an entire colony should not be done and multiple fragments of the same colony should also be not collected. ■ The collection of fragments from a colony should not exceed 5% of the colony size ■ Coral colonies with visible gametes should not be fragmented ■ Branches with injuries, predation lesion, bleaching, etc. should not be collected

Collection of coral fragments

that corals are animals and we are dealing with live wild animals. The direction of collection should start always opposite to the direction of the sea current so that return to the boat with the fragment-filled basket will be easy and safe.

While collecting fragments, smaller colonies, with 30 cm or less in diameter, should be avoided to reduce mortality. Uprooting an entire colony should be avoided in any case and multiple fragments of the same colony should also be not collected. The collection of fragments from a colony should in any case not exceed 5% of the colony size. If donor colonies are loaded with visible gametes, those colonies should be strictly avoided. A hammer and chisel should be used for the fragmentation of donor colonies underwater. Utmost care must be taken while using these tools underwater so that other colonies at the site are not mechanically damaged. Branches with injuries, predation, bleaching, etc. should not be collected for such defects will compromise the survival percentage in the restoration site. Collected fragments should be put in plastic baskets or wire meshes in such a way that they do not collide too much with one another. Collected fragments should be immediately brought to the boat for further process.

6.7. Transportation of collected fragments

Precision and care should be taken during the transportation of fragments from the donor site to the restoration site. On the boat, collected fragments should be immediately transferred to big plastic tubs with seawater and should be given aeration with portable aerators. The tubs should contain water collected from the donor site in order to ensure similar environmental conditions for the collected fragments. Fragments should not be thrown into tubs; instead, they must be put gently keeping in mind that they are live animals. The plastic tubs with coral fragments should be covered by white cloth to avoid direct sunlight. A good indicator for the stress levels of fragments is the mucus production by the polyps. Sea water in the tubs should be changed at regular intervals in order to reduce the stress. Change of water must be done very carefully by pouring the water along the side of the tubs rather than directly on the corals. An expert with scientific knowledge on coral ecology and biology should oversee the entire process.

Table 11: Best practices for the transportation of collected coral fragments

SHOULD DO	SHOULD NOT DO
■ Collected fragments should be immediately transferred to big plastic tubs with seawater and should be given aeration with portable aerators ■ Tubs should be filled with seawater collected from the donor site ■ Collected fragments should be put gently into the tubs ■ The tubs with coral fragments should be covered by white cloth to avoid direct sunlight ■ Seawater in the tubs should be changed at regular intervals in order to reduce the stress ■ Change of water should be done carefully by pouring the water along the side of the tubs ■ An expert with scientific knowledge on coral ecology and biology should oversee the entire process	■ Collected fragments should not be exposed to direct sunlight ■ Fragments should not be thrown into tubs ■ When changing seawater, it should not be directly poured on to corals

Transportation of coral fragments

6.8. Tying of fragments with cement slabs

Tying of the coral fragments to cement slabs should be done during the transportation on the boat to reduce the transplantation time. Before the fragments are tied, the ferro-cement slabs should be washed thoroughly with seawater. Collected coral fragments must be gently taken from the tubs and further fragmented to desirable sizes using a bone cutter. Fragments sized 8 to 12 cm have provided maximum results in Tamil Nadu.

Sizing of fragments can be done preferably within the water tubs. During sizing, any attached predator or space competing organism should be removed from the fragments.

The sized fragments should be tied with washed cement slabs in a horizontal orientation. Horizontal orientation is important to provide fragments with maximum attachment space. The largest part of the fragment should be in contact with the substrate and most of the polyps

Table 12: Best practices for the tying of fragments with cement slabs

SHOULD DO	SHOULD NOT DO
▪ Tying of the coral fragments with cement slabs should be done during the transportation on the boat to reduce the transplantation time ▪ Before the fragments are tied, cement slabs should be washed thoroughly with seawater ▪ Collected coral fragments must be handled gently throughout the process ▪ Collected fragments should be further fragmented to desirable sizes (8 to 12 cm) using a bone cutter. ▪ Any attached predator or space-competing organism should be removed from the fragments. ▪ Fragments should be tied with washed cement slabs in a horizontal orientation. ▪ Largest part of the fragment should be in contact with substrate ▪ Tying of the fragment with the cement slab should be done with a nylon rope on a cable tie. ▪ Tying of fragments with slabs should be very strong ▪ Tying should be done very fast as it keeps the fragments out of the water. ▪ Cement slabs with tied coral fragments should be kept in fresh seawater tubs ▪ Tied up fragments should be rushed to the restoration site as fast as possible. ▪ All remnant pieces of collected fragments irrespective of sizes must be used before finishing the process ▪ An expert with scientific knowledge on coral ecology and biology should oversee the entire process	▪ Collected coral fragments should not be handled roughly ▪ Coral fragments should not be exposed to direct sunlight as it will reduce the survival rate ▪ Tying of fragments with slabs should not be loose ▪ Vertical placement of fragments on slabs should be avoided ▪ Tied up fragments should not be put in trays in a way that they are constantly in friction with other fragments or slabs ▪ Collected fragments should not be wasted without being transplanted onto slabs

Tying of fragments with cement slabs

should be oriented upward in vertical position. Tying of the fragment to the cement slab is very critical for better survival. A nylon rope or a cable tie can be used for tying. The tying should be firm to withstand strong waves and currents. Firm tying makes the attachment easier for transplants. Biodegradable materials such as jute twines can be used, but they are not durable and cannot last until the fragment makes the attachment onto the substrate. Underwater glues can also be used instead of tying. When tying, rough handling of fragments should be avoided. Tying should be very fast as it keeps the fragments out of the water. Only one fragment is generally attached to each slab, however, if the attachment is loose, another fragment can be inserted to make the attachment firm.

Cement slabs with tied coral fragments should be kept in fresh seawater tubs and be rushed to the restoration site as fast as possible. It is recommended to place heavy and sturdy fragments first in the tubs followed by the more fragile ones on top. Remnant smaller fragments, if any, should also be attached to fresh cement slabs altogether, in order not to waste even the smallest of fragments. At any case, fragments should not be exposed to direct sunlight as it will reduce the survival rate. An expert with scientific knowledge on coral ecology and biology should oversee the entire process.

6.9. Underwater fixing of cement slabs with coral fragments

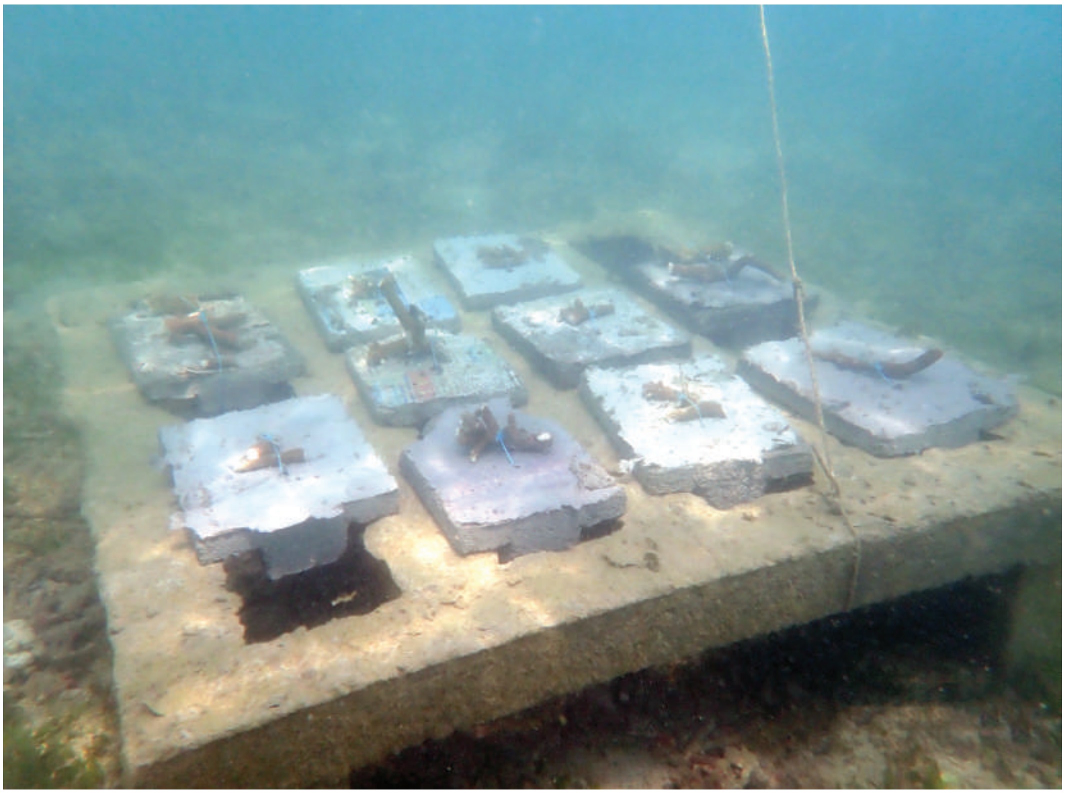
After reaching the restoration site, cement slabs with transplanted coral fragments should be immediately taken underwater to place them on the concrete frames previously deployed. Attachment of fragments with cement slabs should be checked manually for firmness and the checked slabs should be properly arranged in a plastic tray and taken under the water by skilled scuba divers. If the water depth is less than 2 m, snorkelling or free diving can also be employed to transport them from the boat to the concrete frames. If the boat cannot reach the restoration site due to low tide or other reasons, it should be anchored at the nearest point and trays with slabs can be transported with floating buoys to the restoration site.

Before taking the slabs with fragments underwater, the divers should locate the cluster of deployed concrete frames. If frames are already occupied by any other benthic organisms such as algae and sponges, they must be removed before bringing the coral fragments. If there are any sessile coral predators such as snails and starfishes, they must be removed from the frames. Before bringing the transplanted fragments, it should also be ensured that no frame is tilted, buried or dislodged.

When taking the slabs with coral fragments underwater, the diver should maintain proper buoyancy in order not to handle the fragments roughly.

After reaching the bottom, the diver should carefully take the slabs out one by one and place them properly on concrete frames. The hump under the cement slabs should properly be seated within the gap provided in concrete frames. A total of 10 to 12 cement slabs can be placed on each frame with a gap of approximately 5 cm.

After arranging the slabs on frames, they must be manually checked for sturdiness so that they are not moved by waves and currents.

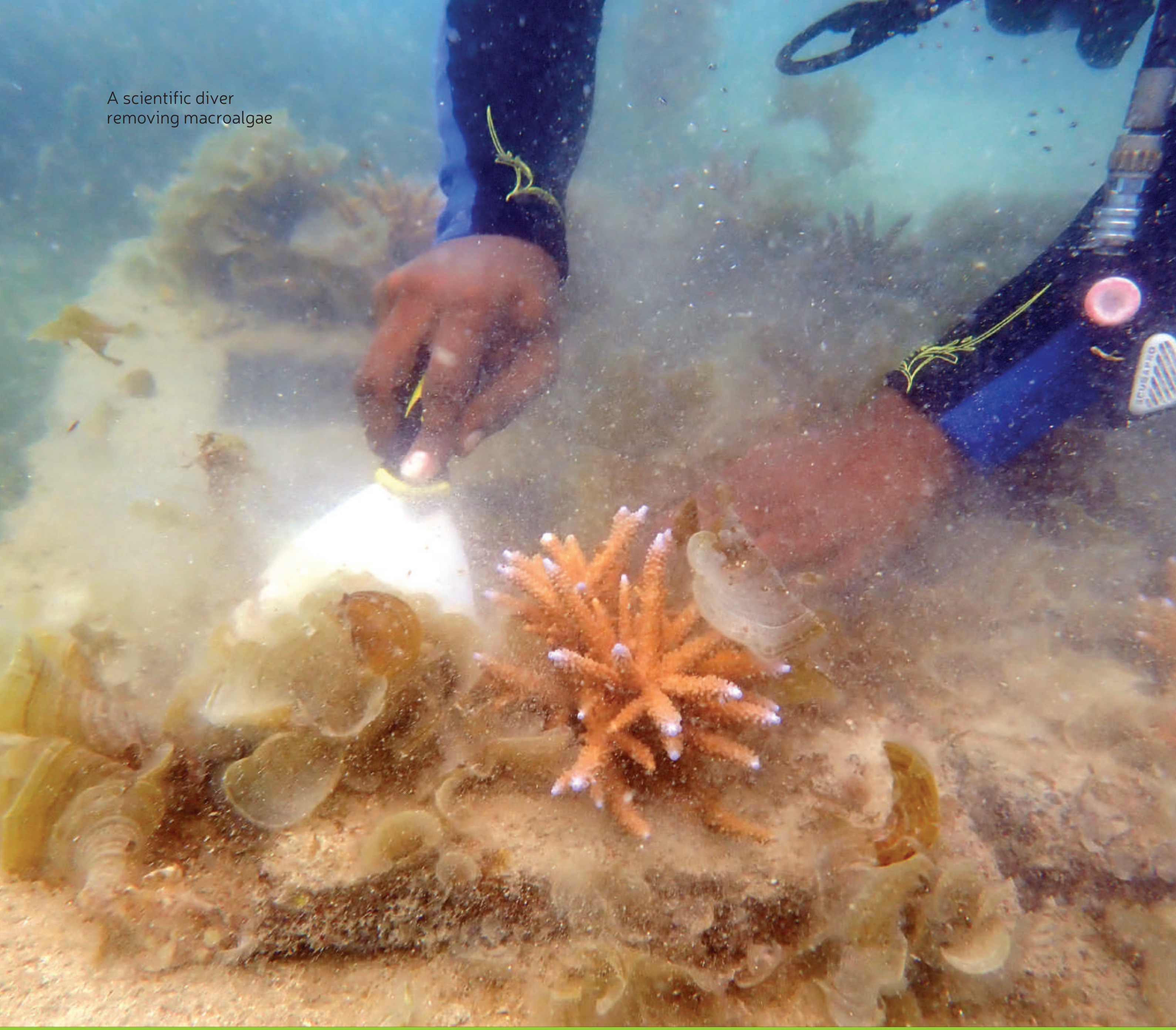


Underwater fixing of cement slabs

Table 13: Best practices for the underwater fixing of cement slabs with coral fragments

SHOULD DO	SHOULD NOT DO
■ Before taking the slabs with fragments underwater, scuba divers should locate the cluster of deployed concrete frames ■ If frames are occupied by any other benthic organisms, they must be removed before bringing the coral fragments ■ If there are any coral predators in the deployed frames, they must be removed ■ Tilted, buried and dislodged frames should be adjusted before bringing the transplanted fragments ■ Cement slabs with transplanted coral fragments should be immediately taken into the water without wasting time ■ Slabs with fragments should be properly arranged in plastic trays and should be taken under the water by skilled scuba divers ■ Before fragments are taken into water, attachment of fragments with cement slabs should be checked for firmness ■ The divers should maintain a proper buoyancy to handle the fragments gently ■ Under the water, slabs should be properly and carefully arranged on concrete frames ■ The hump under the cement slabs should properly be seated within the gap provided in concrete frames ■ A total of 10 to 12 cement slabs should be placed on each frame with a gap of approximately 5 cm ■ After arranging the slabs on frames, they must be checked for sturdiness	■ Fragments tied to cement slabs should not be handled roughly ■ After the tying of fragments, time should not be wasted before taking them underwater ■ The deployed frames should not have space competitors or predators ■ The deployed frames should not be tilted, upside down, buried or vertical ■ Divers who are not able to maintain proper buoyancy should not be involved in this process ■ Fragments with loose tying should not be taken underwater ■ Slabs with fragments should not be left as such if the hump of the slab is not seated properly within the space provided in the frame

Restored corals in the Gulf of Mannar (*Acropora* spp.)



A scientific diver removing macroalgae

7 Maintenance

Coral restoration does not end with the process of carefully transplanting corals onto artificial substrates. It can be considered as half of the work done. Proper and regular maintenance of transplants is of critical importance. A minimum of three years of maintenance is warranted to get best possible outcomes from the restoration effort. Otherwise, survival and growth rates of transplants would be severely compromised. Maintenance should be carried out by scientific divers with expertise in coral ecology and biology. Generally, maintenance is carried out duringthe monthly monitoring but it is preferable to increase the frequency for the first two months. This is the critical period when the transplanted fragments are delicate and need proper maintenance. Hence, weekly maintenance is advised for the first two months.

7.1. Removal of macroalgae

Marine macroalgae can attach to the artificial substrates and due to their faster growth rate they may exponentially grow, invade and suffocate the growing transplants and kill them. Coral-algal phase shifts are possible even in the natural reef environment as reported from many reef regions. Corals of Tamil Nadu have also been reported to be affected by this macroalgal growth when they are heat-stressed. Certain species of algae such as *Padina* spp., *Lobophora variegata,*

A scientific diver carrying out maintenance work

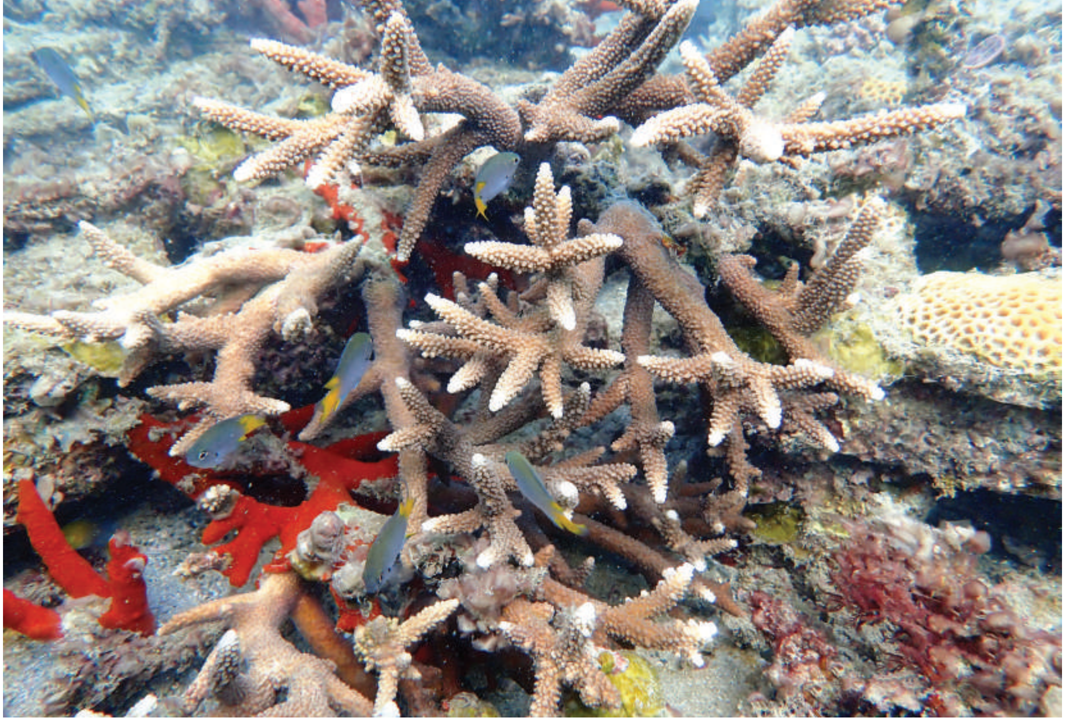
Sargassum spp., and *Caulerpa* spp. are predominantly seen overgrowing at restoration sites in Tamil Nadu. These algae take up the space on the substrates and hinder the transplants' growth. Abrasion caused by algae results in mechanical damage to corals leading to predation and disease infection. Moreover, these occupying algae, by taking up all the available space, rule out the possibility of natural coral recruits to attach on substrates.

Table 14: Best practices for the removal of overgrowing macroalgae from the artificial substrates and transplants

SHOULD DO	SHOULD NOT DO
■ Regular monitoring should be in place to quickly identify the problem of macroalgae overgrowth ■ Macroalgae overgrowing on artificial substrates need to be removed by scientific divers ■ The removal should be carried out using scrappers ■ Utmost care should be taken not to damage the transplants while scraping macroalgae	■ Coral transplants should not be damaged in the process of removing macroalgae ■ Holdfasts of algae should not be left as such in order to stop faster regeneration of algae

Transplants overgrown by macroalgae (*Acropora muricata*)

Removal of macroalgae *(Acropora robusta)*



Overgrowth of the sponge *Clathria* sp. on restored *Acropora muricata*

It is thus important tofrequently look for such proliferation of algae. Algae can bloom within a short time and before they perish may cause damage to restored corals. Algae on the substrates should be removed by scrapping them off by scrappers. Scraping of algae should be carried out carefully so that transplants or coral recruits if any are not damaged. Holdfasts of the algae should be uprooted so that they will not grow from them again. There is no specific periodicity for algal removal and it should be carried out as and when required.

7.2. Removal of other benthic space competitors

Apart from algae, there are several other benthic organisms that can compete with corals for space; they include sponges, octocorals, zoanthids, and ascidians. These competitors can grow over the substrates or transplants affecting the survival and growth of corals. Among these epibenthic organisms, marine sponges have become a significant space competitor to the corals of Tamil Nadu during the past decade. Certain sponge species like *Cliona* spp., *Clathria* spp. and *Terpios hoshinota* have become a menace to corals as these can grow fast and kill corals within a short time. Hence, these need to be scrapped off from the substrates if found. If any coral transplants are found invaded or bioeroded by these sponges, such transplants need to be removed so that other healthy transplants are not affected.

Many of the octocorals and zoanthids are protected by the Wildlife Protection Act, 1972, and hence they should not be removed, while ascidians and other organisms can be removed. In order not to affect the rare and scheduled organisms, scientific divers need to be involved in the removal of benthic organisms.

Table 15: Best practices for the removal of benthic space competitors from the artificial substrates and transplants

SHOULD DO	SHOULD NOT DO
■ Regular monitoring should be in place to identify the problem of overgrowth by benthic organisms such as sponges, octocorals, zoanthids, ascidians, etc. ■ Overgrowing sponges need to be removed by scientific divers without damaging the transplants	■ Coral transplants should not be damaged in the process of removing space-competing epibenthic organisms ■ Organisms that are protected under the Wildlife Protection Act, 1972 should not be removed

Overgrowth of the sponge *Terpios hoshinota* on restored *Acropora intermedia*

7.3. Removal of coral predators

Corals are animals and some predatory organisms such as certain species of fishes, mollusks, crustaceans and echinoderms feed on them. It is not possible to remove corallivorous fishes and hence they need to be left as such. Certain species of snails such as drupellids feed on coral tissue and pave the way for disease infections. Corallivorous snails should be carefully removed from transplants with hands or forceps as the outbreak of these snails can cause significant damage to coral survival and growth. Certain species of echinoderms such as *Culcita schmideliana* has been reported to feed on corals of Tamil Nadu and hence they need to be removed if found on the substrates or transplants. Even though crown of thorns star fish is a serious problem in many reef regions around the world, it has not been observed or reported in the reef areas of Tamil Nadu. Certain crustaceans such as crabs can feed on corals and spread diseases and so need to be removed carefully from the growing transplants.

Care must always be taken while removing the corallivorous organisms so that coral fragments are not damaged, fragmented or dislocated. If any of the organisms involved is protected under the Wildlife Protection Act, 1972, it should not be removed. In order not to affect the rare and scheduled organisms, scientific divers need to be involved in the removal corallivore organisms.

7.4. Removal of fishing nets

Apart from all the biological disturbances, entanglement of fishing nets with the

Table 16: Best practices for the removal of coral predators from the artificial substrates and transplants

SHOULD DO	SHOULD NOT DO
■ Regular monitoring should be in place to identify outbreaks of corallivore organisms such as corallivore fishes, mollusks, crustaceans and echinoderms ■ All the corallivore organisms except fishes should be removed from the substrates and transplants ■ Utmost care should be taken while removing predatory organisms	■ Coral transplants should not be damaged in the process of removing corallivore organisms ■ Organisms that are protected under the Wildlife Protection Act, 1972 should not be removed

Anchoring at restoration site

Trap fishing at restoration site

Removal of entangled fishing nets *(Acropora robusta)*

Table 17: Best practices for the removal of fishing nets from the artificial substrates and transplants

SHOULD DO	SHOULD NOT DO
▪ Regular monitoring should be in place to identify the entanglement of fishing nets with the substrates and transplants ▪ Utmost care should be taken while removing the nets not to damage coral transplants ▪ Knives and scissors should be used to remove entangled nets ▪ When parts of nets are overgrown by corals, the portion of attachment should be left as such ▪ Removed nets should be carefully brought to the boat and sent to recycling units	▪ Coral transplants should not be damaged in the process of removing entangled fishing nets ▪ Removal of nets should not be done with hands in order not to damage transplants ▪ Removed nets should not be thrown again into the water ▪ Parts of nets attached to coral fragments should not be removed

substrates and transplants is a serious issue, which needs to be carefully handled. Direct fishing in the restoration sites and entanglement of drifting abandoned nets can cause mechanical damage to corals. The entangled nets should be carefully removed from the substrates or coral transplants with proper tools. Knives or scissors should be used to remove the nets without damaging the corals. If pulled using hands, there is a possibility of coral fragmentation and hence should not be done.

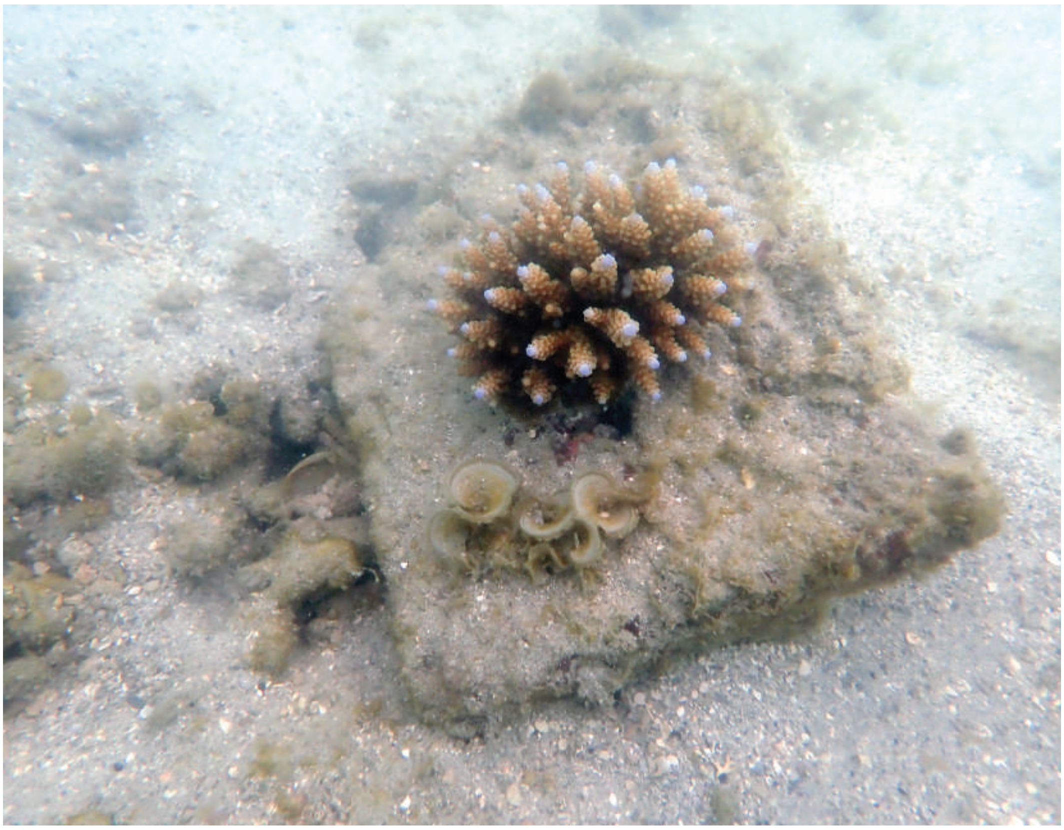
When parts of nets are overgrown by corals, the portion of attachment should be left as such so that the coral is not damaged. Removed nets should be carefully brought to the boat and sent to recycling units.

7.5. Replacement of substrates and coral fragments

Rough waves and faster currents can sometimes dislodge the cement slabs from the concrete frames. If the dislodged slabs fall off the frames upside down, transplants attached to them will die within a few days. Fishing and other human-activities can also tilt, dislodge and even bury the frames and slabs affecting the transplants. Regular

Table 18: Best practices for the replacement of substrates and coral fragments

SHOULD DO	SHOULD NOT DO
▪ Regular monitoring should be in place to identify the dislodgment, tilting and burial of substrates and transplants ▪ Inspection should be made immediately after any storm event for possible damage ▪ Proper arrangement of damaged substrates should be made if there is a possibility of the survival of coral transplants ▪ Fresh fragments should be collected from the donor site to replace dead transplants to keep the coral biomass intact ▪ Artificial substrates should be replaced when they are found damaged beyond manageable level	▪ Dislodged, tilted and buried substrates and transplants should not be left as such



Dislodged cement slabs *(Acropora robusta)*

Arrangement of dislodged slabs *(Acropora robusta)* monitoring of restoration sites will help to identify such problems at the earliest so that such dislocated transplants can be put back to proper form to give them a chance to survive. Inspection should be made immediately after any storm event. At times, transplants are found dead due to such instances and hence need to be replaced.

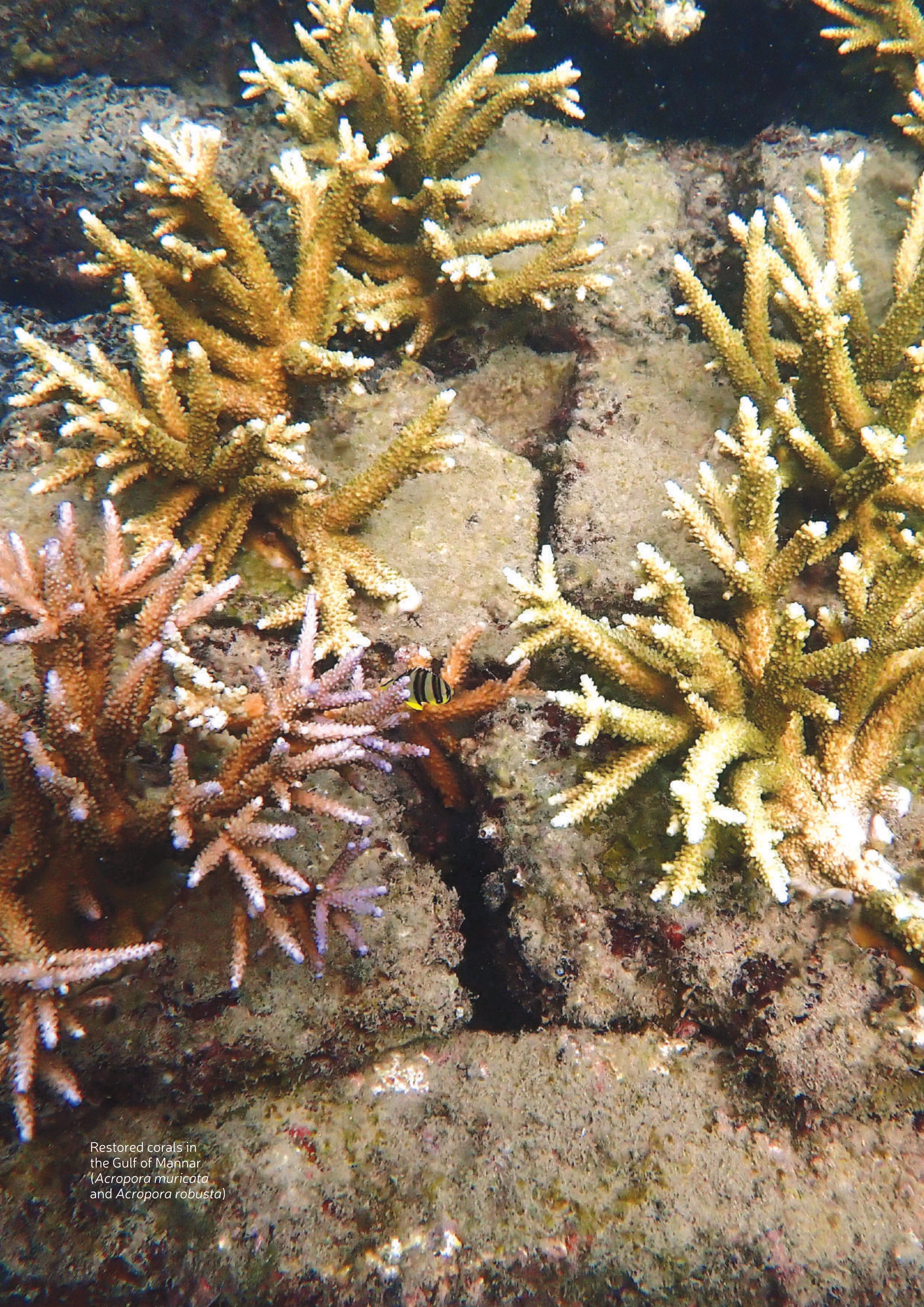
Fresh fragments should be collected from the donor site to replace dead transplants so that the increase of coral biomass will not be compromised. When replacing, frames and slabs already deployed can be used if they are not damaged too much. If they are not usable, fresh substrates need to be deployed to carry out the transplantation.

7.6. Other maintenance requirements

Mechanical damages caused by anchoring, boat grounding, etc. should be monitored and handled immediately. Adjustment and replacement of substrates and coral fragments should be carried out as and when required.

Apart from fishing nets, other marine debris such as plastic bottles, covers, cans, ropes, etc. should be removed from the restoration site to prevent any mechanical damage to transplants.

A scientific diver carrying out maintenance work



Restored corals in the Gulf of Mannar (*Acropora muricata* and *Acropora robusta*)

Restored corals in the Gulf of Mannar (*Acropora muricata*)

8 Monitoring

To evaluate the success of the restoration effort and also to improve the protocols, regular and continuous monitoring is very important. The success of coral restoration efforts in Tamil Nadu is partly due to the continuous evaluation and improvement over the past two decades. Further, continuous monitoring helps in the proper maintenance of restoration sites as regular field visits for monitoring will help to identify problems in advance and to respond quickly. Parameters to monitor include, and are not limited tosurvival, growth, benthic community fluctuations, associated organisms, and environmental conditions. Long-term monitoring is important to properly evaluate the restoration effort. A minimum of three years of regular monitoring would give us a fair idea about how the transplanted corals have coped with the restoration effort. This is a scientific monitoring and hence should strictly be carried out by scientific divers and not by recreational divers or fishermen.

8.1. Survival rate

The primary factor that justifies the success of the restoration effort is the survival of transplanted fragments in the new area on artificial substrates. In a successful transplantation project, transplanted corals will survive and grow in a manner similar to that of naturally occurring corals. Transplanted fragments need to acclimatize to the new environment and form primary

Restored corals in the Gulf of Mannar (*Acropora muricata*)

basal disc (attachment of transplants with cement slab). When the basal disc is formed, it is confirmed that the transplants have successfully circumvented the difficulties in initial acclimatization process.

Surviving corals can be identified easily underwater by their colour and intact mucous layer. The attachment of transplants with the substrate can be seen within two months. Transplanted corals should be

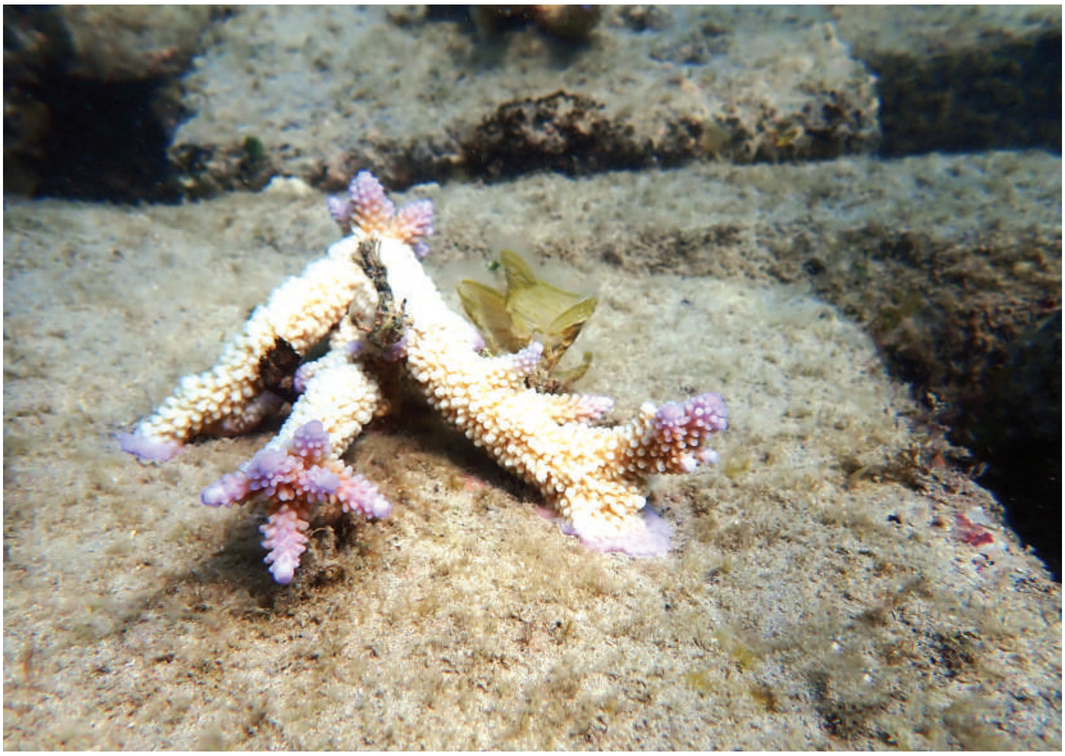
Table 19: Best practices for the monitoring of survival rate

SHOULD DO	SHOULD NOT DO
■ Monthly monitoring should be carried out for the first year ■ Monitoring frequency should be at least once in three months upto three years ■ Monitoring frequency should be at least once in six months after three years ■ Frames should be randomly selected for assessing the survival ■ All fragments on selected frames should be taken into account for survival assessment	■ Coral transplants should not be disturbed during the assessment

identified up to species level and survival rate should be monitored monthly.

For assessing the survival rate of transplants, they can be classified into healthy transplants, partially dead, dead, and detached/lost. Frames should be selected randomly for monitoring the survival among the total number of deployed frames and the number can differ according to the total number of frames at the site.

A minimum of 10% of the total number of



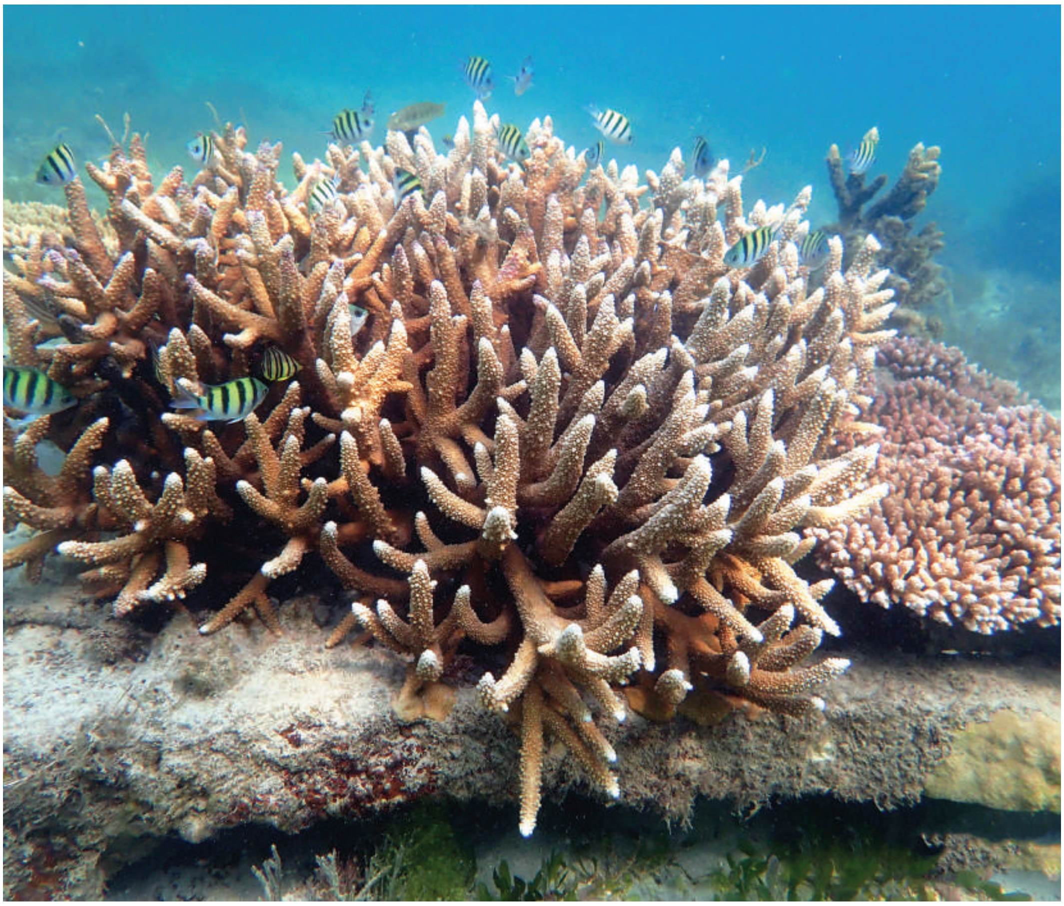
Initial attachment of fragments with substrates *(Acropora robusta)* frames should be selected for monitoring with a minimum of ten frames at a site. All the transplants from the selected frames should be taken into account for the monitoring of survival. Total number of surviving transplants should be counted every month and the survivorship of the coral transplants expressed in terms of the percentage number of living ones. Monthly monitoring is important for the first year and it can be reduced to once in three months upto three years. For the long-term monitoring (more than three years), monitoring frequency can be reduced to once in six months to understand the trend.

8.2. Growth rate

Even though transplants attach themselves to the substrate and survive, they must grow fast to increase the biomass, which is one of the ultimate goals of the restoration effort. Generally, fragmented colonies allocate most of their energy for growth and regeneration. The growth rate

Growth after one year *(Acropora muricata)*

Growth after two years (*Acropora* spp.)



Growth after four years (*Acropora* spp.)

Table 20: Best practices for the monitoring of growth rate

SHOULD DO	SHOULD NOT DO
■ Monthly monitoring should be carried out for the first year ■ Monitoring frequency should be at least once in three months upto three years ■ Monitoring frequency should be at least once in six months after three years ■ Vernier caliper with flexible scales or an underwater measuring tape should be used to measure the diameter of a colony ■ Linear extension of fast-growing species should be measured in different branches of a colony and averaged ■ Transplants used for assessing the survival rate should be used for assessing the growth too ■ Care must be taken not to damage the transplants	■ Coral transplants should not be disturbed during the assessment

of a coral colony is highly variable. It varies from species to species, region to region, morphotype to morphotype, season to season and even from branch to branch within the same colony. Hence, regular and continuous monitoring of the growth of transplants is very important. Monthly data should be collected, which can then be used for calculating the annual growth rate of transplants. The frequency of monitoring should be similar to that of the monitoring of survival as mentioned above. The same transplants used for assessing the survival rate should be used for measuring the growth rate too.

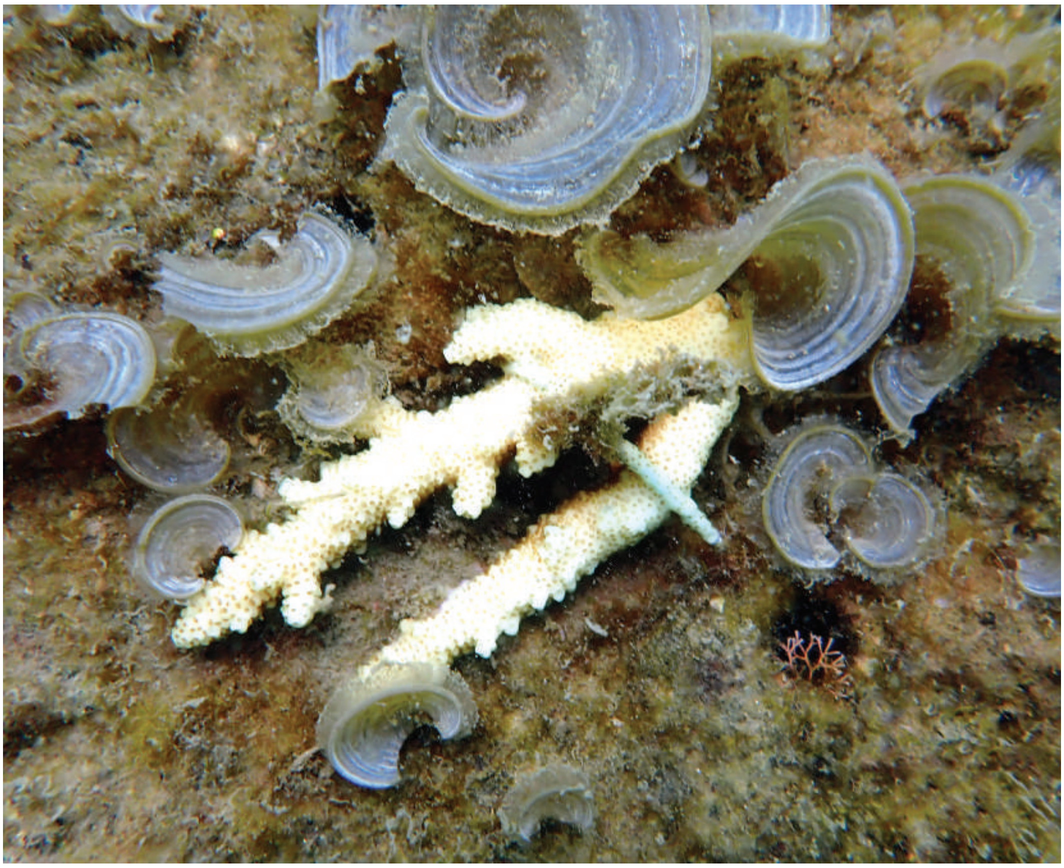
Vernier caliper with flexible scales or an underwater measuring tape can be used to measure the greatest diameter of the growing transplants. Underwater measuring tapes can be used to measure the diameter of the colony too. This method applies to all the species and morphotypes. In addition, linear extension of fast growing corals such as acroporids can also be measured by underwater measuring tapes. When measuring the linear extension, different branches of the same colony should be measured for linear growth and the values should be averaged. Care must be taken while measuring growth such that branches of transplanted corals are not broken/damaged.

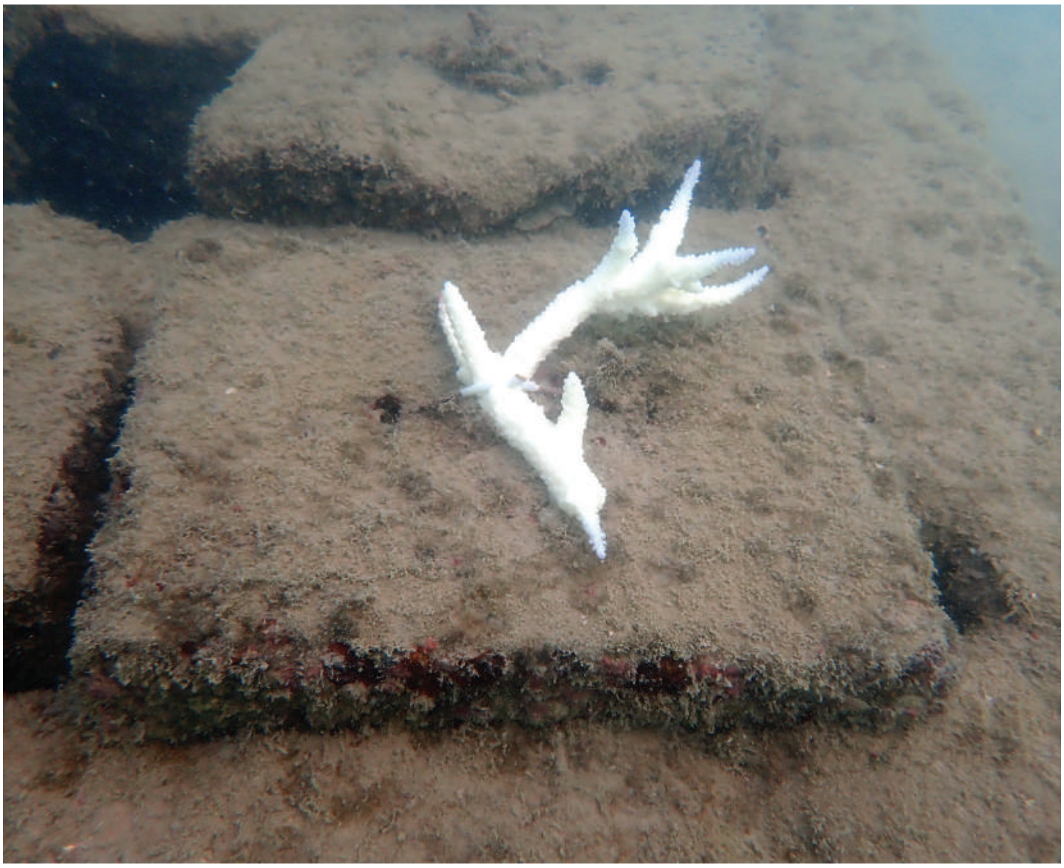
8.3. Monitoring for bleaching and disease outbreaks

Due to global warming and El Niño events, mass thermal bleaching has become recur-

Table 21: Best practices for the monitoring of bleaching and disease outbreaks

SHOULD DO	SHOULD NOT DO
■ Monitoring should be carried out whenever necessary ■ Bleaching should be monitored during the summer months ■ Lesions should be carefully identified and described ■ Infected portion of a colony should be removed if it is assumed that it may spread the disease	■ Coral transplants should not be disturbed during the assessment ■ Wrong identification and description of lesions should not be made





Bleached transplants (*Acropora* spp.)

rent on a global scale. Corals of Tamil Nadu have also been victims of these bleaching events during the past two decades. Hence signs of bleaching should be looked for carefully on the transplanted coral colonies, especially during the summer months between April and June every year. If bleached, the index/rate of bleaching should be assessed using the line intercept and belt transect methods. Bleaching can also be caused by sedimentation and other stressors, which also need to be identified and recorded. Frequency and intensity of coral disease outbreaks have increased over the years among the corals of Tamil Nadu. Hence, transplanted corals should be checked for disease lesions and assessed properly. The person carrying out this monitoring should be able to identify disease lesions such as discolouration, tissue loss and growth anomaly. Wrong identifications and faulty descriptions would mislead the necessary management action. If it is assumed that the disease may spread by physical contact, the infected portion should be removed to reduce further damage.

8.4. Monitoring of benthic space competition

Space competition among the sessile benthic organisms is severe in the reef areas of Tamil Nadu, especially after a severe bleaching event. Hence, transplanted corals should be regularly monitored for space competitors such as macroalgae, sponges, octocorals etc. This monitoring helps in taking necessary maintenance action such as manual removal. As concrete structures are involved, space competition for attachment

Table 22: Best practices for the monitoring of benthic space competition

SHOULD DO
■ Monitoring should be carried out whenever necessary
SHOULD NOT DO
■ Coral transplants should not be disturbed during the assessment

Table 23: Best practices for the monitoring of other biological phenomena

SHOULD DO
■ Monitoring should be carried out whenever necessary
SHOULD NOT DO
■ Coral transplants should not be disturbed during the assessment

and growth would be greater than in a dead reef area. The magnitude and diversity of space competitors should be recorded.This data will help in identifying the status of the reef and at some instances to identify a better restoration site for future efforts.

8.5. Monitoring of other biological phenomena

Apart from the above-mentioned biological phenomena, microalgal blooms, bioinvasion and other such incidents are also possible at the restoration sites. Blooms of *Noctiluca scintillans* have become regular in the reef areas of Tamil Nadu causing mass coral mortalities by depleting the dissolved oxygen levels. During such times, immediate monitoring should be carried out to inspect the impact of the bloom on coral transplants. Similarly, bioinvasionby exotic alga *Kappaphycus alvarezii* has been reported in the Mandapam and Keelakarai regions of the Gulf of Mannar causing severe coral mortalities. Hence, when restoration is carried out in these regions, careful monitoring should be performed to inspect possible invasion of such algae in order to take swift action to remove the threat. Likewise, predator outbreaks and predation lesions should be carefully monitored and handled properly.

8.6. Analysis of environmental parameters

Increasing coral biomass at the restoration sites is expected to improve the water quality and other environmental parameters better than in the pre-restoration period. Hence, detailed data on

Table 24: Best practices for analysing environmental parameters

SHOULD DO
■ Monthly monitoring should be carried out
■ Proper protocols should be followed for sample collection and analysis
■ The trend should be compared with the baseline data
SHOULD NOT DO
■ Coral transplants should not be disturbed during sample collection and assessment

Table 25: Best practices for the monitoring of benthic community structure

SHOULD DO
■ Monitoring should be carried out at an interval of six months
■ The trend should be compared with a nearby natural reef
■ Standard underwater protocols should be followed for the assessment
SHOULD NOT DO
■ Coral transplants should not be disturbed during the assessment

water quality conditions has to be collected from the restoration sites regularly and compared with the baseline data to identify changes. Generally, monthly monitoring is suggested to see the changes and identify the trend. Moreover, most coral species can survive only within a narrow range of salinity and temperature, and any marked changes in parameters such as sedimentation, and dissolved oxygen may affect the growth or survival of transplanted corals. In the context of climate change, there is increased concern about widespread bleaching in association with high water temperatures. Digital thermometer readings just below the water surface and at the depth of transplanted site are to be measured. Dissolved oxygen is necessary for the survival of transplanted coral colonies and should be estimated regularly. Similarly, salinity, pH, turbidity, suspended solids and nutrients should also be estimated regularly using standard protocols in order to identify an issue early and to act accordingly.

8.7. Monitoring of benthic community structure

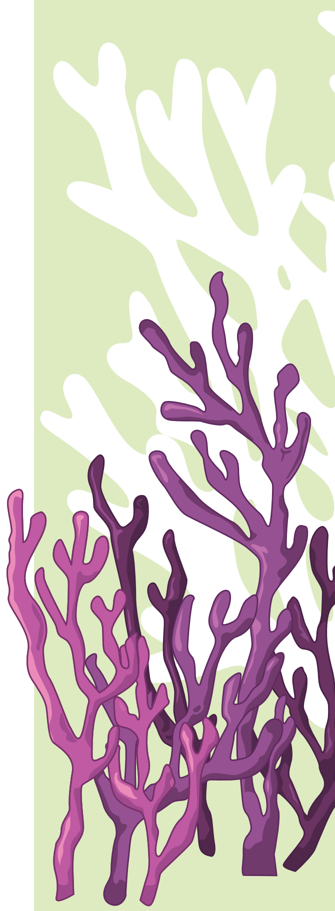
The success of coral restoration can be measured by assessing the changes in the benthic community structure at the restoration site and comparing it with the trend in a nearby natural reef. Benthic community structure encompasses all the sessile benthic organisms including coral transplants. By assessing the benthic community structure at regular intervals, it will be understood how much coral cover and density have increased temporally due to the restoration effort and how it has affected other benthic dwellers. Increase in the live coral cover directly indicates the success of coral transplantation. Apart from the live coral cover, percentage cover of algae and other organisms would provide information about whether the restoration site is in a good condition. Benthic community structure should be assessed by scientific divers using line intercept transect method, belt transect method and quadrat method. It can be done once in six months to see considerable fluctuations.

8.8. Monitoring of associated organisms

The total success of coral restoration is also reflected in the enhancement of the ecolog-

Table 26: Best practices for the monitoring of associated organisms

SHOULD DO
■ Monitoring should be carried out at an interval of six months
■ The trend should be compared with a nearby natural reef
■ Standard underwater protocols should be followed for the assessment
SHOULD NOT DO
■ Coral transplants should not be disturbed during the assessment



Sea cucumber *Holothuria atra* at restoration site

Gastropod *Lambis* sp. at restoration site ical roles that the transplanted corals play. The first noticeable sign is the increase in reef-associated organisms in the restoration site. Hence, the assessment of fishes at the restoration site should be carried out regularly to compare it with the pre-restoration scenario and also to understand the temporal trend. The structural complexity of a habitat is a major factor determining the abundance and diversity of the fish communities. When the transplanted corals grow and increase in biomass, the habitat complexity of artificial substrates increases enhancing fish abundance and thereby indicating the success of coral restoration. To assess the fish communities, underwater fish visual census applying belt transect method is used. The available fish species should be classified according to the trophic groups such as herbivores, carnivores, omnivores, planktivores, corallivores, etc. The increase in benthic macrofauna should also be assessed using quadrat method. The available macrofauna should be categorized according to the taxa such as echinoderms, mollusks, crustaceans, etc.

8.9. Monitoring of sexual reproduction

The survival and growth of transplants is generally in focus in a restoration initiative, but the real success lies in the sexual maturity of transplanted colonies. Restored corals in Tamil Nadu have been reported to actively participate in sexual reproduction. When transplanted corals spawn, they contribute more to the recovery of total coral reefs because the coral supply source is increased and genetic pool diversified. Since the possibility of spawning increases with the growth of transplanted colonies, monitoring should be carried out when the nearby natural corals spawn. The time of spawning varies from species to species and region to region and hence needs to be understood in the natural corals first. The month of March has been reported to be the spawning season for the acroporids on the reefs of Tamil Nadu though more studies are needed to understand the sexual behaviours of other species. Since acroporids are the dominant contributors to coral restoration, reproductive monitoring should be carried out during February to March every year. Observation of pigmented gametes is the sign that corals are about to spawn.

8.10. Monitoring of coral recruitment

Following sexual coral reproduction, coral larvae should find a hard substrate to settle and grow. In some species larvae settle near the parent colony and in some species they travel long distances to settle at different areas. Recruitment of newly settling larvae at the restoration sites should be monitored as it is critical to enhance the coral cover in the area. It is important here to note that concrete structures provided for coral restoration also act as artificial reefs by providing surface to newly settling coral larvae. Visible coral recruits on natural and artificial substrates at the restoration site

Table 27: Best practices for the monitoring of sexual reproduction

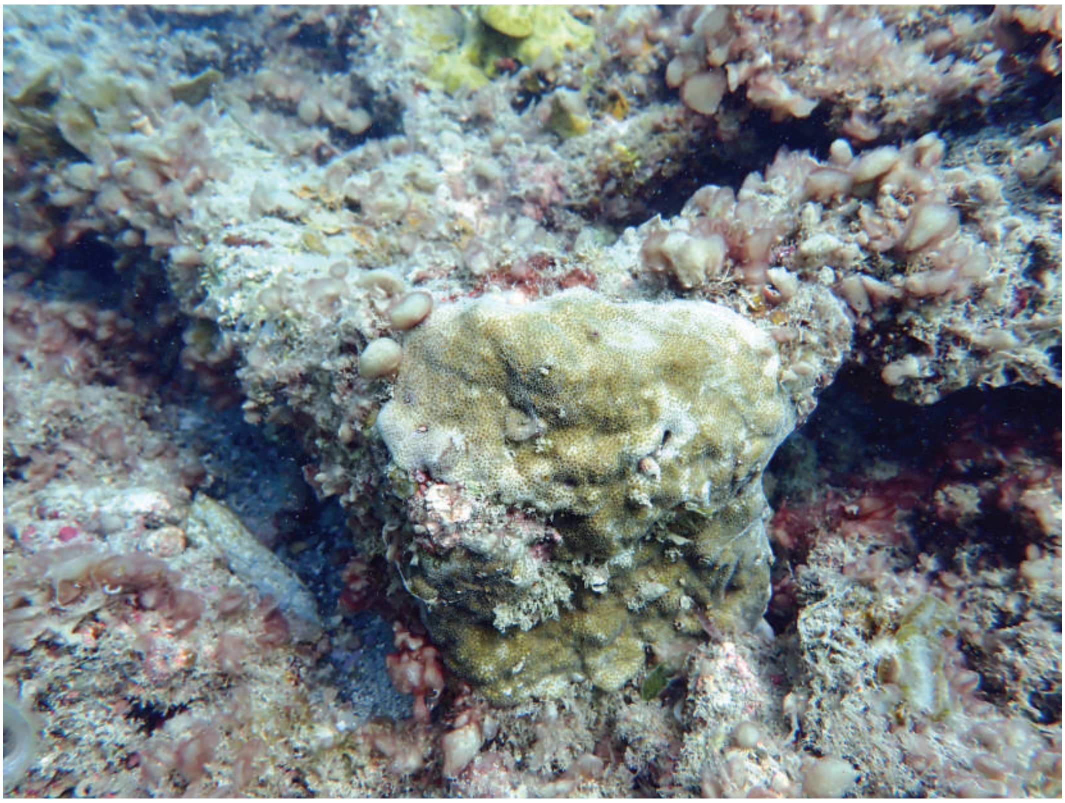
SHOULD DO
■ Monitoring should be carried during the reproductive season
■ The trend should be compared with the nearby natural reef
SHOULD NOT DO
■ Coral transplants should not be disturbed during the assessment

Table 28: Best practices for the monitoring of coral recruitment

SHOULD DO
■ Monitoring should be carried once in six months
■ The trend should be compared with the nearby natural reef
SHOULD NOT DO
■ Coral transplants should not be disturbed during the assessment

should be assessed regularly to understand the trend. At natural substrates, quadrats can be used to assess the recruit density.

Epibenthic attachment of coral recruits on artificial substrates can be counted and the density assessed.



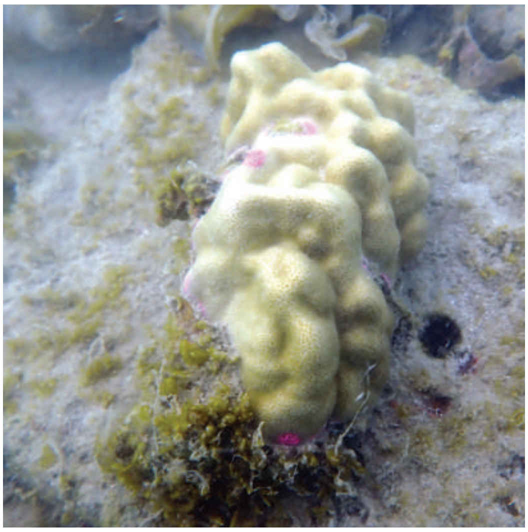
Natural coral recruitment on artificial substrates

DIFFERENT SPECIES OF TRANSPLANTED CORALS

Dipsastraea sp.

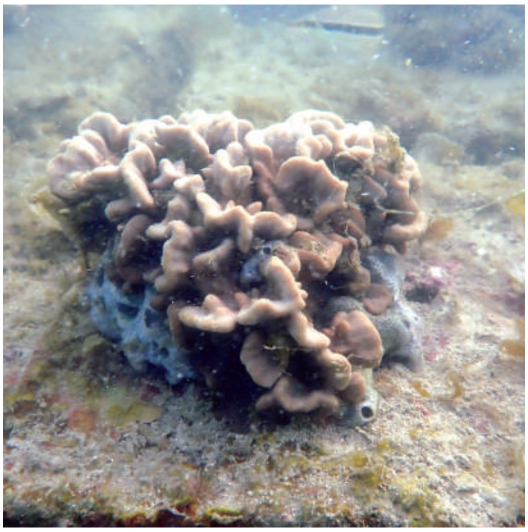
Favites sp.

Echinopora sp.



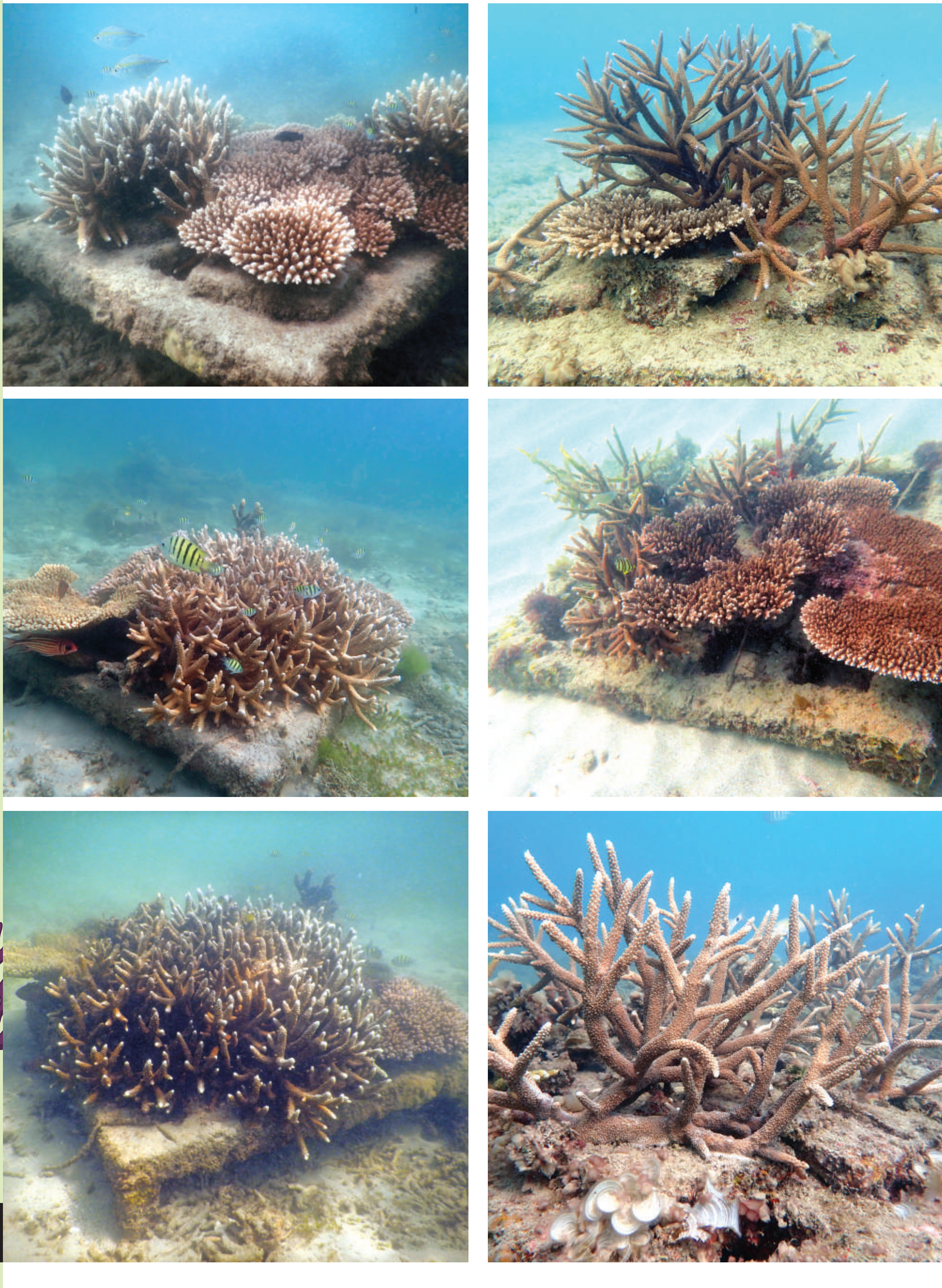
Porites sp.

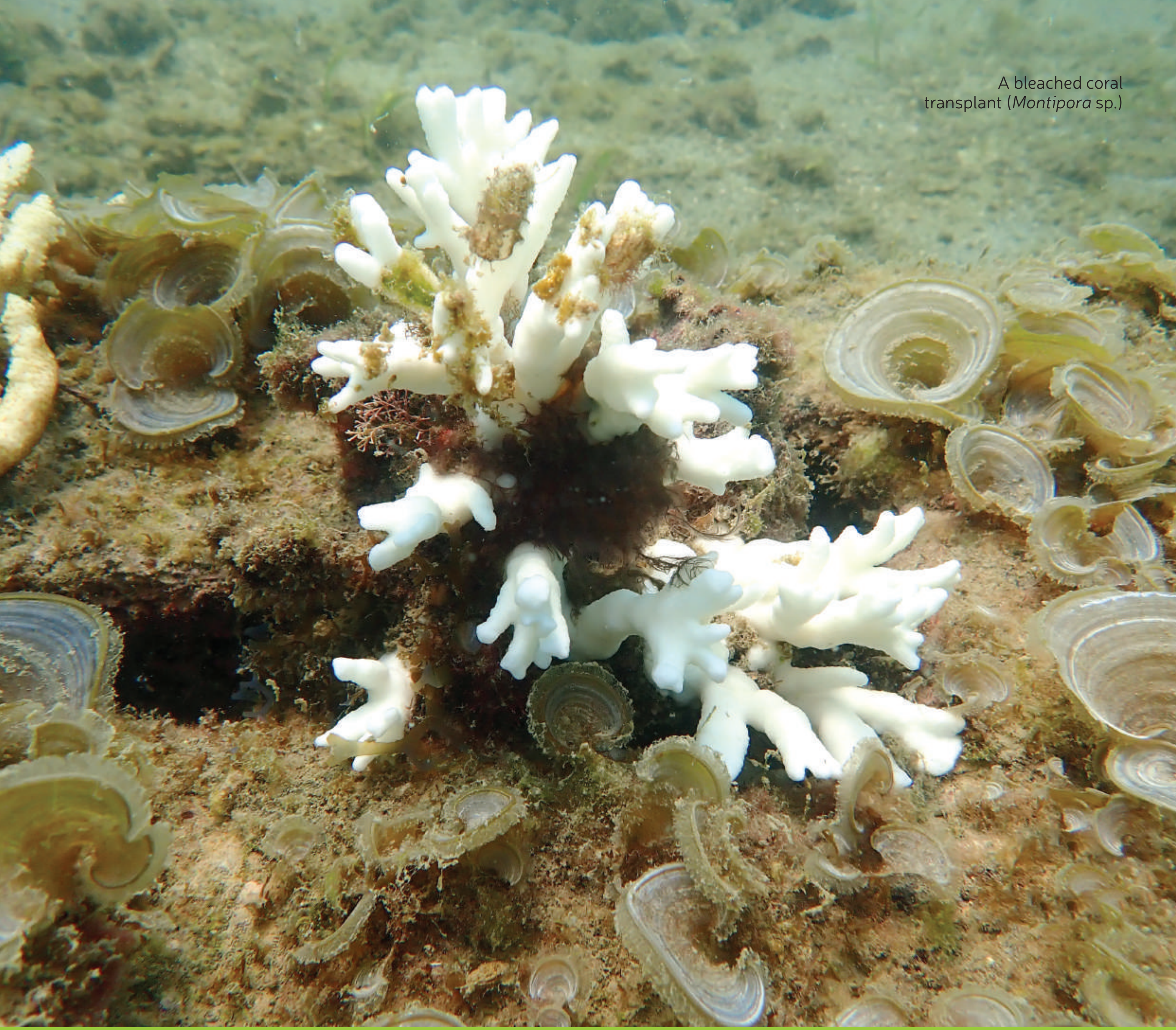
Pavona sp.



Pavona sp.

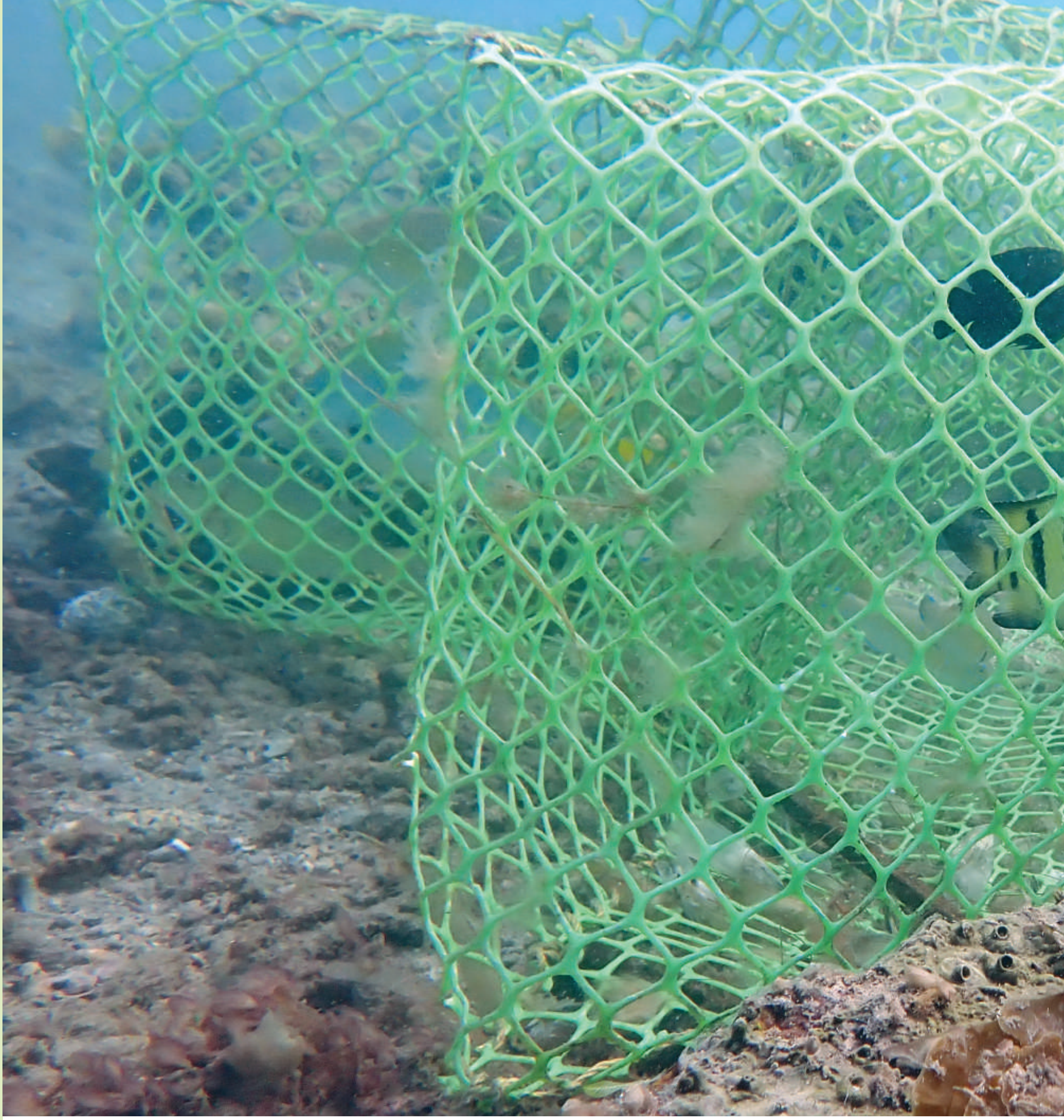
MULTIPLE SPECIES OF GROWN RESTORED CORALS





A bleached coral transplant (*Montipora* sp.)

9
Challenges



The evolution of the current feasible restoration technology has encountered many challenges during the past two decades. It requires skills, knowledge, dedication, vision, funding and strict compliance with legal procedures. The following are the important challenges that have been met with in the past, some of which are still being faced.

9.1. Identification of feasible restoration method

Development of the direct transplantation technology as a feasible method for coral restoration in Tamil Nadu was the primary challenge in the early 2000s. It took extensive literature surveys and experimentations in the field. Then, the need of artificial substrates for transplantation was realized. The sea bottom in the reef areas of Tamil Nadu being unstable due to the earlier mining activities and in need of stable artificial substrates, the identification and design of durable substrates specific to the location was one of the major challenges. Based on initial field observations, several materials were tried for use as artificial substrates for direct transplantation.

9.2. Requirement of skilled manpower

Coral restoration is completely an underwater endeavour that requires scuba diving skills. There are not many

Trap fishing at the restoration site

trained scuba divers in the country who can carry out such underwater tasks. Though recreational diving is currently becoming familiar in India, and more and more people are taking to this hobby, most of the activities in coral restoration require professional scientific divers who have knowledge on coral ecology and biology. The services of recreational divers and traditional skin divers can be used for some activities in the restoration process, but corals, being animals, must be handled properly by scientific divers. It is important here to note that many of the marine biologists in the country are not trained or certified in scuba diving. Further, safety of the divers should be constantly monitored during restoration as expertise and facilities to treat diving-associated injuries are scarce in the country.

9.3. Requirement of facilities

Coral restoration in Tamil Nadu is entirely a field-based effort as there is no infrastructure to keep corals alive in captivity for a long time. Hence, field-based tools and equipment are mandatory to carry out restoration and they are often expensive. Primarily, an exclusive field boat that can float in shallow waters is needed for the various processes from collection to transplantation of coral fragments. While boats can be hired from fishermen, only a boat designed for scuba diving and underwater activities can effectively help carry out the


A coral transplant killed by the sponge *Terpios hoshinota*

work. Scuba diving equipments such as air compressor, BCDs, regulators, masks, fins and accessories are very important for underwater works; these equipments are not only expensive but can be purchased only from specific dealers in India.

9.4. Lack of awareness among the coastal communities

Awareness of the importance of coral reefs has substantially increased among the coastal communities in Tamil Nadu. However, we have to educate them on the importance of coral restoration. This is particularly important as fishing activities at restoration sites often cause significant damage to the restored corals. Deployment of artificial substrates immediately attracts a lot of fish as they provide shelter, which the local fishermen know and so the enhanced fish populations attract the fishermen to fish in the area. Thus, due to their livelihood need, they lay their nets at the restoration sites affecting restored corals without realizing the consequences. Direct mechanical damage caused to the substrates and transplants by fishing activities has to be addressed through awareness creation. Damage caused by such fishing activities significantly reduce the survival and growth rates of restored corals, if not promptly maintained.

9.5. Recurrent bleaching events

Coral bleaching has become an annual feature in the reef areas of Tamil Nadu, though mass coral mortality was witnessed only during the severe events in 2010, 2016 and 2024. Mortality of restored corals along with natural corals due to the bleaching is an important issue not just in Tamil Nadu, but in all the reef areas of the world.

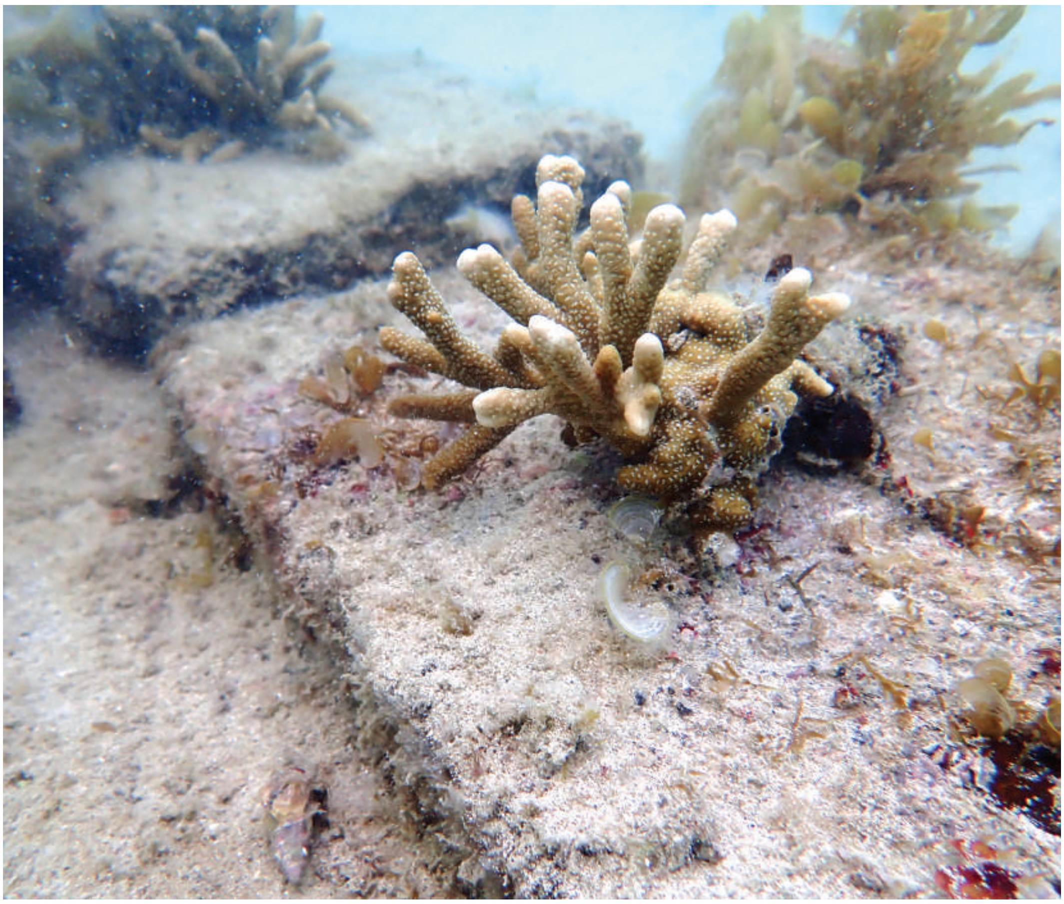
When restoration of a site is followed by a massive bleaching event, it causes severe damage. Yet, it is difficult to carry out or continue the restoration during or immediately after a bleaching event. Another major problem is the proliferation of benthic space competitors after a bleaching event. In particular, fleshy macroalgae can take advantage of the weak status of the heat-stressed corals, and proliferate immediately after the bleaching event, causing further damage to the restored corals.

9.6. Disease outbreaks and other biological phenomena

The restored corals are also affected by issues like disease outbreaks, microalgal blooms, bioinvasion and other biological phenomena that affect the natural reef in their vicinity. Hence, dealing with these issues is a challenge when carrying out restoration. These phenomena can cause mass coral mortalities at a restoration site affecting the overall success of the effort.

9.7. Funding

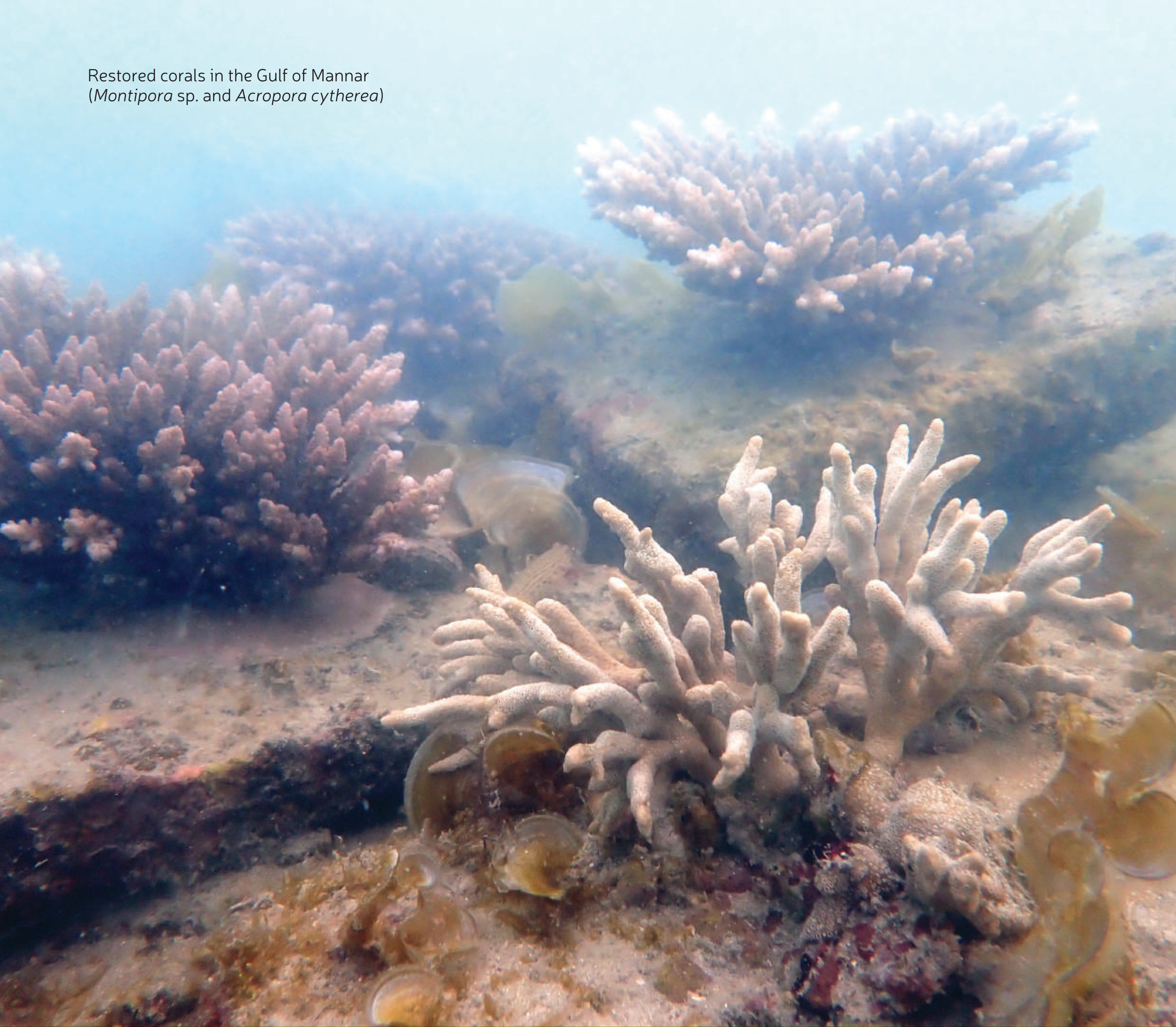
With funds made available by government through various schemes, Tamil Nadu is the front-runner in the country in carrying out wide-scale restoration activities in the state's degraded reef areas. Considering the magnitude of the coral decline, more funding is, however, required for further wide-scale restoration efforts and also for developing / identifying more efficient techniques such as micro-fragmentation. Development of land-based facilities for further research on coral restoration also requires more funding. Inadequate funding for continuous monitoring and maintenance has been an important issuebecause



Restored corals in the Gulf of Mannar (*Montipora digitata*) many projects have funding only for the execution of restoration. It is not possible to maintain the success of a restoration effort without proper follow-up maintenance and monitoring.

9.8. Rough weather

Calm weather is an absolute necessity for the transport and deployment of artificial substrates. Generally, October to March every year is the suitable time for carrying out restoration, but weather has become highly unpredictable over the years. If the sea gets rough after the deployment of substrates and before the transplantation, other epibenthic organisms might get attached to the substrates. In that case, another round of maintenance should be performed before bringing in coral fragments. The coastal belt along the Gulf of Mannar and Palk Bay is highly eutrophic and the sedimentation rate is also comparatively high. Hence, poor visibility is often an important issue that affects the restoration activities. We may have to wait for days or weeks or sometimes even months for the weather and visibility to become conducive to carry out restoration works.



Restored corals in the Gulf of Mannar (*Montipora* sp. and *Acropora cytherea*)

10 Benefits of restoration

Restored corals in the Gulf of Mannar (*Acropora* sp.)

10.1. Coping with the coral loss

The decline of coral reefs has been severe in the reef areas of Tamil Nadu over the past two decades primarily due to climate change impacts and various other natural and human-induced factors. Restoration activities in Tamil Nadu have helped in keeping the coral cover sustainable so far. Without these restoration efforts, the loss would have been much bigger in Tamil Nadu considering the severity of climate change impacts.

10.2. Enhanced larval supply through sexual reproduction

The state's restored corals have been recorded to reach sexual maturity within four years and begin active participation in sexual reproduction. Gametogenic cycle and spawning seasonality of restored corals have been found to be similar to those of nearby natural corals. Thus restoration activities enhance the supply of larvae, which in turn helps the corals to recover naturally from bleaching and other harmful events.

10.3. Provision of substrate for coral recruits

Artificial substrates used in coral restoration have been proved to provide attachment surface for newly settling coral larvae. Thus the artificial substrates enhance the natural coral recovery process. This is

particularly important due to the lack of natural substrates (dead corals) in the reef areas of Tamil Nadu as a result of decades of coral mining activities before 2004.

10.4. Sustenance of reef associated biodiversity

Biodiversity in the degraded reef areas is very low and the restoration efforts increase the density and diversity of reef-associated organisms. Several ecologically and economically important marine species are dependentsolely on live coral cover. Hence, increase of coral cover in the restoration sites has greatly helped in increasing the associated biodiversity including fishery resources. Moreover, artificial substrates used for restoration also help in providing shelter to fishes and other organisms and thereby increase their abundance.

10.5. Livelihood sustenance

The scale of reef-dependent fishery is significant along the coast of the Gulf of Mannar and Palk Bay as thousands of fishermen depend on it for their livelihood. The enhancement of fishery resources in the restoration sites has directly and indirectly helped to protect the livelihood of the fishermen. Many reef fishes such as parrot fishes, groupers, jacks and snappers are of high economic value helping the fishermen to earn more. It is to be noted here that without live corals, many economically important fishes would vanish from the reef areas of Tamil Nadu causing

Natural coral recruitment on concrete frame

a severe decline in fish landing and associated economy.

10.6. Job creation for coastal communities

Community members are involved in various steps of coral restoration in Tamil Nadu such as the tying of coral fragments with cement slabs and the deployment of artificial substrates. Fishing boats for restoration activities are also hired from the fishermen, enabling them to gain some economic benefit. Thus revenue and part-time employment unrelated to fishing are created for the coastal communities through various coral restoration projects along the coast of the Gulf of Mannar and Palk Bay.

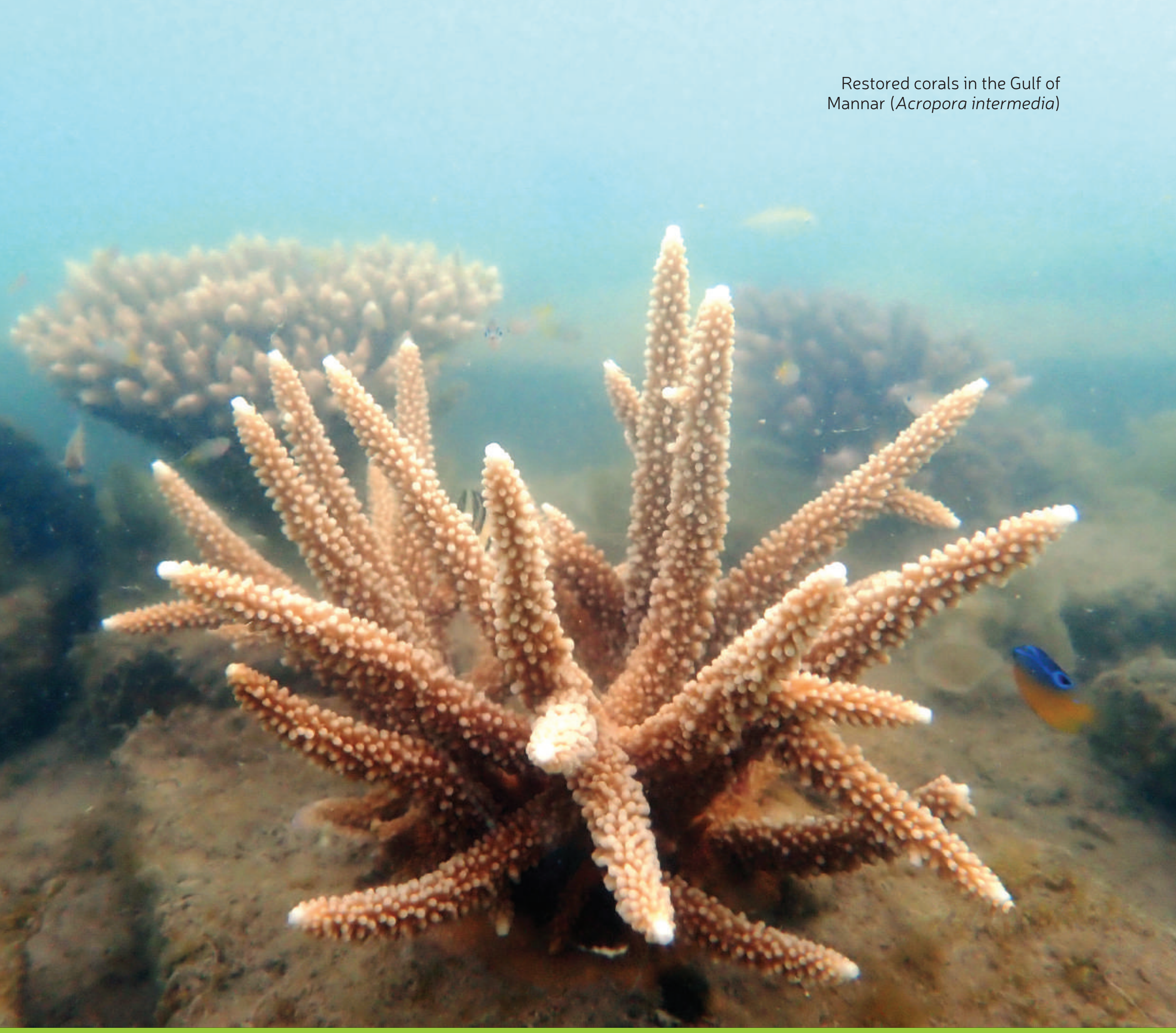
10.7. Awareness creation among the coastal communities

Involvement of coastal communities in restoration activities instils in them a sense of ownership apart from making them knowledgeable about the restoration. This helps in reducing the human-induced threats in the restoration sites, especially unsustainable fishing practices.

Further, the long involvement of community members in wide-scale restoration activities, spanning several months, weans them away, though temporarily, from fishing activities thus reducing the fishing pressure.

10.8. Climate adaptation and mitigation

Being a climate adaptation and mitigation effort, coral restoration helps to reduce the impact of climate change on coral reefs of Tamil Nadu. It also helps in expediting the coral recovery process after a catastrophic bleaching event, disease outbreak, or microalgal bloom.



Restored corals in the Gulf of Mannar (*Acropora intermedia*)

11 Future perspective of coral restoration

The protocols mentioned above have been developed over two decades based on continuous monitoring and evaluation. These are near-perfect protocols for carrying out wide-scale restoration efforts in the reef areas of Tamil Nadu or elsewhere with similar conditions. The following are some of the important activities, which are pro-active measures and, further, they address the ever-changing climatic conditions too.

11.1. More wide-scale restoration in Tamil Nadu

Even though coral restoration efforts in Tamil Nadu have been considerably successful, they are still not sufficient to match the coral loss endured due to both climatic and non-climatic factors. Total reef area cover in the island reefs of the Gulf of Mannar has been reduced from 11,060 ha in 2005 to 6,628 ha in 2021 revealing the magnitude of loss. Moreover, out of the available 6,628 ha, another 2,631 ha are currently in a degraded state (Edward et al. 2023) which need to be restored in a phased manner using the available technology in order to sustain all the associated benefits.

11.2. Scaling up to other reef areas of the country

Coral restoration efforts are carried out in all the other reef areas of the country as well with different technologies and different substrates. However, the magnitude of

Restored corals in the Gulf of Mannar (*Acropora* spp.)

restoration is comparatively very high in Tamil Nadu primarily due to the established technique with measurable outcomes. Hence, the protocols used in Tamil Nadu can be replicated to other reef areas of the country as well. However, region-specific adjustments need to be made before going for wide-scale restoration efforts.

11.3. Continuous improvement

Shifts in benthic community structure and population dynamics are rapidly happening in all the reef areas of the world due to deteriorating climatic conditions. The designs of artificial substrates have seen several modifications over the years based on previous experiments and experiences (Edward et al. 2025). However, the design needs to be constantly evaluated to check if it works properly with changing benthic dynamics and environmental conditions. Procedures should also be continuously evaluated to increase/sustain the survival and growth of restored corals.

11.4. Experiments on modern technologies

Though the established direct transplantation technology works well for the reef areas of Tamil Nadu, most of the species used are fast-growing ones as they are known for their asexual regeneration. Technologies should be perfected for restoring slow growing massive corals. Hence, the newer micro-fragmentation technique should be experimented in Tamil Nadu for feasibility. If the technology works well suiting the local conditions, future wide-scale restoration efforts should also include micro-fragmentation.

11.5. Development of land-based facilities

Land-based facilities to keep corals in captivity—which is very important for research and development—have not been developed in the country so far. To establish coral nurseries and to experiment other modern restoration technologies, land-based coral cultivation infrastructure is mandatory. It is apt to develop such facilities in Tamil Nadu as Tamil Nadu is the pioneer in as well as current practitioner of wide-scale coral restoration efforts in the country. Moreover, reef areas here in Tamil Nadu are along the Indian mainland, which makes it easier to develop and maintain such infrastructure.

11.6. Heat-resistant species

As more thermal anomalies are anticipated in future affecting global coral reefs, restoration efforts should concentrate more on species that can withstand or adapt to such extreme conditions. Hence, coral species with heat-resistant zooxanthellae clades should be identified with focused research and such species should be used for future restoration efforts in order to tackle future climatic conditions.

11.7. Inclusion of Patch reefs

The offshore patch reefs of the Gulf of Mannar should be included in restoration activities either as donor sites or restoration sites. These patch reefs have good coral cover and associated biodiversity, but have often been neglected from conservation and restoration as they predominantly occur outside the boundary of the GOM-MNP. The offshore patch reefs are expected to fare better against thermal anomalies due to the higher depth range. Hence, proactively, efforts should be made to incorporate these patch reefs in future restoration projects.

Restored corals in the Gulf of Mannar (*Acropora* spp.)

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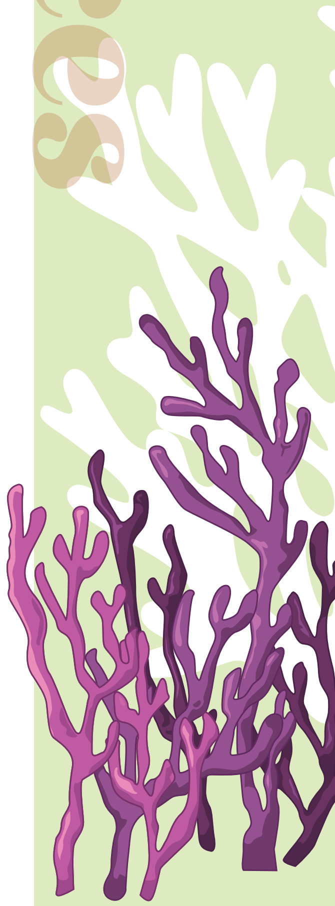

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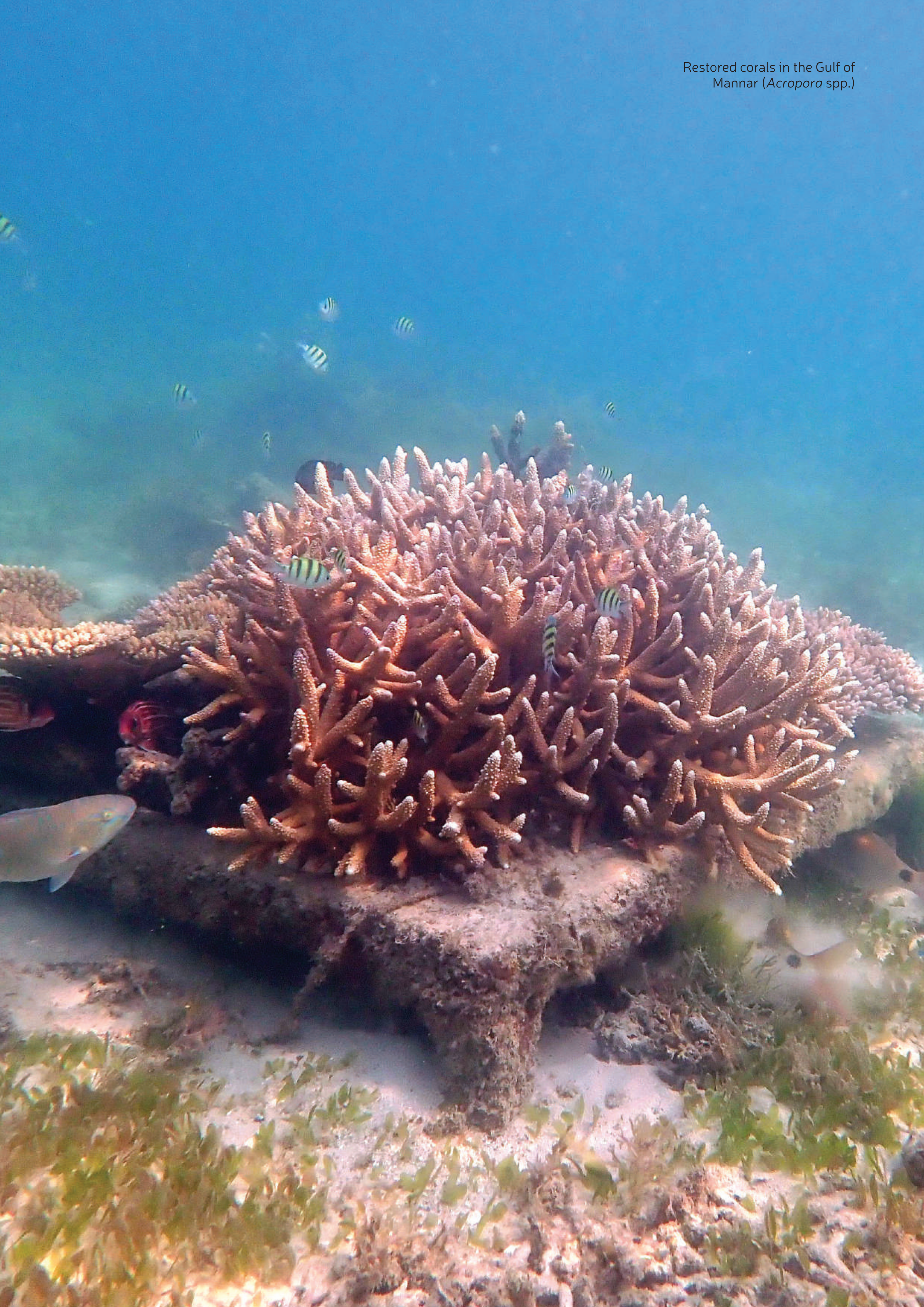

Restored corals in the Gulf of Mannar (*Acropora* spp.)