ASSESSMENT OF THE RESILIENCE POTENTIAL OF THE PALK BAY REEF THROUGH KEY INDICATORS

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By

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Certificate

This is to certify that the thesis entitled "**Assessment of the Resilience Potential of the Palk Bay Reef through key indicators**" is a bonafide record of original research work carried out by **Mr. B. Manikandan** under my supervision in National Institute of Oceanography, Regional center, Kochi, in partial fulfillment of the requirements for the award of **Doctor of Philosophy in Marine Science**. All the relevant corrections and modifications suggested by the audience during the pre-synopsis seminar and recommended by the Doctoral committee have been incorporated in this thesis and no part of the thesis thereof has been presented before for the award of any degree, diploma or associateship in any other University or Institution.

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Declaration

I hereby declare that the thesis entitled "**Assessment of the Resilience Potential of the Palk Bay reef through Key Indicators**" is an authentic record of the original research work done by me under the supervision of **Dr. J. Ravindran**, Senior Scientist, CSIR- National Institute of Oceanography, Regional Center, Kochi- 682018 in partial fulfillment of the requirements for the degree of **Doctor of Philosophy** in **Marine Science** and no part thereof has been presented before for the award of any degree, diploma or associateship or any other similar title in any other University or Institution.

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August 2015 **B. Manikandan**

Dedicated to all

those who

strive to conserve coral reefs

Statement of Contribution by Others

Some of the work I carried out for my PhD was collaborative and performed with technical, theoretical, statistical, editorial or physical assistance of others. I fully acknowledge the contribution of others as outlined below.

Chapter 2 & 5

These chapters contain research that made use of remote sensing based data on Photosynthetically Active Radiation (PAR) and Sea Surface Temperature (SST). Mr. Mani Murali, Scientist, Physical Oceanography Division, CSIR- National Institute of Oceanography and Dr. P. J. Vidya, Research Scholar, Physical Oceanography Division, CSIR- National Institute of Oceanography contributed to the collection of data and processing of the raw data respectively. Mr. Mani Murali also contributed to the written work related to the methodology of PAR data collection and processing.

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B Manikandan

Contents

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List of abbreviations

ANOSIM	-	Analysis of Similarity
ANOVA	-	Analysis of Variance
CCA	-	Crustose Coralline Algae
GoMBR	-	Gulf of Mannar Marine Biosphere Reserve
GoMNP	-	Gulf of Mannar Marine National Park
LIT	-	Line Intercept Transect Method
MODIS	-	Moderate Resolution Imaging Spectroradiometer
MPAs	-	Marine Protected Areas
NE monsoon	-	Northeast monsoon
PAR	-	Photosynthetically Active Radiation
PCA	-	Principal Component Analysis
PCoA	-	Principal Coordinate Analysis
ROS	-	Reactive Oxygen Species
SIMPER	-	Similarity Percentage
SST	-	Sea Surface Temperature
SW monsoon	-	Southwest monsoon
TSS	-	Total Suspended Solids

Chapter 1

General Introduction

1.1 Corals and Coral reef ecosystems

The coral reef ecosystems are the most ancient and dynamic ecosystems on the planet. They are biologically diverse and highly productive ecosystems (Odum and Odum 1955). In general, the term ‘Reef’ refers to the continuous underwater lime stone structures built by marine organisms. Scleractinian corals are the principal reef building organisms and form the reef frame work that serves as a habitat for numerous life-forms (Owen et al. 2012). Corals are the colonies of individual polyps which secrete an external calcium carbonate skeleton through the process of calcification (Smith 1983). The coral calcification process is driven by the symbiotic microalgae called zooxanthellae that reside within the coral tissues. The corals are classified as hermatypic and ahermatypic corals based on their ability to secrete calcium carbonate skeleton and build reefs. Hermatypic corals host zooxanthellae, secrete calcium carbonate skeleton and build reefs. Ahermatypic corals are azooxanthellate species and do not build reefs (Marshall 1996). The other reef building organisms include crustose coralline algae (CCA), encrusting algae and calcareous algae all of which secrete hard calcium carbonate and contribute to the reef growth (Castro and Huber 2003). In addition, sponges, octocorals and other invertebrates also contribute to the process of reef formation.

Since corals are the primary reef building organisms, their growth requirements limit the distribution of reefs. Coral reefs are predominantly present along the tropical coast lines between the latitudes 30 °N - 30 °S which constitute half of the world's coast lines (Spalding et al. 2001). The distribution of corals is influenced by various factors including temperature, light availability, sediment load, substrate type, depth and turbulence, all of which may act independently or synergistically to prevent or promote the reef growth (Veron 2000). The upper temperature limit for the growth of corals is 30 °C, although certain corals can withstand temperatures up to 35 °C. Cold water corals which are found globally at the depths >70 m from the coastal Antartica to Artic circle can thrive at a temperature of 4 °C. Corals thrive well in the shallow, clear waters with maximum light penetration since light is essential for photosynthesis by their symbiotic partner zooxanthellae.

Coral reefs cover <0.5% of the ocean floor (Lough 2008) and serves as home to 25% of the known marine population. Coral reefs provide numerous economical, ecological, biotic and biogeochemical services that benefit the people living along the tropical coastlines and also contribute to the ocean processes. Healthy coral reefs are a source of food for millions; protect coastlines from waves, storms and erosion; provide habitat for other organisms, spawning and nursery grounds for economically important fish species; provide jobs and income to local people from fishing, recreation, and tourism; source of new medicines, and are hotspots of marine biodiversity (Cesar 2003, Moberg and Folke 1999). The standing stock of fishes in the coral reefs comprises a significant portion of the total fish stock in the world ocean (Sorokin 1993, McAllister 1994). A healthy coral reef of 1 km^2 can support over 300 people in the absence of other protein sources (Jennings and Polunin 1996). The export of organic matter and combined nitrogen from coral reefs contributes to the productivity of Ocean. Coral reefs forms Islands facilitating the settlement of human population (Stoddart 1973); promote the growth of seagrass and mangrove ecosystems by dissipating the wave energy and creating lagoon and sedimentary environment (Birkeland 1985, Ogden 1988); serve as a breeding, feeding and spawning ground for multiple organisms thereby maintaining the immense biological diversity. The role of coral reefs as nitrogen fixers (Sorokin 1993) contribute to the productivity of adjacent pelagic communities due to the release of excess nitrogen fixed in the reef ecosystem (D'Elia 1988, Sorokin 1990).

1.2 Changes in coral reef ecosystems and their implications

Coral reef ecosystems are highly dynamic and extremely sensitive to the fluctuations in their environmental conditions. Despite their services, the coral reef ecosystems are under continuous degradation globally due to human induced climate change and environmental pollution (IPCC 2001, Wilkinson 2008, Riegl et al. 2012). The rate of degradation of corals was high enough to thrust the corals to the risk of extinction (Carpenter et al. 2008). The carbon dioxide and temperature levels are projected to exceed their threshold limit to corals pushing them to extreme conditions which they had never experienced before (Hughes et al. 2003). The climate change exert its impacts through variety of processes including warming seas, ocean acidification, diseases, altered currents, strong storms and rising seas. All these processes are capable of degrading corals by inducing physiological stress response and mechanical damage. Loss of corals will result in trophic cascades and turns a coral dominant reef in to an algal dominant reef losing its aesthetic values and functions.

The ever increasing Sea Surface Temperature (SST) disrupts the coral-algal symbiosis resulting in coral bleaching (Brown 1996). Corals, the major reef building organisms are the visible bio-indicators alarming the rise in SST. The major bleaching event that occurred in 1998 significantly reduced the live coral cover up to 50% globally (Wilkinson 2000). Since then, the frequency of bleaching events increased though they were less severe compared to the 1998 event and become a common phenomenon globally, reducing the live coral cover in most of the reefs (Spencer et al. 2000, Marshall and Baird 2000, Arthur 2000, McClanahan 2007a). Coral bleaching leads to severe ecological implications including coral mortality, reduced coral growth, changes in community structure, decrease in species diversity and decrease in reef fish assemblage (Booth and Beretta 2002, Bellwood et al. 2006a, Baird and Marshall 2002, Glynn 1996, Ostrander et al. 2000). In addition, coral bleaching also weakens the reef frame work and results in the loss of critical habitats for the reef fishes (Baker et al. 2008).

The uptake of CO_2 by the ocean reduced the pH of the seawater and it influences the biological systems in the ocean. Changes in pH of the ocean compromise the role of corals as the primary reef building organisms by affecting the coral growth and calcification process making them more vulnerable to natural stress (Feeley et al. 2004). The growth of corals and other calcifying organisms has to be at pace with the erosion failing which the ocean acidification process will lead to loss of corals by eroding their skeleton thereby weakening the reef frame work. In addition, high CO_2 induces bleaching in corals and also decrease their productivity (Anthony et al. 2008).

Coral diseases linked to climate change are often difficult to predict as several factors are involved in inducing the outbreak of diseases (Bourne et al. 2009, Ainsworth et al. 2010). Transport of Aeolian dust from Saharan Africa is considered to be the outcome of climate change and hypothesized to cause coral disease in Caribbean reefs (Shinn et al. 2000). The Sea level rise linked to climate change is not a major threat to corals as the projected rates of increase in sea level is low enough to keep the fast growing corals at pace (Knowlton 2001). However, the existence of slow growing corals is at risk (Hoegh-Guldberg 1999). The frequency and severity of tropical storms is expected to increase in future. Gardner et al. (2005) reported that the Caribbean corals require at least 8 years to recover from the damage incurred by the storms. Increase in the frequency of the storms will reduce the time available for the corals to recover. The other impacts of climate change include changes in species composition, primary and secondary production, diversity and community structure (Harley et al. 2006).

Unlike climatic stressors which evoke a chronic response among corals, human activities inside a coral reef ecosystem evoke a quick lethal response among the coral population. Continuous increase in the coastal population along the tropics increased the risk to reefs in the form of sedimentation, pollution, coastal development and over exploitation of reef resources (Wilkinson 1999). Collectively, all these activities lead to the degradation of corals which will have profound implications over the entire reef ecosystem (Hodgson 1999, Halpern et al. 2008). The human induced threats have weakened the recovery potential of corals from natural stress leading to their mortality and permanent loss (Ravindran et al. 2012). The reefs that occur adjacent to the land are severely affected by sedimentation (Dubinsky and Stambler 1996).

In shallow reefs there is a continuous re-suspension of sediments due to currents and tidal fluctuations which allows the sediment to settle on corals. This reduces the light available to corals for performing photosynthesis and depletes the energy stock of corals (Bryant et al. 1998). Organic and Inorganic pollution leads to nutrient enrichment in reefs that encourage algal population and bio-erosion thereby weakening the reef frame work (Glynn 1997). The impacts of nutrient enrichment are exaggerated with fishing pressure. Increased fishing pressure results in reduced herbivory which in turn promotes the algal growth in a coral dominated ecosystem. The macroalgae possess the potential to prevent the recovery of corals post a stress event like bleaching; kill the corals by secreting toxic metabolites (Rasher et al. 2011); trap the sediments and prevent the settlement of new coral colonies (Birrell et al. 2005).

1.3 What is Resilience?

The term Resilience refers to the ability of a system to absorb the recurrent stress and adapt to it without changing to an alternate stable state and maintain its functions (Hughes et al. 2010). Several factors including live coral cover and diversity, herbivore fish biomass, coral recruitment, Ecosystem connectivity etc plays a critical role in strengthening the resilience potential of the coral reef ecosystems (McClanahan et al. 2012). Whereas, other factors like over exploitation of reef resources, frequent community phase shifts, increase in the frequency of natural threats, development of coastal areas adjacent to the reef and poor management of the reefs will weaken the resilience potential of the coral reef ecosystems.

1.4 Need for a Resilience based Management System

The coral reef ecosystems can recover to their normal state post a stress event provided with favorable conditions and no further disturbances from other sources. The recovery of corals post a stress event depends on numerous factors including food availability (Connolly et al. 2012), reef characteristics, reef connectivity, reduced anthropogenic stress (Graham et al. 2011), effective management through Marine Protected areas (MPAs) (Mumby and Harborne2010) and a healthy stock of herbivore fish population (Mumby et al. 2007). In addition to recovery, the corals have evolved adaptive strategies to withstand the stress generated by the processes of climate change (Berkelmans 2006). Corals mitigate the thermal stress through adaptive processes including symbiont shuffling (Rowan 2004, Kinzie et al. 2001), acclimatization and genetic adaptation (Coles and Brown 2003). Corals also possess internal mechanisms to adapt ocean acidification by up regulating the pH at their site of calcification (McCulloch et al. 2012). The impacts of climate change processes are exacerbated when combined with the impacts generated by local scale regional stressors. No adaptive mechanisms have been described to be possessed by corals against human induced local threats.

Majority of the studies describing the impacts of climate change and environmental stress deal with individual level changes in response to a single factor (Hughes et al. 2003, Harley et al. 2006). Under natural conditions, two or more factors interact and act synergistically to drive the organism beyond their threshold limit. It is important to address the synergistic effect of climatic and environmental factor as the effect of one factor can either strengthen or dilute the effect of other factor. MPAs offer protection to the reefs at different scales from human induced threats. However, the profound activities of humans inside the reef ecosystem and poor execution of the management practices have diluted the potential of MPAs from protecting the reefs. The coral ecosystems can be managed by regulating the human activities inside it. However, such regulations cannot prevent the changing climate or warming seas from taking toll over corals. A resilience based management strategy is essential to minimize the impacts generated by the climatic processes thereby to facilitate and enhance the natural recovery of corals post a disturbance event.

1.5 Scientific Knowledge on the corals of Indian Reefs

India has a vast coast line that extends up to 8000 km. Coral reefs occur along the Gulf of Kachchh and Lakshadweep archipelago on the west coast and Gulf of Mannar(GoM) & Palk Bay and Andaman & Nicobar Islands in the east coast (Vineeta

Hoon 1998) (Fig 1.1). Lakshadweep reefs are coral atolls whereas the other reefs are of fringing and barrier reefs. Small patchy reefs occur along the central western coast of India between Maharastra and Goa (Venkataraman et al. 2003). Andaman & Nicobar Islands in the Bay of Bengal and Lakshadweep Islands in the Arabian Sea are the major reef formations in India encompassing a reef flat area of 795.7 km^2 and 136.5 km^2 respectively. Coral reefs are estimated to cover an approximate area of 2375 km^2 in India (Venkataraman 2007).

The Palk Bay reef in the southeast coast of India is the study area chosen for this study. It occurs between the Latitude 9°55’-10°45’N and Longitude 78°58’-79°55’E. The Palk Bay reef is of fringing type located 200-500 m away from the shore. The reef is discontinuous and extends about 7 km towards the north eastern side of Mandapam peninsula. In total, 63 species of corals belonging to 23 genera were reported earlier in Palk Bay with variety of flora and fauna associated with it (Pillai 1969). The diversity and distribution of corals and other associated fauna in Palk Bay has been well documented (Mahadevan and Nayar 1972, Pillai 1969, Rao 1972). Few studies have addressed the impacts of Tsunami and bleaching on the corals of Palk Bay (Kumaraguru et al. 2005, Kumaraguru et al. 2003, Arthur 2000). However, the profound impacts of human activities and climatic factors at individual and at community level within the reef ecosystems of Palk Bay have not been addressed.

The corals in Palk Bay are strongly influenced by both the climatic and anthropogenic factors apart from the other biological agents. The Northeast (NE) monsoonal winds stir up sediments from the substrate increasing the amount of sediment settling on corals. This had reduced the live coral cover in Palk Bay and restricted the species diversity of corals to massive forms with large polyps which are capable of removing the sediments settling on them (Pillai 1975). Tropical cyclone that occurred in 1964 incurred severe mechanical damage to corals and reduced the live coral cover in Palk Bay (Pillai 1975). Increase in SST during summer results in Coral bleaching. Three major bleaching events were reported in Palk Bay reef which significantly reduced the live coral cover (Arthur 2000, Pet-Soede et al. 2000, Kumaraguru et al. 2003, Ravindran et al. 2012).

Sedimentation linked to the monsoonal patterns and tidal flux is the major factor affecting the corals in Palk Bay (Wilson 2005). Anthropogenic influences such as high fishing pressure, pollution, mechanical damage and high sedimentation have largely contributed to coral degradation in Palk Bay. Palk Bay reef was a potential fishing ground for small-scale fishermen throughout the year except during the period of NE monsoon that falls between October to December every year. The peak fishing season in Palk Bay is between January to September and the fishing effort ranges between 30 days boat^{-1} in the intensive reef fishing sites and 15±4 days boat^{-1} in lightly fished reef sites. The existing reef fishing practices in Palk Bay include deploying underwater cages, shore seine, trap nets, bait fishing and throw nets (Kumaraguru et al. 2008). Of these practices, trap net fishing and cage fishing incur mechanical damage to the corals affecting their structural complexity and these two practices are followed by majority of the fishermen in Palk Bay.

The biological agents that pose threat to the corals of Palk Bay include the predators and borers. While the predators feed directly on the coral polyps, the borers lead to the erosion of individual coral colonies (Ormond et al 1973). The borers include sponges, polychaetes, barnacles, bivalves and molluscs. Two species of polychaetes (Pillai 1975), 20 species of sponges (Thomas 1972) and 17 species of bivalves (Appukuttan 1972) were reported to be the common coral borers in Palk Bay.

1.6 Research Problem addressed

The Palk Bay reef in the Southeast coast of India is influenced by both climatic as well human activities to larger extent. The Gulf of Mannar Marine Biosphere Reserve (GoMBR) encompasses both Palk Bay and Gulf of Mannar (GoM). However, the Palk Bay was less protected compared to the adjacent GoM despite its biological significance and species richness. The corals in Palk Bay are highly influenced by bleaching, monsoonal pattern and sedimentation (Kumaraguru et al. 2003, Ravindran et al. 2012, Wilson et al. 2005). Human pressure in the form of reef fish exploitation, careless boat operations and pollution linked with the climatic factors such as thermal stress, monsoonal pattern and sedimentation and contribute to the degradation of corals in Palk Bay. The level of degradation of corals and the factors driving it are the critical problems that have obvious implications in formulating policy and improving the management of these ecosystems. Moreover, the 1998 bleaching event significantly reduced the live coral cover in Palk Bay. Thereafter two other major bleaching events were reported in 2002 and 2010 (Kumaraguru et al. 2003, Ravindran et al. 2012). There are no systematic studies that have quantified the recovery of corals and its resilience in Palk Bay post the bleaching events.

In the proposed study, I attempt to characterize the trend of those factors that influence the resilience potential of the Palk Bay reef. The resilience potential of a reef depends on numerous factors including coral recruitment, herbivore fish population, community-phase shifts, ecosystem connectivity and effective management. Knowledge on the trend of those factors that influence the resilience potential of a coral reef ecosystem of concern is essential, as it can help managers to avoid ecosystem catastrophes by devising a resilience based management strategy. At present there is no resilience based management system governing the Palk Bay. It is important to devise a local management strategy that focuses on the fisheries management, limitations of terrestrial input and offering protection to the core and adjacent ecosystems (Adam et al. 2011).

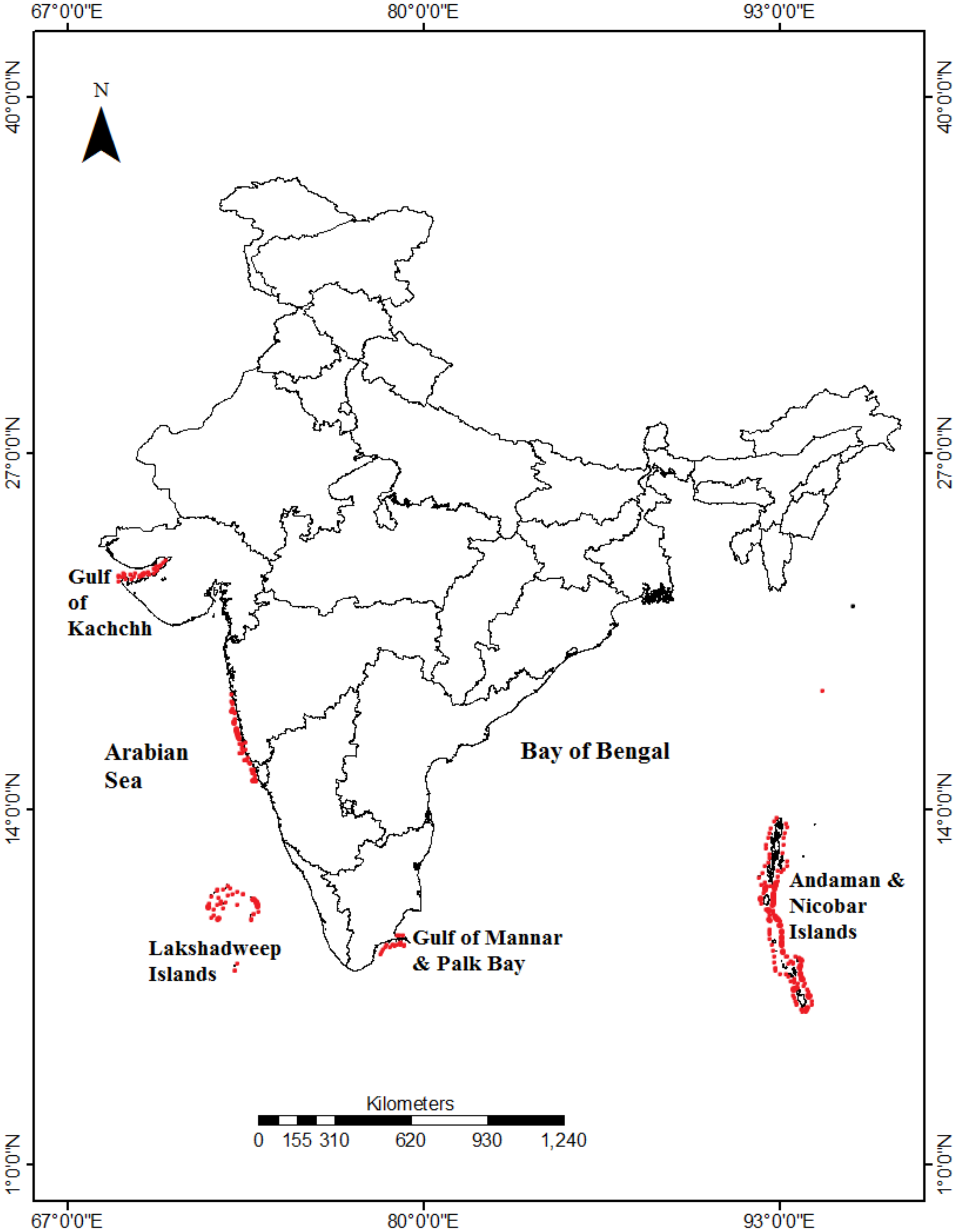


Fig 1.1. Map showing the distribution of coral reefs in India.

1.7 Major Objectives of the Study

- ✓ To determine the rate and recruitment pattern of corals and the survival rate of new recruits in Palk Bay.
- ✓ To determine the community dynamics and their impacts on the coral ecosystems of Palk Bay.
- ✓ To determine the bleaching and recovery patterns among the corals of Palk Bay.
- ✓ To determine the standing stock of reef fish and exploitation and its impact on coral ecosystem of Palk Bay.

Chapter 2

Coral recruitment pattern and survival of juvenile corals amid recurrent stress events

2.1. INTRODUCTION

Continuing degradation of global coral reefs warrant the need for a resilience based management of coral reef ecosystems which in turn require the evaluation of key factors that contribute to the recovery and resilience of a degraded reef. Corals are the primary reef building organisms and loss of corals deprives the functional and economic values of the reef affecting the reef dependents. The 1998 bleaching event degraded and reduced the live coral cover up to 50% worldwide (Wilkinson 2000). The Caribbean reefs are largely degraded due to hurricanes, overfishing and diseases and the live coral cover was reduced up to 90% (Hughes 1994). In Southeast Asia, the human activities including destructive fishing, overfishing, pollution, diseases and sedimentation from inland sources had largely contributed to the degradation of corals (Burke et al. 2006). Community shift towards an algal dominated state due to poor water quality and increased human pressure degraded the Florida reefs (Porter et al. 2002). Large scale mortality of corals in response to any stress event often leads to the replacement of corals with macroalgae or other benthic organisms (Bak et al. 1984, Alvarado et al. 2004, Norstorm et al. 2009). In order for these reefs to recover to a coral dominated state, an adequate supply of coral larvae from other pristine reefs were required that are able to settle and grow successfully resisting the stress conditions.

2.1.1. Coral recruitment and its contribution towards resilience

The worldwide degradation of corals underscores the need for an effective resilience based management system which in turn emphasizes the need for identifying the key resilience indicators in a reef ecosystem. Coral recruitment is one among the key resilience indicators that determines the health of a reef and helps in the development of a policy for an effective reef management (McClanahan et al. 2012, West and Salm 2003). In general, coral recruitment is defined as the successful settlement of the coral larvae over any hard substrate and attaining a size visible to a naked eye by growth (Moulding 2005). The sexual reproduction of corals and the ensuing larval dispersal enabled the corals to distribute their off-springs over a wide geographic area contributing to the replenishment of a degraded coral reef ecosystem.

Recovery of a coral population in a degraded reef post a stress event like bleaching, storm & cyclones and algal blooms depends on numerous factors including the regeneration of the affected colonies, self-seeding of the reef by the surviving colonies and supply of coral larvae from distant reefs (Obura 2005, Gilmour et al. 2013). High coral recruitment rate enables a reef to be coral dominant and the surviving recruits serve as the seeds for a degraded reef within few years of their settlement (Obura 2005). When the coral recruitment rates were high, the reef can recover quickly despite the type and severity of the disturbance event (Graham et al. 2011). Under reduced fishing pressure, successful settlement and recruitment of coral larvae has the potential to reverse an algal dominated reef in to a coral dominated reef (Elmhirst et al. 2009). Anthropogenic intervention has no significant impact on the recruitment of corals which in turn leads to the recovery of an anthropogenically disturbed reef (Sawall et al. 2013).

2.1.2. Factors affecting coral recruitment

The recovery potential of a degraded reef becomes undermined when the recruitment of new coral colonies becomes inadequate. Availability of coral larvae, their successful settlement and post settlement survivability are the three critical factors determining the recovery and maintenance of the degraded coral reef ecosystems (Ritson-Williams et al. 2009). Several stressors including poor water quality, human intervention, predation and climatic conditions influenced the coral larvae in different stages of their life history. Ocean acidification reduced the availability of Crustose Coralline Algae (CCA) which in turn reduced the coral larval settlement and their settlement behavior (Doropoulos et al. 2012). Experimental evidences indicate that Ocean acidification has the potential to reduce the fertilization rate and settlement success of coral larvae (Albright et al. 2010). Similarly coral bleaching which occurs as a result of elevated temperature and radiation has the potential to reduce the reproductive output of the corals (Baird and Marshall 2002).

The abundance and diversity of fishes in a coral reef ecosystem serves many purpose including creating substrates for coral recruitment by grazing the turf algae. Removal of reef fishes from the coral reef ecosystem influence the recruitment pattern of corals by enabling the proliferation of macroalgae over the available hard substrates. This in turn poses stiff competition to corals for space and prevents the settlement of new coral recruits (Kuffner et al. 2006). Similarly removal of predatory fishes, affected coral recruitment by producing a sea urchin dominated grazing community which in turn reduced the CCA cover (O'Leary et al. 2012). CCA induce the settlement of coral larvae by producing chemical signals (Heyward and Negri

1999). However, only few species of CCA facilitate the settlement of coral larvae and many other species of CCA possess anti settlement defence mechanism (Harrington et al. 2004). In Jamaican reefs, recovery of the herbivory sea urchin *Diadema* sp had promoted the density of new coral recruits (Carpenter and Edmunds 2006).

Macroalgae bloom which primarily occurs due to reduced herbivory, nutrient enrichment and wide spread coral mortality prevents the settlement and recruitment of new coral colonies by competing for space (Hughes 1994, Szmant 2002, Kuffner et al. 2006). Coral reef ecosystems with high macroalgae cover coupled with less coral recruitment and low growth rate of corals were extremely vulnerable to the disturbances generated by the processes of climate change (Hoey et al. 2011). Macroalgae kills corals and new coral recruits directly in variety of ways including smothering, mediating pathogens and secreting allelophobic chemicals (Rasher et al. 2011). Other than macroalgae, the turf algae in association with sediment inhibit the settlement of coral larvae (Arnold et al. 2010, Birrell et al. 2005).

In general, the density of new coral recruits was low in the areas with high sedimentation (Edmunds and Gray 2014, Trapon et al. 2013). Though high level of sedimentation has no impact on the gamete development or fecundity (Padillo-Gamina et al. 2014), it is known to reduce the level of fertilization success by preventing the settlement of coral larvae (Perez et al. 2014, Erftemeijer et al. 2012). Other natural stressors like cyclones will result in the loss of entire colony or patches of tissue within a coral colony which in turn compromise their sexual fecundity (Williams et al. 2008). Creating marine reserves and effective enforcement of laws minimized the human intervention inside the marine reserves and increased the density of new coral recruits which in turn promoted the resilience potential of the reef (Mumby et al. 2007).

2.1.3. Recruitment failure and its implications in the reef ecosystem

The inability of a degraded reef to regain their coral population and subsequently recover to a coral dominated state is largely due to the changes in the fecundity, fertilization success, larval dispersal and recruitment. Failure of any of the above process promotes shift in the community composition of corals and reduction in the live coral cover (Hughes et al. 2010). Coral recruitment failure leads to a lack of growth or retarded recovery of reefs in case of degradation and causes local extinction of species post a disturbance event (Hughes and Tanner 2000). Loss of corals also weaken the reef structure making it more vulnerable to the natural stressors like cyclones, wave action etc. and eliminate the important micro habitats available for fishes (Glynn 1997).

In addition to adequate supply of coral larvae and high recruitment rate, the survivability of the juvenile corals in response to the prevailing stress conditions in the recipient reef also plays a critical role in determining the resilience potential of a reef. The Palk Bay reef located in the southeast coast of India was largely affected by the 1998 bleaching event. Thereafter, two other massive bleaching events reported in 2002 and 2010 in the reef (Kumaraguru et al. 2003, Ravindran et al. 2012). Collectively, these events reduced the live coral cover, diversity and density of the corals in the reef. Recovery and resilience of the Palk Bay reef is not known as there were no systematic studies carried out in those lines. Live coral cover is a simple and powerful parameter to evaluate the status and health of a reef. Increase in the live coral cover is determined by the growth of the existing live corals and/or addition and growth of new recruits. Any process that alters the live coral cover indicates the reduction in the health of a reef and denotes their degradation. So, these parameters can be used to determine the resilience potential of a reef. The major goals under this objective was to assess the live coral cover, its diversity and recruitment pattern of juvenile corals as an indicator for determining the potential recovery and resilience of the coral reef assemblages in the Palk Bay reef through monitoring over a period of two years. Three spatially distant reefs were selected along Palk Bay which is influenced by the human activities at different levels. The specific goals of this objective include (i) to assess the live coral cover, its diversity and coral recruitment pattern (defined by the diversity, density, size structure and taxonomic composition of the juvenile corals) (ii) to determine the annual coral recruitment rate over the natural substrates such as dead coral skeleton and CCA and (iii) to assess the survivability of the juvenile corals during the observation period in response to the prevailing stress conditions in Palk Bay. This assessment will contribute in the management plan for the conservation of Palk Bay reef.

2.2. MATERIALS AND METHODS

2.2.1. Study sites

The study was carried out at three spatially distant reefs (Vedhalai, Mandapam and Pamban) along the Palk Bay named on the basis of their near shore locations and influenced by different scales of human activities (Fig 2.1). The human activities including reef fishing, drifting of boats, trawl boat passage, boat cleaning and shore seine operations were moderate in Vedhalai; high in Mandapam and low in Pamban reefs (Table 1). Two study sites were selected in each reef and observed for the live coral cover, rate and recruitment pattern of corals and survivorship of juvenile corals in response to the stress conditions prevailing in Palk Bay. The juvenile corals were identified to the genus level. In addition, diversity of adult coral colonies at the study sites was recorded to know whether the Palk Bay reef is self seeded or connected with other reefs. Species level identification of juvenile corals and adult coral colonies was not possible due to the legal restrictions in the collection of coral samples in India.

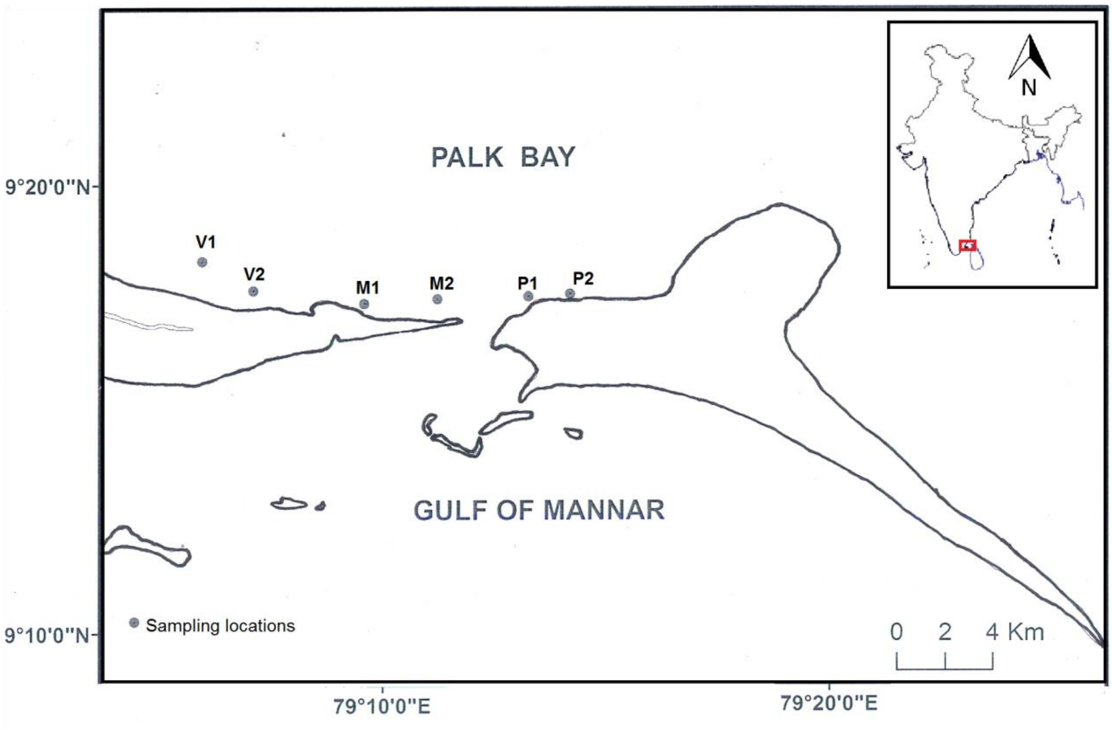


Fig 2.1. Map showing the location of the study sites observed for coral recruitment pattern and survivorship of juvenile corals at Palk Bay reef. V1 & V2 – Vedhalai; M1 & M2 – Mandapam; P1 & P2 – Pamban.

Table 1- Human activities and types of disturbances at the study locations along the Palk Bay reef.

Location	Disturbance level	Types of disturbances
Vedhalai	Moderate	Reef fishing; Drifting boats over corals; seaweeds culturing
Mandapam	Severe	Reef fishing, boat drifting; trawl boat operations; boat cleaning; sewage discharge; shore seine operations; trap net fishing
Pamban	Low	Reef fishing

2.2.2. Benthic composition

The percent cover of live corals and other benthic components including dead corals, macroalgae, rubbles and sand were estimated following the Line Intercept Transect (LIT) method (English et al. 1997). Four 20 m transects were established, two parallel to the shore and other two perpendicular to the shore at each study site. Benthic forms that falls under the transect were recorded and their average percent cover was calculated.

2.2.3. Coral recruitment pattern

A modified belt-transect method (English et al. 1997) with a swath of 5 m was employed to study the recruitment pattern of the juvenile corals at the study sites. Corals of the size ≤5 cm in diameter was considered for this study as it translates into both recruitment as well the survivability for~2yrs with a presumed growth rate of 1-3 mm diameter every month (Moulding 2005, Bak and Engel 1979). In total, four 20 m transects were laid, two parallel and two perpendicular to the shore at each study site. All the juvenile corals that fall within the effective width of the transect were enumerated, measured to their nearest size (mm) and identified at genus level (Veron 2000). The average density was expressed as a number of coral juveniles m^{-2} averaged over all the four transects at each study site. The taxonomic composition was calculated as the percentage of juveniles in each genus relative to the total number of juveniles in the other genera. The diversity of adult coral colonies was determined on the same transects surveyed for juvenile corals.

2.2.4. Coral recruitment rate

The recruitment rate of corals was assessed over the natural substrates such as dead coral skeleton and CCA following the permanent quadrat method (English et al. 1997). The standard method of deploying artificial substrates such as tiles was not employed, as it will not reflect the actual scenario. Moreover, the size of the juveniles of ≤5 cm which helped in this approach for the underwater observation. An area of 1 m^2 size comprising hard substratum such as dead coral skeleton, CCA etc. was demarcated using a portable quadrat and fixed in permanence. In total, 10 quadrats were established in each site and each quadrat was placed atleast 5 m apart during September 2012. The quadrats were thoroughly examined visually and also digitally using a high resolution underwater photography to create a baseline on the presence of juvenile corals. The quadrats were re-examined similar way in September 2014 for the presence of any juveniles. The juveniles within each quadrat were enumerated and pooled across the quadrats in each study site and reported as a number of juvenile corals 10 m^{-2} 2 $years^{-1}$.

2.2.5. Survivability of juvenile corals

The juvenile corals were tagged initially in September 2013 before the commencement of Northeast (NE) monsoon that usually occurs between October to December every year and the seawater remains turbid till March of the next year due to high level of suspended sediments. A total of 100 juveniles were tagged by nailing the numbered poly propylene tags at each study site to study their survival rate in response to the NE monsoon associated sedimentation stress. The tagged juveniles were visually and digitally observed post NE monsoon during April 2014 to estimate their survivability. The survivability was assessed by visually estimating the number of juveniles that were alive, dead and partially dead relative to the total number of juveniles that were tagged alive before the NE monsoon. Similarly, juveniles were tagged during March 2014 and thereafter monitored every month at regular intervals till September 2014 for their vulnerability to bleaching and related mortality.

Vulnerability is calculated as the percentage of juveniles that were bleached and remained unresponsive to bleaching relative to the total number of juveniles tagged.

2.2.6. Environmental conditions during stress events

The Palk Bay reef is influenced by both Southwest (SW) and NE monsoon. During NE monsoon, the wind generated waves stir up the bottom sediments and leave them in suspension thereby increasing the level of suspended sediments in the water column and the rate of sedimentation over corals. It is not possible to determine the rate of sedimentation by deploying sediment traps due to high wave action and poor visibility. Hence the amount of total suspended solids (TSS mg/l) in the water column was measured during the NE monsoon period (Oct 13 - Jan 14). In addition, TSS was also measured during the pre NE monsoon (Jun 13 – Sep 13) and post NE monsoon period (Feb 14 – May 14) to know the level of variation in the amount of TSS during different seasons.

Data on sea surface temperature (SST) was obtained from a daily 9 km optimum interpolated global SST (MODIS+TMI) dataset for the period of March 2014- August 2014 (www.misst.org). The data was a merged product of both day and night in the Infrared and microwave wavelengths. From those data, average SST for every eight days was calculated and plotted. Photosynthetically Active Radiation (PAR) data at the ocean surface with a spatial resolution of 4 km was obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite. Similar to SST, the PAR values averaged for every 8 days was obtained for the period of March to September in 2014. The data was downloaded from the website (http://oceandata.sci.gsfc.nasa.gov). MODIS-Aqua satellite has ocean bands 8, 9, 10, 11, 12, 13, 14 in the visible range and the PAR values are estimated using these bands with specific algorithms (Frouin 2002). Data was flagged off for few days within the study period due to its poor quality. The accuracy of PAR data from MODIS-Aqua has average errors in the order of 5-8%, with individual estimation errors as high as 21% (Van Laake and Sanchez-Azofeifa 2005). This PAR data was used, as the high resolution PAR measurements are not available in this region. Since the sampling depth is around 2 m in clear waters, the PAR value on the surface may not change significantly during the downwelling. This PAR value must be giving representative information on the available light as the conditions remain same in the water column.

2.2.7. Analysis

Analysis of the data included the comparison of diversity, density and taxonomic composition of juveniles across the study sites. Shannon diversity Index (H') and Pielou's evenness index (J') was calculated for both juvenile corals and adult coral colonies and compared. One-way Analysis of Variance (ANOVA) was used to test the significance of differences in the density of juveniles between the study sites in Palk Bay. The data on the density of juveniles at each study site has been log transformed to meet the assumptions of ANOVA including normality and homogeneity of variance. K-dominance curve was plotted for generic richness of the juveniles at the study sites where the different genera of the juvenile corals were ranked in their decreasing order of abundance. The relationship between the generic richness of the juveniles and adult coral colonies were analysed by calculating the correlations between the abundance of the juvenile corals and adults.

The study sites at Vedhalai, Mandapam and Pamban were segregated based on the taxonomic composition of the juveniles using Bray-Curtis similarity analysis under paired linkage. The data was fourth root transformed before the analysis. Analysis of Similarity (ANOSIM) was used to test the significance of differences in the taxonomic composition of juveniles between the study sites. Similarity percentage

(SIMPER) analysis was used to determine the contribution of each individual genus to the observed differences in generic composition between the study sites. All the analysis was performed using the PRIMER statistical software version 6.1.15 based on Warwick and Clarke (1991) and Clarke (1993).

2.3. RESULTS

2.3.1. Benthic composition

The average live coral cover along the Palk Bay reef was 8.25% and it was high in Vedhalai and low in Mandapam. The average live coral cover at the study sites varied between a minimum of 0.5% ± 7.7 (M2) to a maximum of 12.8% ± 4.5 (V1). The macroalgal cover was lower than the live coral cover at Vedhalai and Pamban and higher at Mandapam. Overall, macroalgae accounted for an average cover of 19.01% in Palk Bay and varied between a maximum of 27.9% ± 8.8 (V2) to a minimum of 2.1% ± 16.9 (V1) at the study sites. CCA were abundant in Mandapam and low in Vedhalai and Pamban. Also, the percent cover of Sand & Rubbles was several times higher in Mandapam compared to Vedhalai and Pamban. Average dead coral cover at Palk Bay was 27.4% and it varied among the study sites between 43.2% ± 15.8 (V1) to 8.3% ± 19.1 (M2). The percent cover of different benthic forms at the study sites of Palk Bay was summarized in the Fig 2.2.

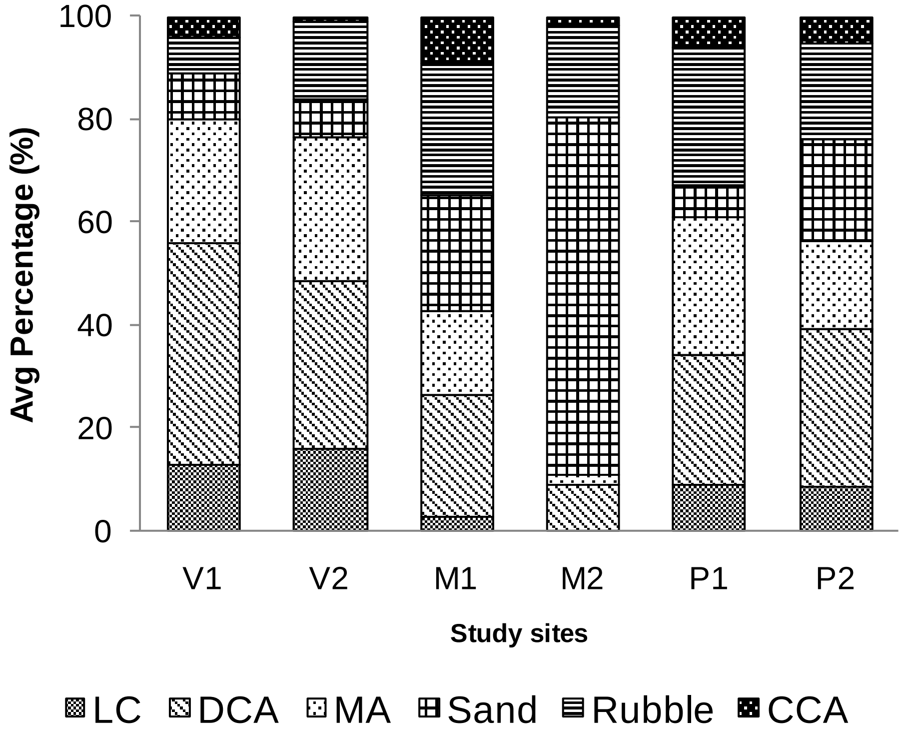


Fig 2.2. Average percent cover of different benthic forms at the study sites of Palk Bay. LC- live corals; DCA- dead corals with algae; MA- macroalgae; CCA- crustose coralline algae.

2.3.2. Juvenile and Adult coral diversity

The diversity of both juvenile and adult coral colonies were high in Pamban followed by Vedhalai and Mandapam. In total, 97 juveniles of 6 genera; 102 juveniles of 5 genera and 118 juveniles of 10 genera were recorded fromthe transects established at the study sites of Vedhalai, Mandapam and Pamban respectively. The mean generic richness of the juvenile corals across the study sites varied between a maximum of 10 genera (P2) to a minimum of 3 genera (M1). The corresponding Shannon diversity index (H', $\log_e$ based) was typically high in P2 (2.03±0.75) (Mean ± SD) and low in M1 (0.48±0.8) and the juveniles of different genera were more evenly distributed in P1 (0.87) and P2 (0.88) followed V2 (0.83) (Fig 2.3a). Juvenile corals of the genus *Leptastrea, Favia, Favites* and *Porites* were prevalent in all the study sites. Other juveniles of *Acropora*, *Goniastrea*, *Galaxea* and *Hydnophora* were present only at the study sites of Pamban and absent at Vedhalai and Mandapam. The study sites at Vedhalai and Mandapam were largely dominated by the juveniles of *Porites* and *Leptastrea* sp whereas the study sites at Pamban was dominated byjuveniles of *Goniastrea* and *Acropora* sp.

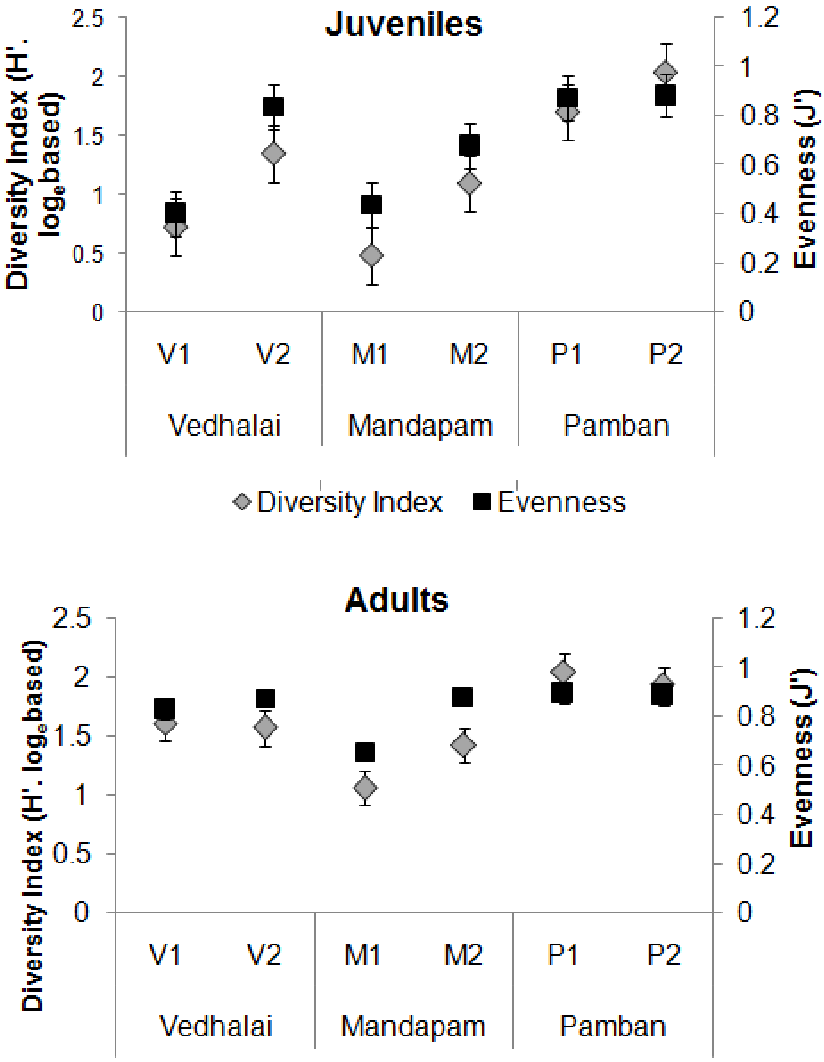


Fig 2.3. Shannon diversity index (H') and Pielou's evenness index (J') of the juvenile corals (2.3a) and adult coral colonies (2.3b) at the study sites of Palk Bay. Error bars indicate standard error.

Similar to juveniles, the diversity of adult coral colonies was high in the Pamban followed by Vedhalai and Mandapam. In total, 166 colonies of 7 genera; 35 colonies of 6 genera and 167 colonies of 12 genera were recorded fromthe transects established at the study sites of Vedhalai, Mandapam and Pamban respectively. The mean generic richness of the adult colonies varied between a minimum of 3 genera (M1) to a maximum of 12 genera (P2) and it showed a weak positive correlation with the diversity of juveniles corals (r= 0.59). The diversity index of adult colonies was high in P1 (2.055±0.4) and low in M1 (1.061±0.59) and adult colonies of different genera were more evenly distributed in P2 (0.91) and P1 (0.89) (Fig 2.3b). The highest generic diversity of the juveniles and adult coral colonies was evident in P2 and P1 as per the cumulative percentage of dominance of different genus ranked on the logarithmic scale (Fig 2.4a & 2.4b). However, the variation in generic richness of the juveniles (One-way ANOVA, F= 0.79; F_{crit}= 2.38; p value = 0.58>0.05) and adult colonies (One-way ANOVA, F= 1.6; F_{crit}= 2.31; p value = 0.15>0.05) was not statistically significant between the study sites.

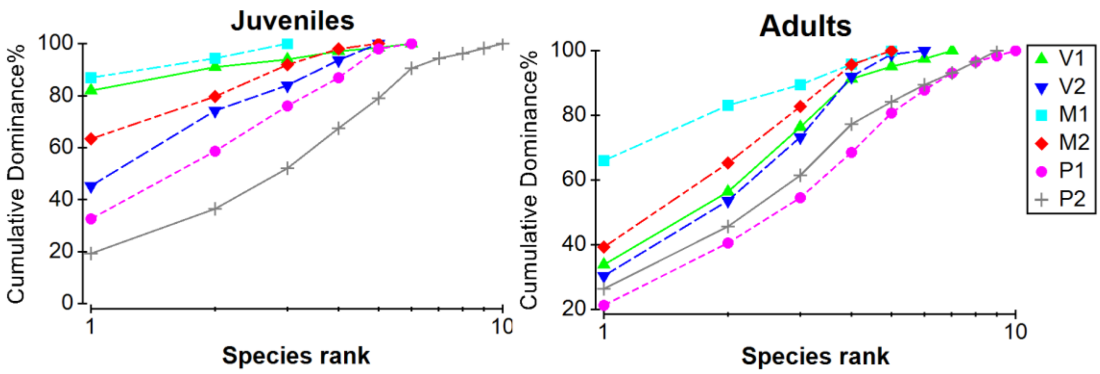


Fig 2.4. K-dominance curve showing the variation in the generic richness of juvenile corals (2.4a) and adult coral colonies (2.4b).

2.3.3. Density and Taxonomic composition of juvenile corals

Mean density of the juvenile corals was high in Pamban (5.35 recruits m^{-2}) followed by Mandapam (2.83 recruits m^{-2}) and Vedhalai (2.34 recruits m^{-2}). The average density of the juveniles differed significantly between the study sites (One-way ANOVA, F=6.07; F_{crit}= 2.25; p value = 0.00005<0.05) and it varied between a maximum of 6.2 ± 2.1 m^{-2} (P1) to a minimum of 1.4 ± 2.75 m^{-2} (M1) (Fig 2.5). *Leptastrea* and *Porites* sp were the most dominant genera contributing >90% to the total generic composition of the juveniles at the study sites V1 and M1 and >70% at V2 and M2. *Goniastrea* sp was dominant at P1 and P2 contributing >32% to the total generic composition. Juveniles of the *Galaxea* and *Hydnophora* sp were present only at P2 and each of these genera contribute <2.5% to total generic composition of the juveniles (Table 2).

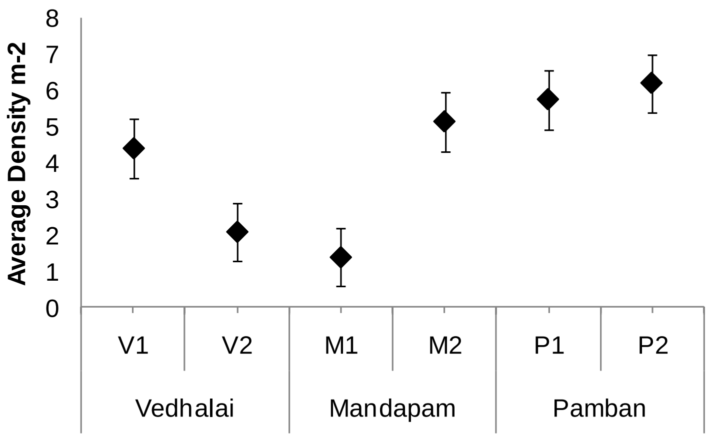


Fig 2.5. Average density of juvenile corals across the study sites of Palk Bay. Error bars indicate standard error.

Table 2- Taxonomic composition (%) of juvenile corals at the study sites of Palk Bay.

S.No	Genus	V1	V2	M1	M2	P1	P2
1	*Goniopora*	1.5	0.0	0.0	0.0	0.0	2.4
2	*Leptastrea*	81.8	45.2	86.8	12.2	10.9	14.6
3	*Porites*	9.1	29.0	7.5	63.3	17.4	12.2
4	*Favia*	3.0	9.7	5.7	6.1	26.1	14.6
5	*Favites*	3.0	9.7	0.0	16.3	10.9	22.0
6	*Cyphastrea*	1.5	6.5	0.0	2.0	0.0	4.9
7	*Goniastrea*	0.0	0.0	0.0	0.0	32.6	4.9
8	*Acropora*	0.0	0.0	0.0	0.0	2.2	19.5
9	*Galaxea*	0.0	0.0	0.0	0.0	0.0	2.4
10	*Hydnophora*	0.0	0.0	0.0	0.0	0.0	2.4

As per the results of Bray-Curtis cluster analysis under paired linkage, the study sites along the Palk Bay reef were grouped into 2 main clusters with 80% similarity based on the taxonomic composition of juvenile corals (Fig 2.6). The study sites P1 and P2 were grouped together and the study sites V1, V2 and M2 were merged in one single group due to the similarity in the taxonomic composition of juvenile corals. The study site M3 differed from other study sites in the taxonomic composition of juvenile corals and form an individual cluster. SIMPER analysis showed that the taxonomic composition of the juvenile corals was highly dissimilar between Mandapam and Pamban with an average dissimilarity of 41.80%. Abundance of the juveniles of *Goniastrea* and *Acropora* sp had largely contributed to the observed differences in the taxonomic composition of the juveniles between the study sites in Pamban, Vedhalai and Mandapam (Table 3).

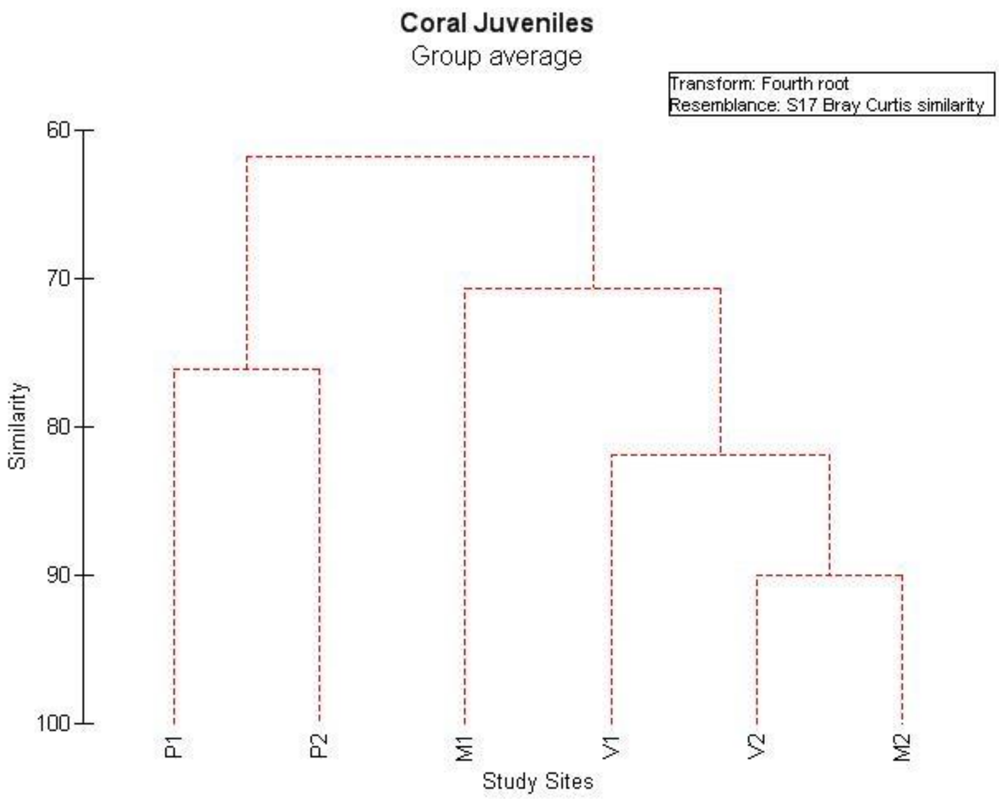


Fig 2.6. Bray-Curtis cluster analysis of the study sites at Palk Bay based on the taxonomic composition of the juvenile corals.

Table 3- Results of SIMPER analysis and One-way ANOSIM (R value and Significance level) on the abundance (percent cover) of juvenile corals at the study sites of Palk Bay reef.

Vedhalai vs Mandapam					
R value = -0.25; Level of Significance (%) = 100; Avg. dissimilarity= 21.70					
Benthic component	*Average abundance*		*Average dissimilarity*	*% contribution*	*Cum %*
	Vedhalai	*Mandapam*			
Favites	1.54	1.01	6.01	27.70	27.70
Cyphastrea	1.35	0.60	4.82	22.21	49.91
Goniopora	0.55	0	3.20	14.77	64.68
Porites	2.03	2.24	3.20	14.77	79.44
Leptastrea	2.80	2.46	3.19	14.71	94.15
Vedhalai vs Pamban					
R value = 1; Level of significance (%) = 10; Average dissimilarity- 36.10					
Benthic component	*Average abundance*		*Average dissimilarity*	*% contribution*	*Cum %*
	Vedhalai	*Pamban*			
Goniastrea	0	2.09	9.09	25.17	25.17
Acropora	0	1.77	7.47	20.69	45.85
Cyphastrea	1.35	0.50	4.39	12.16	58.01
Leptastrea	2.80	1.79	4.37	12.11	70.12
Goniopora	0.55	0.86	2.88	7.99	78.11
Favia	1.54	1.94	1.97	5.47	83.57
Mandapam vs Pamban					
R value = 0.917; Level of significance (%) = 10; Average dissimilarity- 41.80					
Genus	*Average abundance*		*Average dissimilarity*	*% contribution*	*Cum %*
	Mandapam	*Pamban*			
Goniastrea	0	2.09	10.00	23.92	23.92
Acropora	0	1.77	*8.19*	19.59	43.51
Favites	1.01	1.91	*5.24*	12.53	56.04
Goniopora	0	0.86	*3.86*	9.24	65.28
Leptastrea	2.46	1.79	*3.52*	8.43	73.71
Cyphastrea	0.60	0.50	*3.10*	7.41	81.12

2.3.4. Size structure of juvenile corals

The overall distribution of juvenile corals of various size classes varied between the study sites. The percentage of juvenile corals of <1 mm and >3 mm size were high at the study sites of Vedhalai and Pamban respectively. Whereas, juvenile corals of size 1-3 mm was high in Mandapam. The percentage of juvenile corals of <1 mm size varied between a minimum of 0 ± 13.8 at M1 to a maximum of 27.3 ± 13.5 at V1. Similarly, the juvenile corals of the size class 1-3 mm was high in M1 (67.9% ± 17.8) and low in P2 (32.1% ± 18). Juveniles corals of the size class 3-5 mm was high in P2 (51.8 ± 15.7) and low in V1 (19.7 ± 16.4) (Fig 2.7).

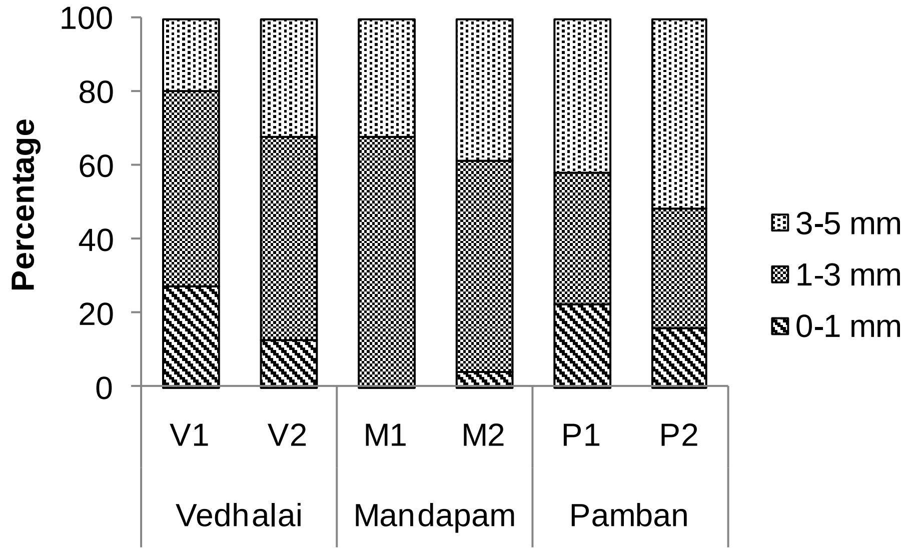


Fig 2.7. Average percentage composition of juvenile corals of different size classes at the study sites of Palk Bay.

2.3.5. Recruitment rate of corals

In total, 56 juvenile corals were recorded from the permanent quadrats deployed at all the study sites of Palk Bay during the study period. The rate of recruitment ranged between a minimum of 3 recruits 10 m^{-2} 2 yrs^{-1} (M1) to a maximum of 12 recruits 10 m^{-2} 2 yrs^{-1} (P2) across the study sites (Fig 2.8). The mean recruitment rate of the corals was high in Pamban (12 recruits 10 m^{-2} $2yrs^{-1}$) followed by Mandapam (6 recruits 10 m^{-2} $2yrs^{-1}$) and Vedhalai (5.5 recruits 10 m^{-2} $2yrs^{-}1$). Though the rate of recruitment showed variation, it does not differ significantly between the study sites (One-way ANOVA, F=1.4; F_{crit}=2.24; p value = 0.2>0.05). The size of the observed juveniles ranged between a minimum of 6 mm to a maximum of 10 mm in diameter. *In-situ* identification of the juveniles at species level was difficult due to their small size and poorly developed corallites.

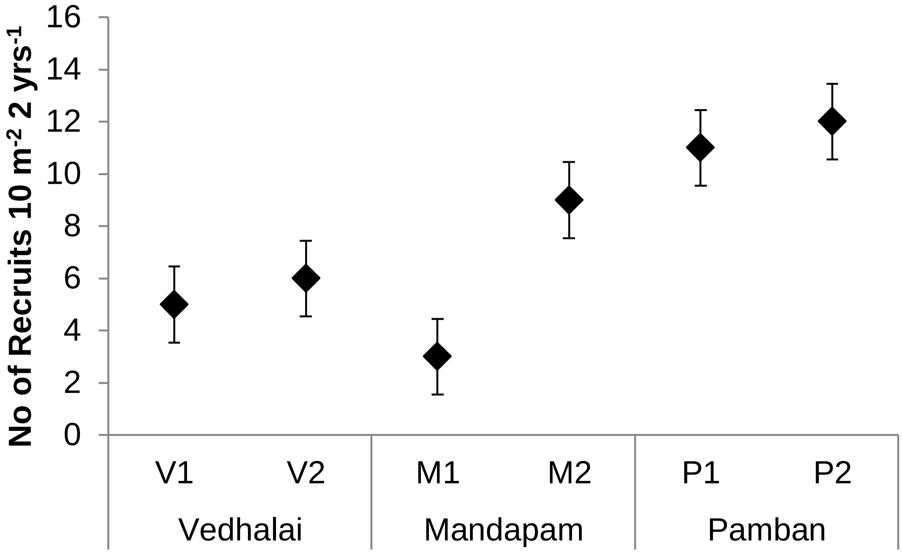


Fig 2.8. Recruitment rate of corals in the natural substrate during the study period of two years (2013-14) at the study sites of Palk Bay reef. Error bars indicate standard error.

2.3.6. Survival and Mortality of juvenile corals

A maximum of 93.1% of the juvenile corals survived the sedimentation stress during NE monsoon period. In total, 41 of 600 tagged juveniles were dead post NE monsoon corresponding to a relative mortality percentage of 6.9%. Individual corallites of the dead juveniles were covered with sediment and sand particles (Fig 2.9). Mortality in response to sedimentation was high with *Favia* sp (9.7%) followed by *Porites* sp (8%) (Fig 2.10). An average of 94% juveniles in Vedhalai and 93% juveniles each in Mandapam and Pamban survived the sedimentation stress during the NE monsoon. Though the survivability and mortality of the juvenile corals varied across the study sites along the Palk Bay reef, it did not show a statistically significant variation (One-way ANOVA, $F=0.351$; $F_{crit=}$ 2.57; p value $0.9>0.05$). The survival and mortality rate of the juveniles in response to sedimentation at each study site was summarized in the Fig 2.11.

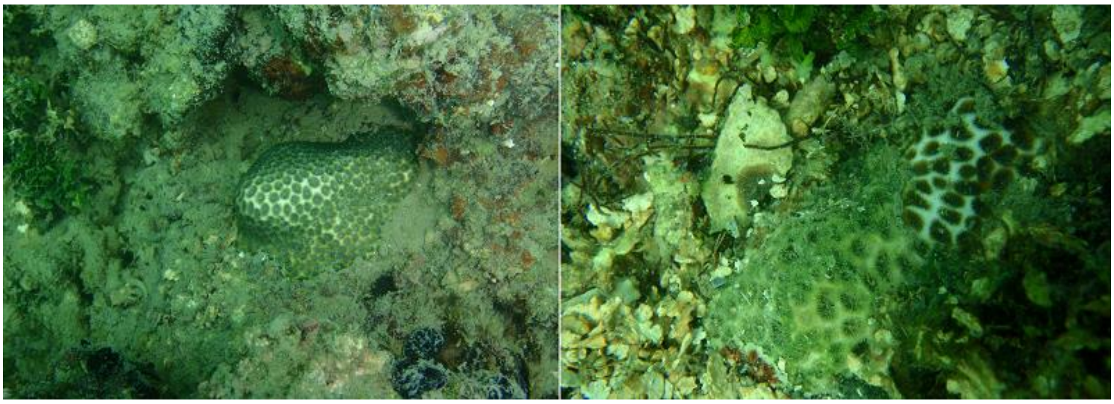


Fig 2.9. *Leptastrea* sp that was tagged alive before Northeast Monsoon (NE) observed dead post NE monsoon. Individual corallites of the juvenile were covered with sand particles.

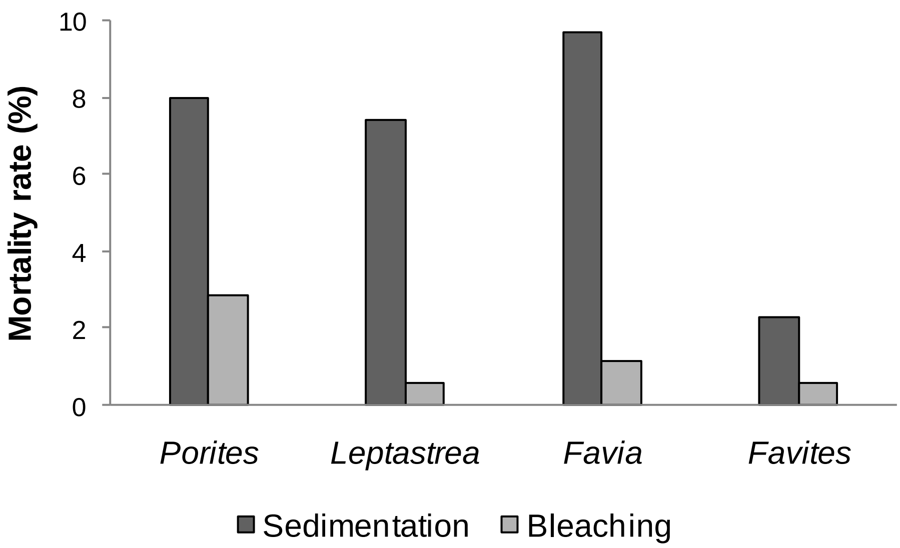


Fig 2.10. Average percentage of mortality among juvenile corals of different genera in response to the sedimentation and bleaching stress at the study sites of Palk Bay.

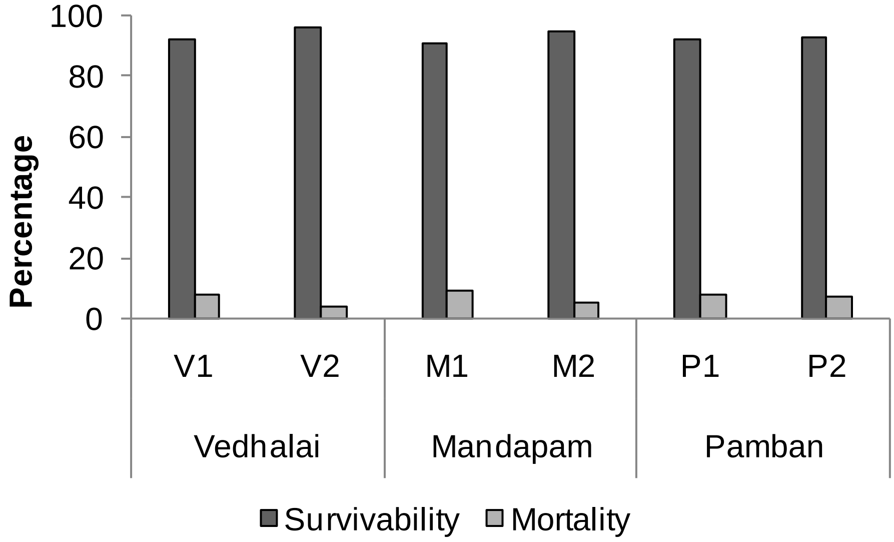


Fig 2.11. Average percentage of juvenile corals that survived and undergone mortality post the Northeast monsoon at the study sites of Palk Bay.

The juvenile corals that survived the sedimentation stress were continuously observed for their survivability in response to bleaching during the summer of 2014. Additional juvenile corals of the same genera were tagged to compensate for their loss due to sedimentation stress to makeup the number to 600. Similar to the sedimentation stress, there is no statistically significant difference in the survivorship of the coral juveniles in response to bleaching between the study sites (One-way ANOVA, $F=1.90$; $F_{crit}=2.57$; p value= $0.12>0.05$) during summer. Of the 600 juveniles tagged in total, 378 were bleached of which only 9 were observed to be dead corresponding to a relative percentage of 1.5%. The rate of mortality was high among the *Porites* sp and low with *Favites* and *Leptastrea* sp (Fig 2.10). A pooled average of 98.7% of the juveniles survived bleaching. No bleaching related mortality was observed among the coral juveniles at the study sites of Vedhalai. Whereas, an average of 2.5% and 1.4% juveniles undergone mortality at the study sites of Mandapam and Pamban respectively. An average of 54% of the juveniles bleached and 46% were not. The average percentage of bleached juveniles were high in Pamban (61% ± 8.2) compared to Vedhalai (48.5 ± 5.5) and Mandapam (49% ± 3.8). The percentage of juveniles that were bleached and non-bleached at each study site was presented in the Fig 2.12a. Juveniles of *Porites* sp were highly sensitive to bleaching as 76.5% of them were bleached whereas, *Leptastrea* sp were least sensitive with 35.4% of bleaching. The percentage of juvenile corals of different genera that were bleached and non-bleached was presented in the Fig 2.12b.

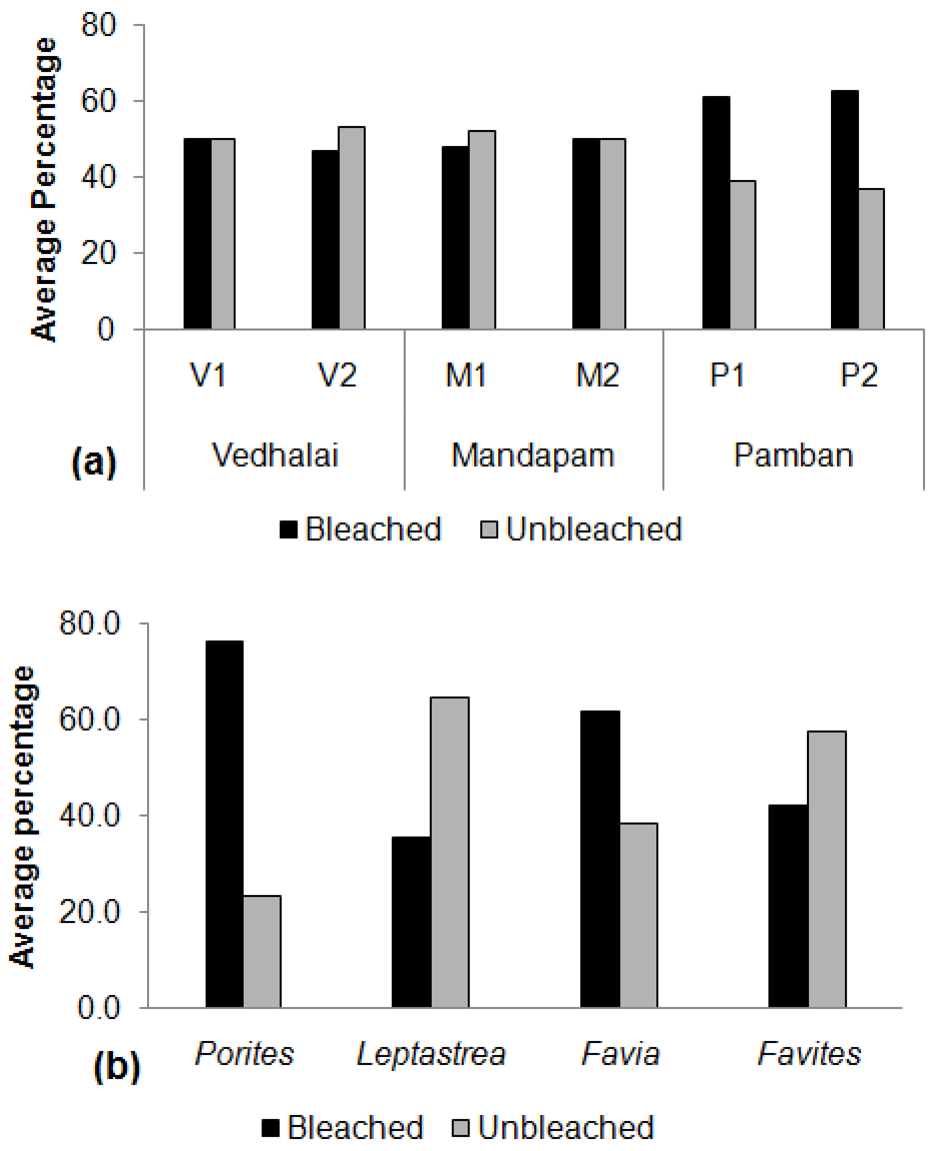
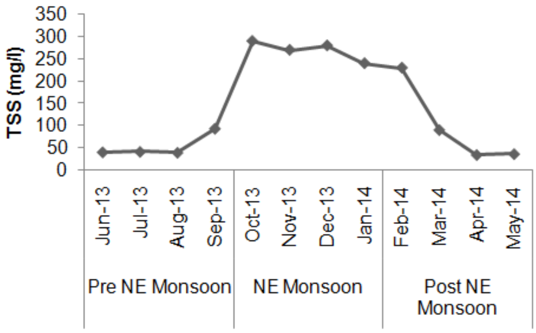


Fig 2.12. Average percentage of juvenile corals that was bleached and unbleached during the summer 2014 at each study site (2.12a) and between juveniles of different genera (2.12b).

2.3.7. Environmental conditions during the stress events

There were no statistically significant differences in the amount of TSS (mg/l) in the water column between the study sites in Palk Bay (One-way ANOVA, F=0.83; F_{crit}=2.57; p value= 0.6>0.05). Hence the data on TSS was pooled across the study sites and the average TSS was compared between the NE monsoon, pre-NE monsoon and post-NE monsoon periods. The amount of TSS was high during the NE monsoon period ranging a maximum of 290 ± 20 mg/l to a minimum of 240 ± 30 mg/l (Fig 2.13a). The amount of TSS during the pre and post monsoon periods was comparatively low ranging between 34-93 mg/l and it differs significantly from that of the amount of TSS during NE monsoon period (One-way ANOVA, df=2; F=16.31; F_{crit}=4.25; p value = 0.001<0.05).



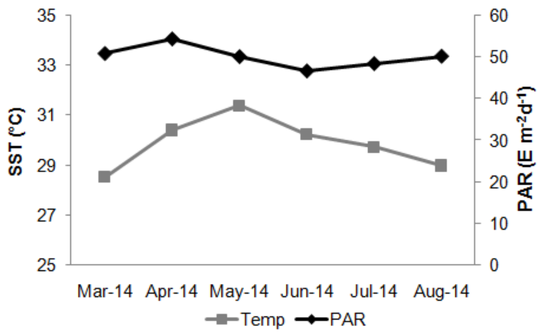


Fig 2.13. Average TSS (mg/l) during Northeast monsoon and non-monsoon periods at the study sites of Palk Bay (2.13a); Average Sea Surface Temperature (SST) and Photosynthetically Active Radiation (PAR) during the bleaching period in Palk Bay reef (2.13b).

The monthly variation in the average SST and PAR was presented in the Fig 2.13b. The average SST gradually increased above 28°C during March 2014 and it increased above 30°C in April 2014. It further increased above 30.5°C in May 2014 and remains persistent till June 2014. The average SST dropped below 30°C during the final week of June 2014 and further decreased below 29°C in July and August 2014. The average SST differs significantly between the successive months of bleaching (One-way ANOVA, df= 5; F=18.3; F_{crit}= 2.80; p value= 2.62E-06<0.05). Similarly, the average PAR also differs significantly during the bleaching period (One-way ANOVA, df= 5; F= 3.36; F_{crit}= 2.80; p value= 0.02<0.05). It was very high exceeding 51 $Em^{-2}d^{-1}$ during March 2014 and it remains high above 50E $m^{-2}d^{-1}$ till May 2014. It drops below 49 E $m^{-2}d^{-1}$ during first week of June 2014.

2.4. DISCUSSION

The average live coral cover in Palk Bay reported in this study is low compared to the other major reefs in India and subtropical countries. Also, majority of the existing live corals were under stress due to turf and macroalgal smothering reducing the percent cover of healthy live corals (Manikandan et al. 2014). Presence of diverse and healthy live coral cover in a reef enhances its resilience by inhibiting the settlement of other species which are known to reduce coral growth and survival (Philips et al. 2014). However in Palk Bay, the diversity of the reef building corals was greatly reduced from their earlier record of 63 species to 34 species (Venkataraman and Rajkumar 2013). Massive and sub-massive forms of corals were dominant in Palk Bay which is likely to reduce the refugiums available for the other associated organisms such as reef fishes by reducing the substrate complexity (Komyakova et al. 2013). In the current scenario, the chances that live coral cover will contribute to the recovery and resilience of Palk Bay reef is less and it requires adequate supply of coral larvae from other pristine reefs to restore the lost diversity of corals.

Juvenile corals were more diverse and abundant in the less human influenced Pamban compared toVedhalai and Mandapam which are moderately and severely influenced by the human activities respectively. Ocean currents influence the distribution of juvenile corals through larval dispersal pattern at the time of coral spawning (Richmond 1987, Lee et al. 1992, Cowen and Sponaugle 2009). The exact time of coral spawning and the number of spawning events in a year is not known in the Indian reefs though few reports claim it to be occurring at the end of March every year (Raj and Patterson Edward 2010, Jasmine et al. 2013). In the neighboring Southeast Asian countries such as Indonesia and Malaysia the mass spawning event occurred at different time intervals between April to October (Tomascik et al. 1997, Muhammad faiz et al. 2015, Chelliah et al. 2013). Other than the natural factors, human induced disturbances such as reef fishing and boat drifting can affect the coral recruitment by reducing the structural complexity and the availability of hard substrates which are essential for the successful settlement of coral larvae. The reefs in Vedhalai and Mandapam are identified as reef fishing hot spots for small scale fisherman's and it had contributed largely to the reef degradation by transforming the healthy live corals into a turf algal smothered ones (Manikandan et al. 2014). In addition, other hard substrates such as dead coral skeleton were also smothered by the turf algae which have the potential to trap the suspended sediments from the water column and prevent the settlement of coral larvae (Birrell et al. 2005). Collectively, all these factors contributed to the lower diversity and density of the juvenile corals in Vedhalai and Mandapam compared to Pamban reefs.

The diversity of juvenile corals was similar to the adult coral colonies in Vedhalai and Mandapam and dissimilar in Pamban. This implies that the reef in Vedhalai and Mandapam is mostly self seeded and the reef in Pamban is connected to the other distant reefs in addition to self seeding. Juvenile corals of *Porites*, *Leptastrea*, *Favia* and *Favites* were highly prevalent along the entire Palk Bay reef and juveniles of *Acropora*,*Goniastrea*, *Galaxea* and *Hydnophora* sp were recorded only from the Pamban (Fig 2.14).

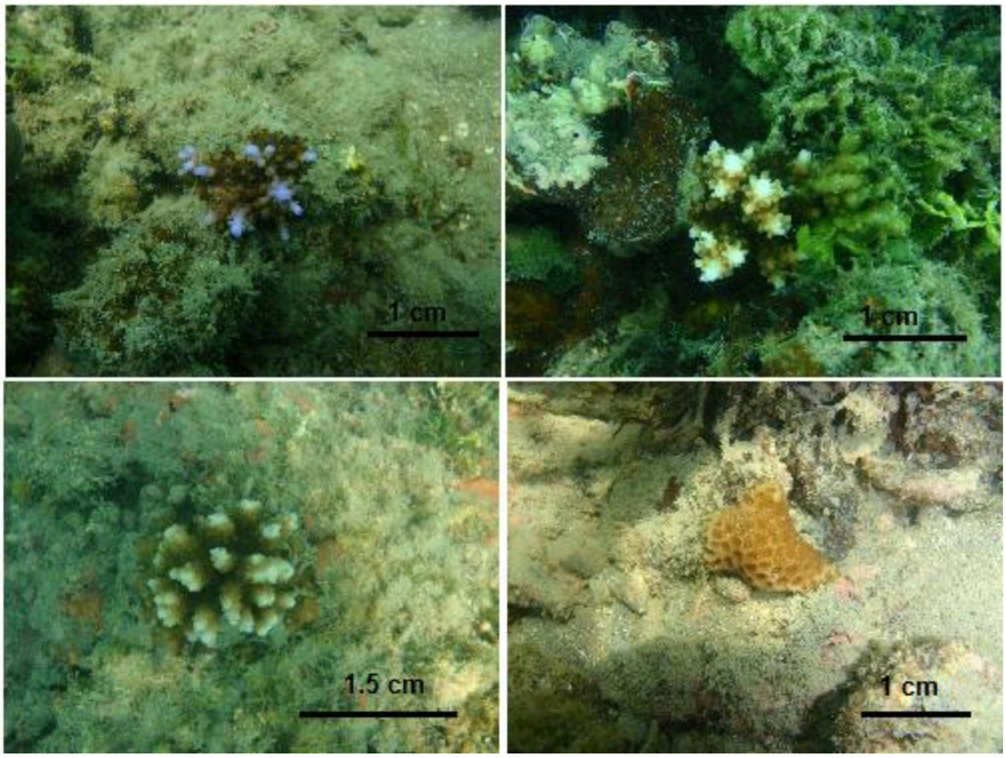


Fig 2.14. Juvenile corals of different species of *Acropora* (Top & Bottom left)and *Goniastrea* sp (Bottom right) at the study sites of Pamban in Palk Bay reef. Adult colonies of the same species were absent in Palk Bay reef.

However, the adult colonies of the same species was absent in Pamban implying that the larvae of these particular species might be transported from other distant reefs, most possibly from the Gulf of Mannar (GoM) reefs. This process of larval dispersal from a parent reef and its ensuing settlement and growth in a distant reef is termed as connectivity and it is a critical component contributing to the recovery and resilience of a reef (Mumby and Hastings 2008). The Palk Bay reef is separated from the adjacent coral islands of GoM by the Rameswaram Island. Mixing of water occurs between Palk Bay and GoM and vice versa through the Pamban pass channel and also through a series of submerged banks between India and Srilanka during NE and SW monsoon respectively (NIO 2012). The SW monsoon currents that occur between May-September are stronger compared to the NE monsoon currents during November-February (Shankar et al. 2002). The flow of water towards the west-east direction during SW monsoon might facilitate the transport of larvae from GoM to Palk Bay which could possibly have an influence over the distribution and diversity of coral juveniles at the Pamban along the Palk Bay reef.

Juvenile corals of higher size class (3-5 mm) were abundant in Pamban compared to Vedhalai and Mandapam. This implies that the survivability of the juvenile corals was maximum in the less human dominated reef environments. Juveniles of *Porites, Leptastrea, Favia* and *Favites* which are reported to be stress tolerant (Baker et al. 2008) were highly prevalent in the Vedhalai and Mandapam reefs where the human activities were high. This shows that juveniles of less tolerant coral species such as *Acropora* and *Goniastrea* sp are often unsuccessful and only the stress tolerant genera were successful in the human dominated reefs. Though the human activities have no direct impact over the reproductive potential of the corals or its recruitment, it can indirectly affect the coral recruitment by depleting the coral larval sources (Goreau et al. 2000), altering the water currents thereby altering the larval dispersal routes, and by creating the local pollution barriers which reduce the survivability of the coral larvae (Richmond 1993).

There are no reports on the density of juvenile corals from the other major reefs in India. The density of juvenile corals reported in this study was closer to those values reported in Mesoamerican barrier reef (Ruiz-Zarate and Arias Gonzalez 2004); Biscayne national park (Miller et al. 2000) and Gulf of Thailand (Yeemin et al. 2009). However, the values of juvenile coral densities were reported as high as 28 to 59.5 recruits m^{-2} in an undisturbed reef ecosystem such as Chagos archipelago (Sheppard et al. 2008) and Palymra atoll (Roth and Knowlton 2009). The variation in the juvenile coral density between Pamban, Vedhalai and Mandapam along the Palk Bay reef demands an explanation. Spatial variation in the juvenile coral densities is explained by numerous factors that include larval production in the parent reef, larval mortality, larval dispersal and their settlement and survival (Underwood and Keough 2001). The density of juvenile corals was high in the reefs with increased herbivory (Edmunds and Carpenter 2001), low turbidity and low sedimentation rate (Ruiz-zarate and Arias Gonzalez 2004). Apparently, any of these processes could contribute to lower density of juvenile corals in Vedhalai and Mandapam compared to Pamban along the Palk Bay reef. The density of the juvenile corals was not dependent on the abundance of adult coral colonies in a reef (Edmunds 2000). Hence, the density of juvenile corals was low in Vedhalai despite the high live coral cover compared to Pamban.

Coral recruitment rate during the study period of two years in Palk Bay reef was low compared to other major reefs and there are no reports on coral recruitment rate from other Indian reefs. Majority of the earlier studies employed the standard method of deploying settlement tiles to assess the rate of coral recruitment (Fisk and Harriot 1990, Dunstan and Johnson 1998, Adjeroud et al. 2007) which may not reflect the actual environmental condition. The rate of coral recruitment was high when they were provided with an artificial substratum like settlement tiles (Harriot and Fisk 1998, Glassom et al. 2004). In this study, the recruitment rate was assessed on the natural substrates in order to reflect the original scenario in the reef ecosystem of Palk Bay. Though there is an adequate larval supply, their successful settlement and growth determines the annual recruitment rate in a region. A very high sedimentation rate (Wilson et al. 2005) and a low herbivory process in Palk Bay reef (Manikandan et al. 2014) could possibly have a negative influence over the annual recruitment rate of corals in Palk Bay. The shallow nature of Palk Bay reef favors continuous re-suspension of sediments during NE monsoon, thereby increasing the rate of sedimentation over the corals. In addition, sediment transport from GoM to Palk Bay through the Pamban pass channel during SW monsoon also increased the rate of sedimentation over the reef ecosystems of Palk Bay (Rao 2002). Continuous increase in the rate of exploitation of reef herbivore fishes in Palk Bay favors the colonization and persistence of macroalgae. Collectively, these factors significantly reduced the substratum availability for the settlement of juvenile corals (Unpublished data).

Increase in the frequency of natural stress events like bleaching and predator outbreaks in the recent past minimized the time available for the recovery of coral populations (Donner et al. 2005) and also affects their fecundity (Baird and Marshall 2002). Though the new coral recruits were able to settle down and grow, their survivability in response to frequent stress events have significant implications over the recovery and resilience of a reef ecosystem. In this study, the survivorship of juvenile corals was assessed in response to increased sedimentation during NE monsoon and bleaching during summer which occurs back to back within a short time interval. The rate of mortality was low among the juvenile corals and it is important to note that the diversity of juvenile corals were dominated by *Leptastrea, Porites, Favia* and *Favites* sp all of which were reported to be stress tolerant (Baker et al. 2008). The prevalence of stress tolerant juvenile corals and their survivability in response to the prevailing stress conditions can potentially contribute to recover the live coral cover in Palk Bay reef.

The survivability of juvenile corals in response to sedimentation largely depends on their settlement position. In Palk Bay, majority of the coral juveniles settled on the vertical substrate and the *Leptastrea* sp settled largely under the holes and crevices (Personal observations). Also, the juveniles under the holes and crevices are highly pigmented to harbor maximum available sunlight under reduced light level due to increased suspended sediments in the water column. Apparently, these factors contributed to the success of juvenile corals in response to increased sedimentation. The juvenile corals were observed to be bleached in response to the increase in the SST during summer. The average SST increased above 31.5°C apparently higher than their normal bleaching thresholds (Fitt et al. 2001). The number of days during which the average SST rose above 30°C was also significantly higher during the bleaching event in 2014 compared to the bleaching episodes in previous years (Unpublished data). During such warm years, the juvenile corals were reported to grow slowly and die rapidly changing the generic abundance of juvenile corals in a region (Edmunds and Gray 2014). In contrast, the juvenile corals in Palk Bay recovered from bleaching despite the prolonged increase in SST above their threshold limits indicating their adaptive potential to the temperature stress.

In conclusion, results of this study suggest that human activities indirectly influenced the diversity and distribution of juvenile corals within a reef ecosystem which would transform into a serious implication over the community structure, recovery and resilience potential of the Palk Bay reef in future. The factors contributing to the observed variation in the juvenile coral recruitment pattern and its survivability needs further research. The chances that the existing live coral cover will contribute to the recovery and resilience of the Palk Bay reef is very low due to the continuous decrease in the healthy live coral cover. However, the current study found the evidence of reef connectivity in the Pamban region of the Palk Bay reef which will contribute to restore the coral diversity. Survival of juvenile corals in response to the prevailing stress conditions in Palk Bay is a promising factor of reef resilience and will enable the Palk Bay reef to be coral dominant in future. However, low diversity of corals will increase the vulnerability of Palk Bay reef to the species specific endemic diseases. Loss of corals in such cases will severely affect the Vedhalai and Mandapam reefs where the coral recruitment occurs mostly by self seeding.

Chapter 3

Coral community dynamics

3.1. INTRODUCTION

The coral reef ecosystems are subjected to sequential disturbances triggered by climatic and environmental factors that alter the community structure of a reef. Coral reef ecosystems are continuously degraded due to their frequent exposure to severe local scale disturbances induced by climate and human activities (Burke et al. 2006). These processes collectively changed the face of coral dominant systems into an algal dominant one. The corals and other reef organisms exist in a highly balanced state in order to maintain the community structure of a reef and its functions (Margaos et al. 1996). Any imbalance, due to the disturbances will lead to a decline in the live coral cover with an associated increase in the macroalgal cover (McCook 1999, Nystrom and Folke 2001, Szmant 2002) or other benthic organisms (Norstrom et al. 2009) collapsing the structure and entire functions of the reef.

The resilience of a coral reef ecosystem largely depends on its ability to absorb the recurrent stress and adapt to it without changing in to an alternate stable state (Hughes et al. 2010). Phase-shifts refers to a shift from one persistent assemblage of species to another species. In a coral reef ecosystem, phase-shifts often refers to a shift between the Coral and macroalgal populations. Coral - macroalgal phase-shifts have been earlier recorded in Great Barrier Reef, Hawaii, Reunion Island and Jamaica (Bak et al. 1984). The phase-shifts need not be always between the coral and macroalgae and it has been reported to occur with other species including sponges, zoanthids and tunicates (Chiappone et al. 2002, Alvarado et al. 2004, Norstorm et al. 2009). Though macro algae are the natural components contributing to the high productivity of the reef ecosystems, they are considered to be the dominant competitor for space and out-compete other reef organisms including corals. A shift towards the macroalgae population could be either reversible or irreversible. Recovery of a reef back to a coral dominant state depends on numerous factors including the coral species composition, herbivory process and other environmental conditions. Reversal of these phase-shifts occurred in some parts of Great Barrier Reef (Bellwood et al. 2006b, Diaz-Pulido et al. 2009), Caribbean reefs (Edmunds and Carpenter 2001) and Jamaica (Idjadi et al. 2006). However, certain coral reefs fail to recover post recurrent disturbances and remain stable in their alternate state mainly due to the chronic stressors which prevent their recovery and push the corals beyond their threshold limit leading to their mortality.

3.1.1. What triggers macroalgae bloom?

The undesirable persistent shift between the coral and algal population are often triggered by numerous environmental factors including over exploitation of reef herbivore fishes, added nutrients from point and non-point sources in land, coral mortality due to bleaching, predator outbreaks and recruitment failure (Bruno et al. 2009, Hughes et al. 2010, Fung et al. 2011). Any stressor which ultimately results in coral mortality and reef degradation leads to macroalgal shifts. Exploitation of herbivore fishes beyond their sustainable limit was considered to be the prime factor resulting in macroalgal dominance (Jennings and Kaiser 1998, McManus et al. 2000, Ledlie et al. 2007). In general, the herbivore reef fish are classified as scrapers, grazers and browsers based on its function in the reef (Bellwood 1994). Scrapers remove algae, sediment and other material by taking non-excavating bites thereby creating a substrate for the settlement of new recruits. Similarly, the grazers feed on epilithic turf algae which in turn limit the growth of macro algae (Bellwood and Choat 1990). Exploitation of these herbivore fish leads to severe catastrophic phase shifts affecting the structure and integrity of the reef. Nutrient enrichment has promoted the growth of macro algae over corals in the absence of herbivory (Thacker et al. 2001, Koop et al. 2001, Jompa and McCook 2002). In Jamaica, a combination of overfishing, hurricanes and diseases reduced the live coral cover with an increase in the macroalgal cover (Hughes 1994). A brief episode of coral bleaching which results in coral mortality subsequently leads to the dominance of macro algae (Ostrander et al. 2000).

3.1.2. Implications of macroalgae bloom in coral reef ecosystems

The impact of macro algae communities in coral reef ecosystems has been extensively reviewed and described (Tanner 1995, McCook et al. 2001, Kuffner et al. 2006). The macro algae can negatively influence the corals by smothering, shading, overgrowth, enhancing the coral microbial activity (Smith et al. 2006), being a vector harboring potential pathogens and affecting the regeneration of tissues (Bender et al. 2012). The calcium carbonate deposition during an occurrence of high algal biomass is largely attributable to the algal deposition and the so formed reef structure is inappropriate for fish habitat and shore line protection (McClanahan 1995). The algae, based on their functional properties differ in their effect on corals (Jompa and Mc Cook 2003). Recent studies showed the algae secrete toxic chemicals that killed live coral tissue (Rasher et al. 2011). The algal turfs trap the sediments and smother the corals thereby killing it. Propagation of macro algae during a bleaching episode could hinder the recovery of corals after bleaching (Ravindran et al. 2012). The corals were capable of recovering to their normal state after a major stress event like bleaching and it has been the key for reef resilience. Macroalgae and algal turfs in combination with sediment affect the coral resilience by preventing the settlement of new coral recruits (Birrell et al. 2005). Coral recruits require hard substrates including crustose coralline algae (CCA) for their successful settlement and growth. However, macroalgae pose a stiff competition by smothering the available hard substrates and prevent the settlement of new coral recruits (Kuffner et al. 2006).

Short term propagation of macroalgae was considered to be a normal process occurring in a reef (Hughes et al. 2010). Though macroalgae was a natural component in the reef ecosystem of Palk Bay, their dynamics and influence over the other benthic communities was less studied. The specific goal under this objective was to assess the changes in the benthic community structure driven by the macroalgal blooms. The study was carried out in two spatially distant locations, Vedhalai and Mandapam along the Palk Bay reef for a period of two years, 2013 and 2014. Though there are many factors that interact to cause macroalgal bloom, this study focus on the influence of such blooms over corals and other reef components and their subsequent recovery potential.

3.2. MATERIALS AND METHODS

3.2.1. Study sites

Two spatially distant reefs, Vedhalai and Mandapam along the Palk Bay reef were selected for monitoring the community dynamics. Vedhalai was located at the western end of the Palk Bay reef stretch and dominated by the live and dead corals of the genus *Porites*, *Favia* and *Favites* sp. The substratum was largely composed of broken coral fragments with intermittent sand patches. The depth ranges between a maximum of 3 m during high tide to a minimum of 2.3 m during low tide. The reef at Mandapam was located at the central part of the Palk Bay reef and dominated by CCA. The substratum was largely composed of sand patches and rubbles. Among live corals, *Porites* and *Leptastrea* sp were dominant. The depth ranges between a maximum of 2.1 m during high tide to a minimum of 1.3 m during low tide. Location of the study sites are shown in the Fig 3.1. The reefs at both Vedhalai and Mandapam are intensively fished and the standing stock of reef fish is consistently low with limited diversity of herbivore fishes (Manikandan et al. 2014).

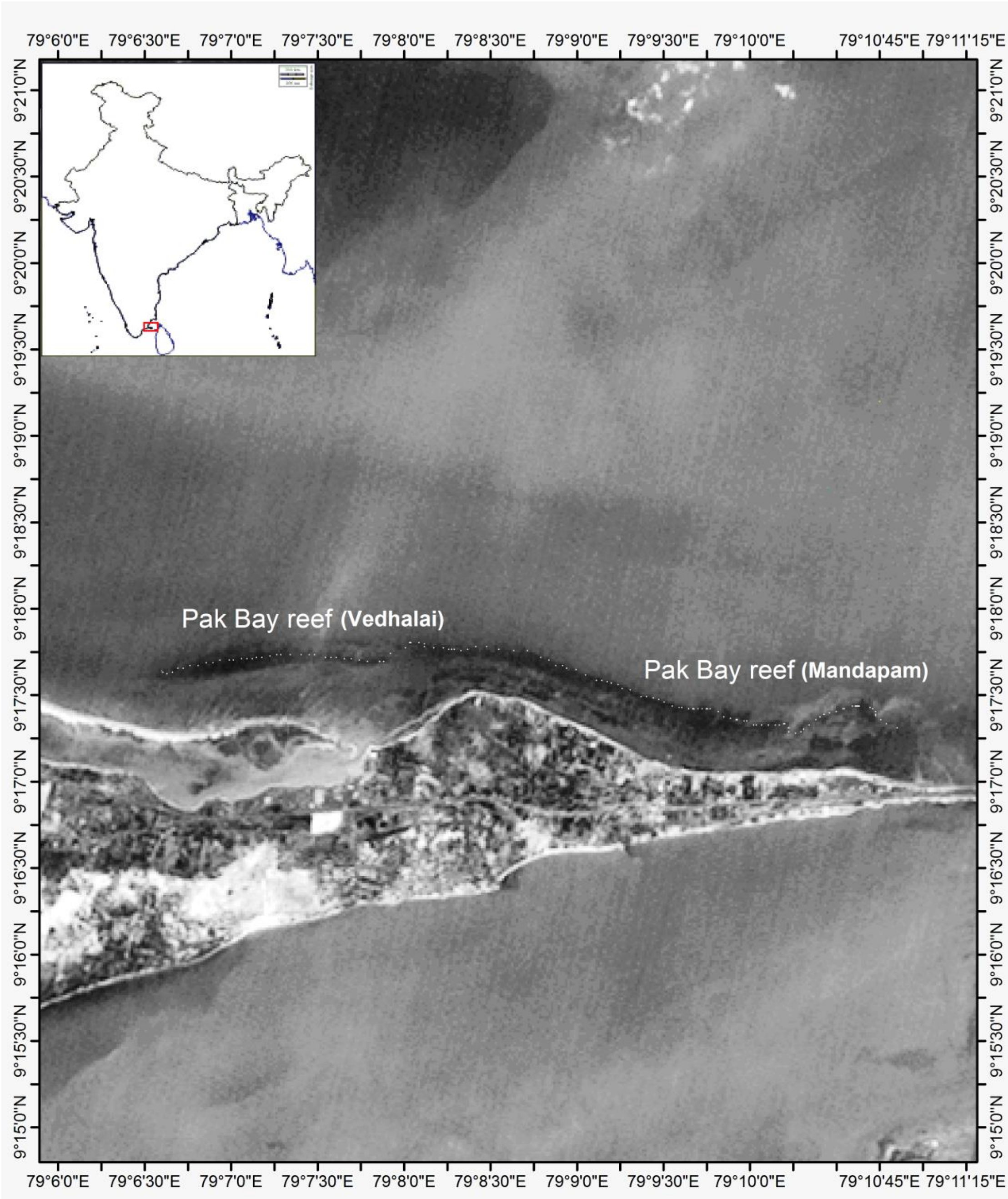


Fig 3.1. Map showing the reef outline along Vedhalai and Mandapam where the permanent quadrats were established to monitor community dynamics.

3.2.2. Photo-sampling method

A total of 200 quadrats of 1 m^2 size was established permanently in the study sites of Vedhalai and Mandapam (100 quadrats in each site) for monitoring the community dynamics. These permanent quadrats were precisely demarcated using nails for continuous systematic monitoring and each quadrat is parted from each other by atleast 2 m. Each quadrat was photographed individually using an Olympus µ-tough 8000 underwater camera in macro mode. The camera was mounted on to a custom made quadrat stand to ensure the proper positioning of the camera over the quadrat and to keep the focal distance and sampling area fixed. In addition, the corals within the quadrat were photographed individually for identification and the corals were identified using the standard keys described by Veron (2000) and Venkataraman et al. (2003). Preliminary survey on the percent cover of different benthic forms was carried out during September 2012. This data was used as a reference to compare the changes in the percent cover of different benthic forms during the subsequent observations in 2013 and 2014. Thereafter, the observations were carried out between April – September in 2013 and 2014. Other months are not supportive for conducting the survey due to monsoon and resultant poor visibility. The photographs of each individual quadrat were printed, overlaid on a graph sheet and processed to estimate the percent cover of different benthic forms following Manikandan et al. 2014. Those live corals which are healthy (HLC) and exhibiting partial mortality due to turf algal (LC/TA) and macroalgal colonization (LC/MA) was categorized individually to assess the status of existing live corals. The live corals in different states and other distinguishable features within the quadrat, both biotic and abiotic was traced in the graph sheet and their area cover was calculated with a factor of simple proportion relative to the total area of the quadrat in the graph sheet. The terminology used for different benthic categories and their description is given in Table 4.

Table 4- Terminology of different biophysical forms recorded from the study sites of Palk Bay and their codes and description.

Benthic Categories	Code	Description
Sand	S	Sand patch
Rubbles	R	Broken fragments of corals
Healthy Live Corals	HLC	Live corals without any infection by borers, turf and macroalgae
Live corals smothered by Turf algae	LC/TA	Live coral colony exhibiting partial mortality due to turf algal smothering.
Live corals smothered by Macroalgae	LC/MA	Live coral colony exhibiting partial mortality due to macroalgal colonization
Macroalgae	MA	Fleshy/weedy brown, red and green macroalgae
Halimeda	HA	Calcareous algae *Halimeda* sp
Dead Corals with algae	DCA	Dead Coral still standing, smothered by thin fibrous turf algae.
Crustose Coralline Algae	CCA	Heavily calcified hard calcareous red algae
Degraded Crustose Coralline Algae	DCCA	Crustose coralline Algae turned black in color and degraded.

3.2.3. Analysis

The percent cover of different benthic forms was calculated for each individual quadrat and the data retrieved from all the 100 quadrats in a study site was pooled to derive the average percent cover of each benthic form at the study site for the given time interval. A paired t- test was used to test the significance of variances in the temporal pattern of the percent cover of each benthic form during the study period. Since the macroalgal bloom reduced the availability of hard substratum, we used a linear regression analysis to determine the level of variation in the percent cover of hard substratum driven by the variation in the percent cover of macroalgae. The average percent cover of macroalgae grouped over the entire study period was used as an independent variable and the average percent cover of hard substratum cover was used as a dependent variable. The total percent cover of hard substratum is obtained by summing up the percent cover of live and dead corals in Vedhalai; CCA and live corals in Mandapam. All the analysis was performed using SPSS statistical software, Version 16.0. In addition, Bray-Curtis cluster analysis was done on the fourth root transformed data on the percent cover of different benthic forms to find out the similarities in the benthic composition over time. Multivariate analysis was performed using the statistical software PRIMER Version 6.1.15.

3.3. RESULTS

3.3.1. Initial assessment

Preliminary assessment carried out during September 2012 revealed that the coral reef communities at Vedhalai were dominated by Dead corals (49.2% cover) and HLC (14.6%), with a moderate cover of sand (11.4%), Macroalgae (8.9%) and *Halimeda* sp (6.3%). In total, 2.3% and 2.1% of the living corals were smothered by turf algae and macroalgae respectively. Five genera of corals including *Porites*, *Leptastrea, Favia*, *Favites* and *Cyphastrea* were recorded from the permanent quadrats established at the study site of Vedhalai. Corals of *Porites* and *Favia* sp were largely affected due to turf and macroalgal colonization.

Similarly, the coral reef communities at the study sites of Mandapam were dominated by CCA (48.9% cover), with a poor cover of HLC (1.2%), *Halimeda* sp (4.6%) and dead corals (0.22%). The sand patches were interspersed with rubbles and they together contribute 45.08% to the total benthic cover suggesting that the reef structure is less complex in Mandapam compared to Vedhalai. In total, 3 genera of corals were recorded including *Porites, Leptastrea* and *Favia.*No macroalgae was recorded from the permanent quadrats established at Mandapam during this preliminary assessment. The percent cover of different benthic forms during the preliminary assessment at the study sites of Vedhalai and Mandapam were presented in the Fig 3.2a and 3.2b respectively.

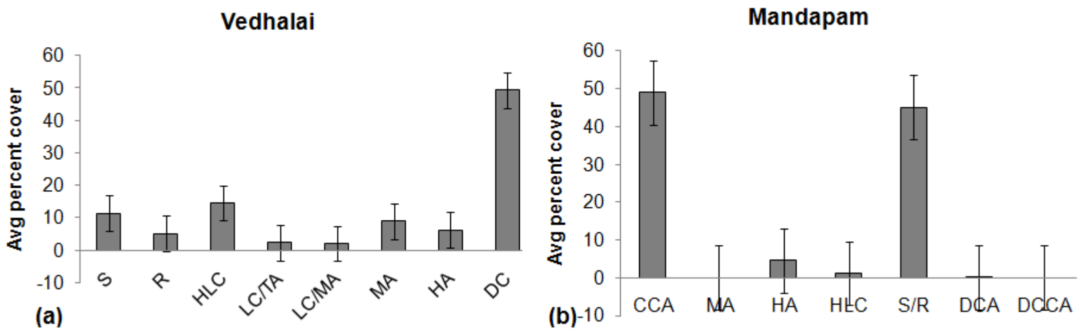


Fig 3.2. Average percent composition of different benthic forms at the study sites of Vedhalai (3.2a) and Mandapam (3.2b). Error bars represent standard deviation.

3.3.2. Coral community dynamics at Vedhalai

Caulerpa racemosa bloom was noticed as the observations were started in April for the year 2013. The *C. racemosa* bloom covered majority of the substratum and increased the percent cover of macroalgae to 24.6 ± 8.1% (Mean ± SD) during April 2013 at the study sites. This had decreased the percent cover of other benthic components including HLC. The percent cover of macroalgae further increased and reached a maximum of 25.8 ± 9.7% in May 2013. Further observations in June and July revealed a reduction in the percent cover of macroalgae to 8.3 ± 7.8%, mainly due to their seasonal dieback. The macroalgal cover was further reduced to 7.1 ± 9% at the end of observations in September 2013 (Fig 3.3a). Meanwhile, the HLC cover reduced to 10.3 ± 1.9% with a corresponding increase in the percent cover of LC/TA and LC/MA to 3.4 ± 0.2% and 2.7 ± 0.7% respectively (Fig 3.3b). Temporal pattern in the percent cover of different benthic forms at the study sites of Vedhalai varied between 2013 and 2014. The variation in the average percent cover of rubbles, LC/TA, *Halimeda* sp and Dead corals in 2013 and 2014 was statistically significant (p value <0.05). However, the variation in the average percent cover of HLC, macroalgae, LC/MA and sand was not statistically significant, p value > 0.05 (Table 5).

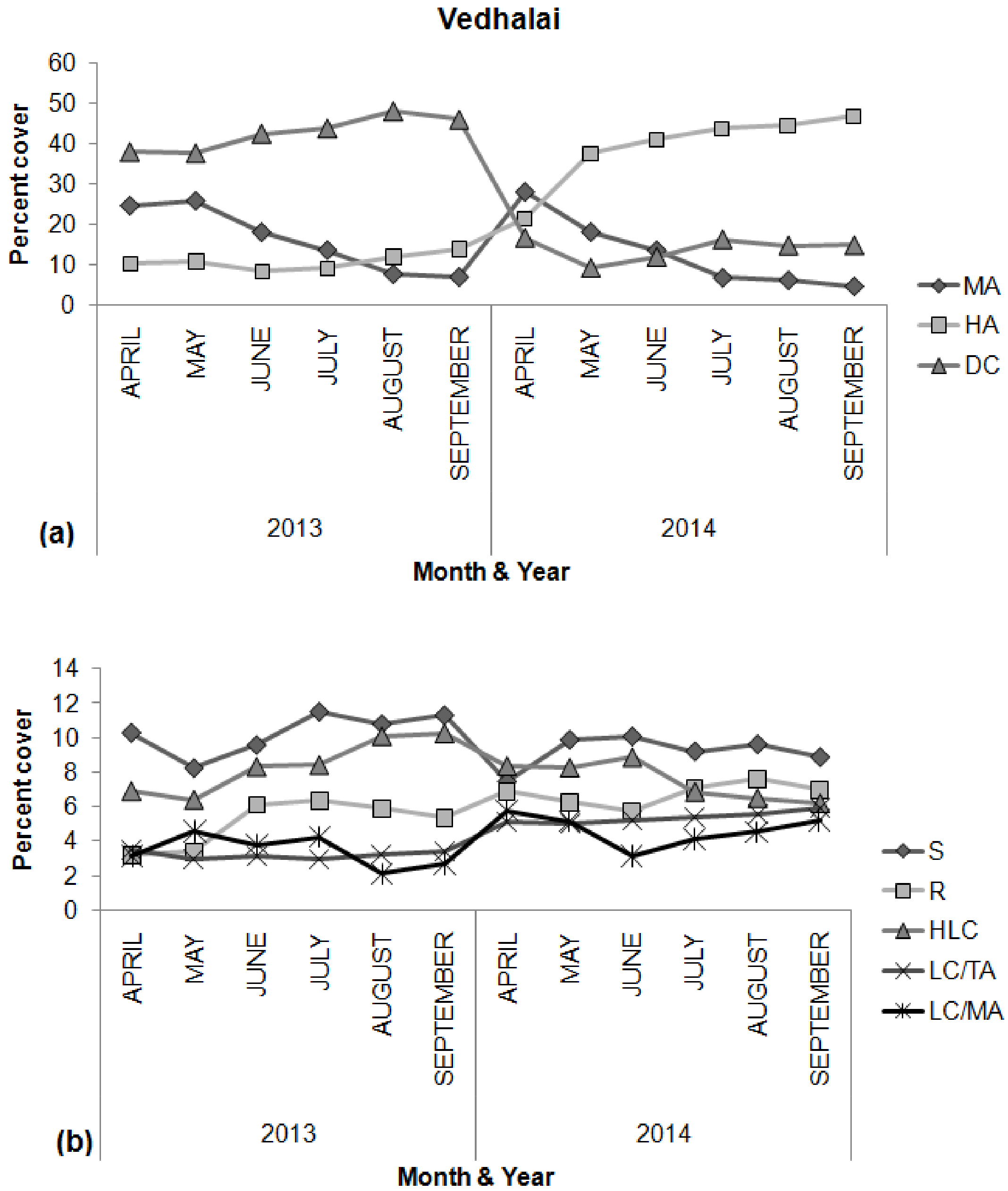


Fig 3.3. Temporal pattern in the average percent cover of different benthic forms at Vedhalai during 2013 and 2014.

Table 5- Results of paired t-test testing the significance of variation in the temporal pattern of the percent cover different benthic forms in Vedhalai.

Biophysical form	t value	df	Level of significance (0.05)
Sand	1.489	5	0.197
Rubble	-2.874	5	0.035
HLC	0.852	5	0.433
LC/TA	-15.8	5	0.0005
LC/MA	-2.058	5	0.095
MA	1.052	5	0.3
HA	-7.796	5	0.001
DCA	16.8	5	0.0005

Like 2013, the macroalgal cover was high during the months of April (27.9 ± 15) and May (18.9 ± 5.2) due to *C. racemosa* bloom with subsequent reduction of bloom in the following months of 2014. However, the calcareous algae *Halimeda* sp grew gradually in 2014 and their percent cover increased to 46.89 ± 7.6% during the final observations in September 2014. It grew as dense patches over the dead coral skeletons and other available hard substrates including live corals. No recovery signs were observed among the HLC and on the whole their percent cover decreased to 6.21 ± 1.3% compared to the initial cover of 14.6 ± 1.7% with a net reduction of 8.3% (Fig 3.4a). The decrease in the HLC cover is associated with an increase in the percent cover of LC/TA by 3.68% and LC/MA by 3.14%. Based on the coefficient of determination value (R^2= 0.98), 98% of the variation in the percent cover of hard substratum components including live and dead corals is driven by the variation in the percent cover of macroalgae (Fig 3.5a).

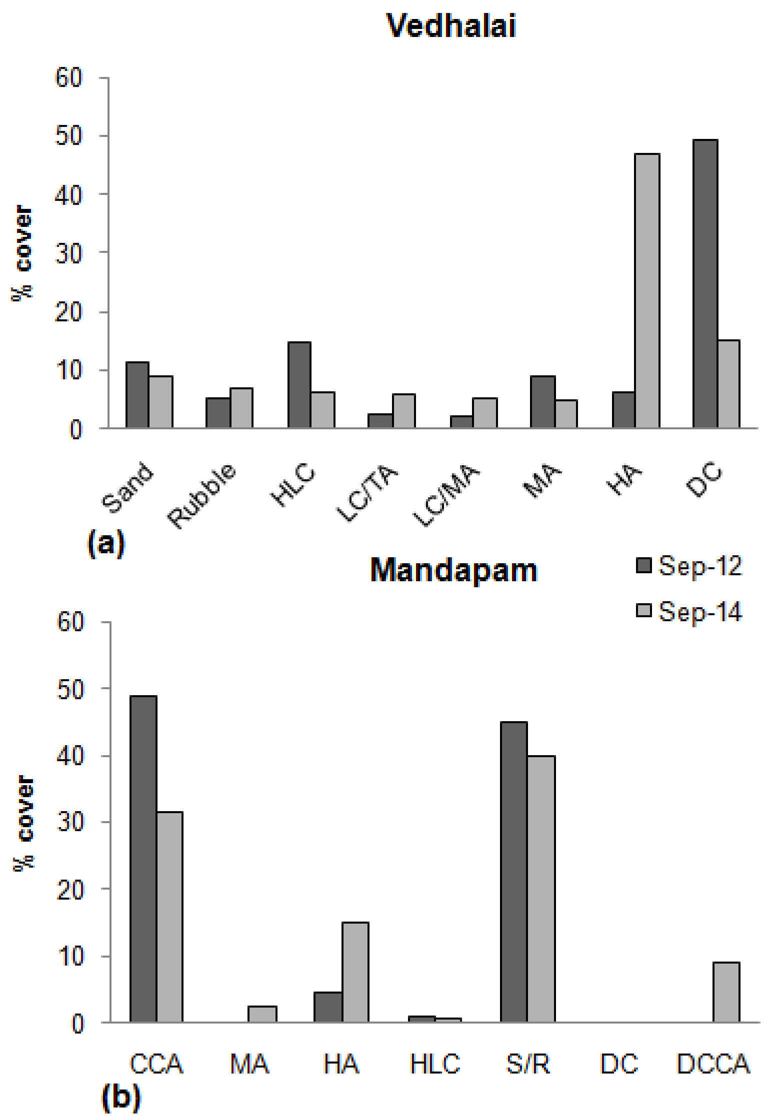


Fig 3.4. Comparison between the average percent cover of different benthic forms during the preliminary (Sep-2012) and final (Sep-2014) observations at Vedhalai (3.4a) and Mandapam (3.4b).

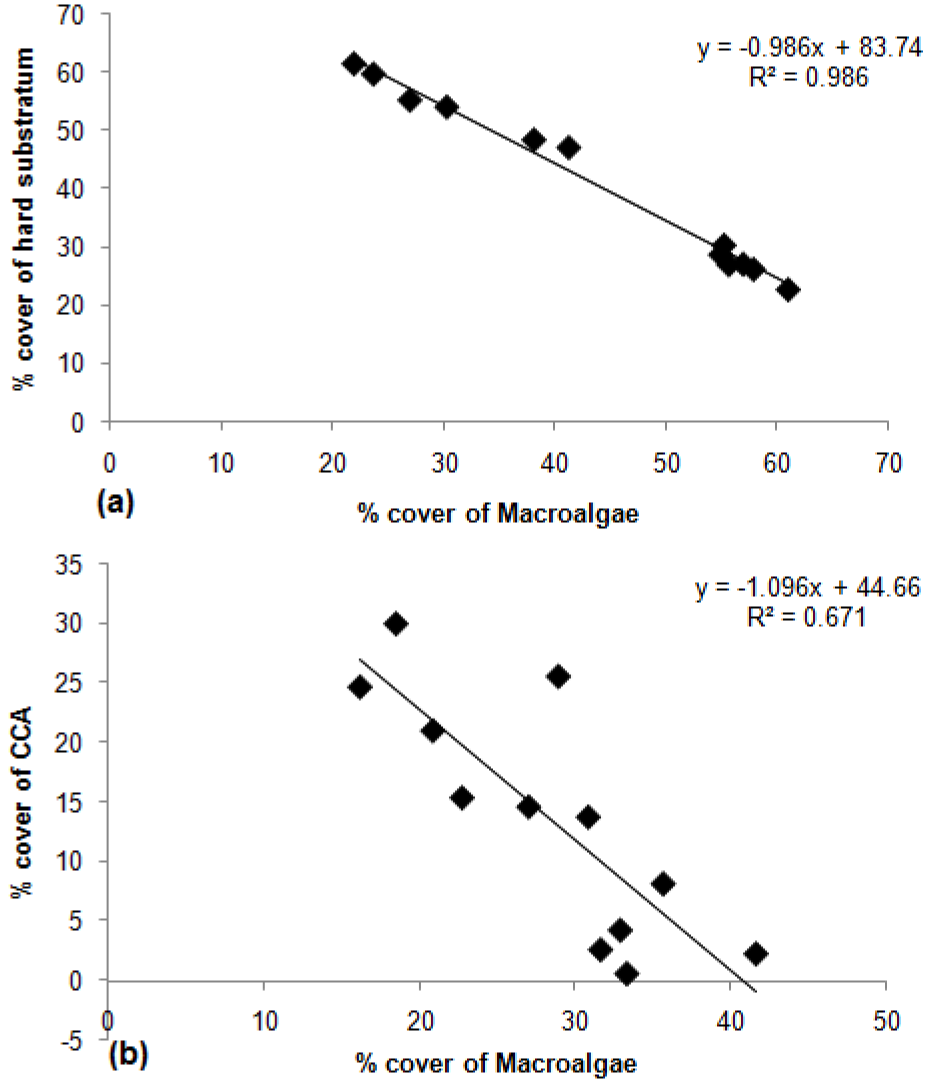


Fig 3.5. Relationship between the variations in the percent covers of macroalgae and hard substratum at Vedhalai (3.5a) and between macroalgae and CCA cover at Mandapam (3.5b).

The sampling months were grouped in to five individual clusters based on the similarity in the percent cover of different benthic components during the observations in Vedhalai (Fig 3.6). The consecutive sampling months of 2013 i.e. April-May, June-July and August-September each forms a single cluster with a similarity percentage of 97.7, 98.1 and 98.3% respectively. However in 2014, the April month forms a single cluster due to high macroalgal cover. The subsequent sampling months May-June and July-Sep forms two individual groups with similarity value of 96.9 and 98.8 % respectively. As per the results of SIMPER analysis, the benthic community structure in Vedhalai differed between 2013 and 2014 with an average dissimilarity of 11.45%. The abundant growth of *Halimeda* sp in 2014 and the subsequent decrease in the dead coral cover contributed a maximum of 28.7% and 25.15% respectively (Table 6).

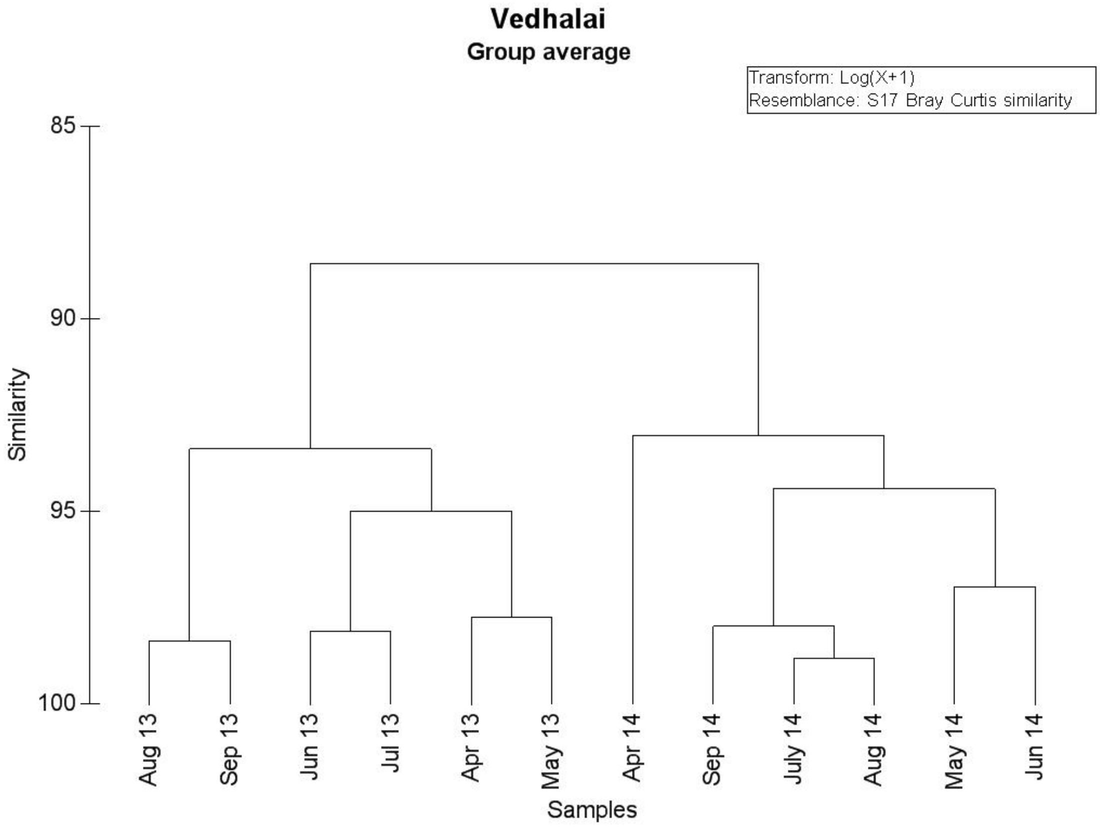


Fig 3.6. Bray-Curtis cluster analysis of the sampling months based on the average percent cover of different benthic components at Vedhalai.

Table 6- Results of SIMPER analysis on the average percent cover of different benthic components at Vedhalai during the study period (2013 & 2014).

Vedhalai 2013 vs 2014, Average Dissimilarity – 11.45 %					
Benthic component	**Average abundance**		**Average dissimilarity**	**% contribution**	**Cum %**
	2013	**2014**			
HA	2.44	3.67	3.29	28.72	28.72
DC	3.77	2.70	1.74	25.15	53.87
MA	2.74	2.47	1.74	15.19	69.06
LC/TA	1.43	1.86	1.13	9.91	78.97
LC/MA	1.47	1.73	0.80	6.99	85.96
RUBBLES	1.78	2.05	0.75	6.59	92.55

3.3.3. Coral community dynamics at Mandapam

Multiple algal blooms were observed in Mandapam during 2013. Similar to Vedhalai, *C. racemosa* bloom was noted during April 2013 and it increased the macroalgal cover to 25.5 ± 8.2% (Fig 3.7a). *C. racemosa* grew over the CCA substrates, smothered them completely and decreased the percent cover of CCA to 28.9 ± 0.3% compared to 48.9% during the preliminary observation in September 2012. Unlike Vedhalai, the persistence of *C. racemosa* was low in Mandapam as it was observed to be washed off during the next observation in May 2013. The total macroalgal cover was reduced to 2.33 ± 15% with an increase in CCA cover to 41.58 ± 12.6%. However, 2.26 ± 1.4% of the CCA previously smothered by macroalgae was degraded. Subsequent observations in June 2013 revealed the growth of other macroalgae *Enteromorpha flexuosa* over the CCA substrates. An average percent cover of 8.19 ± 9.1% of *E. flexuosa* was recorded on the permanent quadrats in Mandapam during the Month of June 2013. Further observations revealed a gradual increase in the percent cover of *E. flexuosa* reaching a maximum of 29.9 ± 12.6% during August 2013 with corresponding decrease in CCA cover to 16.21 ± 12.4%. In addition, 7.1 ± 3.4% of the CCA which were colonized by the *E. flexuosa* was degraded during September 2013 (Fig 3.7b) (Fig 3.8).

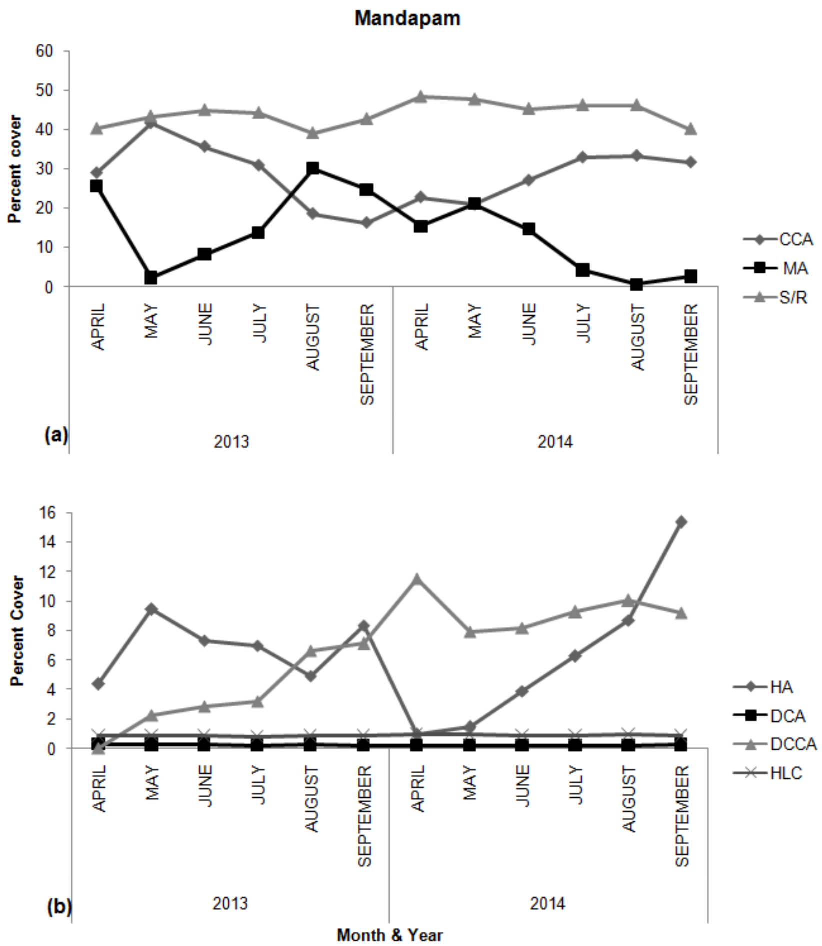


Fig 3.7. Temporal pattern in the average percent cover of different benthic forms at Mandapam during 2013 (3.7a) and 2014 (3.7b).

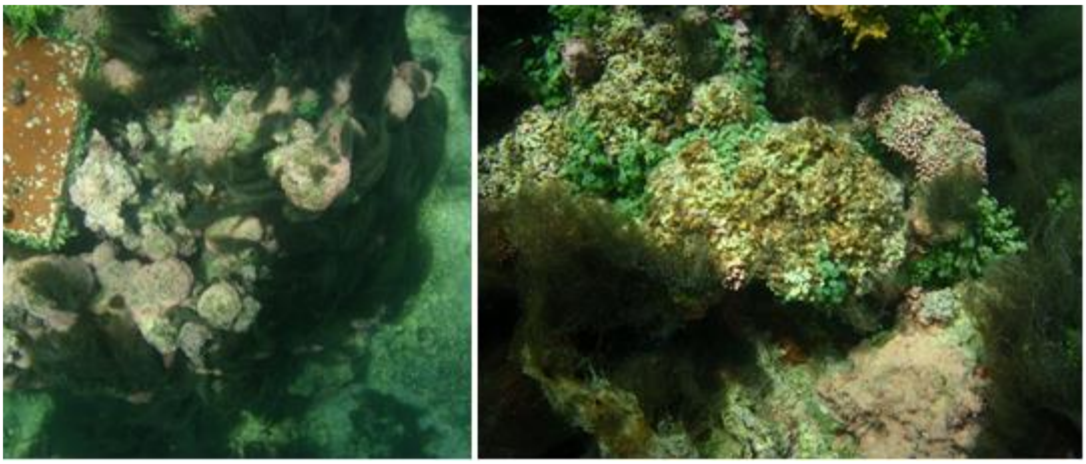


Fig 3.8. Degraded crustose coralline algae in Mandapam post *Enteromorpha flexuosa* bloom.

The variation in the temporal pattern of the percent cover of various benthic forms including Macroalgae, HLC, *Halimeda* sp, Sand, Rubbles and Dead corals at the study sites of Mandapam were not statistically significant between 2013 and 2014. Whereas, there exists a statistically significant variation in the temporal pattern of the percent cover of CCA and degraded CCA (Table 7). When the observations were renewed in April 2014, *C. racemosa* bloom covered the CCA substratum. However, their total percent cover accounts for 15.37 ± 5.6%, comparatively lower than their total cover recorded during the same period in 2013. The macroalgal cover reached a maximum of 20.98 ± 11.2% during May 2014 and decreased further during the subsequent observations. Unlike 2013, there were no multiple algal blooms at the study sites of Mandapam. However similar to the study sites at Vedhalai, *Halimeda* sp grew abundantly over the CCA substrates and their percent cover reached a maximum of 15.32 ± 6.6% during the final observations in September 2014.

In total, 11.51 ± 2.1% of the CCA in the Mandapam, earlier colonized by *E. flexuosa* was degraded as the observations were renewed in April 2014. Continuous observations revealed a recovery of CCA population as their percent cover rose up to 33.3 ± 5.2% in August 2014 compared to 22.74 ± 5.3% in April 2014. Comparison of the percent cover of different benthic forms between the preliminary assessment in September 2012 and final observation in September 2014 revealed a net decline of 17.28% of CCA (Fig 3.4b). In addition, 9.2 ± 0.14% of CCA was observed to be degraded with no signs of recovery. Based on the coefficient of determination value (R^2=0.67), 67% of the variation in the percent cover of CCA is driven by the variation in the percent cover of macroalgae at the study sites of Mandapam (Fig 3.5b).

Table 7- Results of paired t-test testing the significance of variation in the temporal pattern of the percent cover different benthic forms in Mandapam.

Biophysical form	t value	df	Level of significance (0.05)
CCA	-3.390	5	0.019
MA	1.053	5	0.340
HA	0.364	5	0.731
HLC	0.094	5	0.929
S&R	-1.933	5	0.111
DCA	0.955	5	0.383
DCCA	-4.298	5	0.008

In Mandapam, the sampling months were grouped in to four individual clusters and the sampling month April 2013 forms a separate individual cluster due to high macroalgal cover (Fig 3.9). The sampling months August-September 2013 and May-July 2013 were merged in to clusters with an average similarity of 97.1 % and 96.8 % respectively. In 2014, the sampling month April was merged with May and June with an average similarity of 96.4 %. Similarly, July-September forms a separate cluster with an average similarity of 94.7 %. The benthic community structure differed with an average dissimilarity of 11.63% in Mandapam between 2013 and 2014 (Table 8). The persistence of macroalgae and the simultaneous rise in the percent cover of DCCA had contributed a maximum of 34.09% and 30.67% to the observed dissimilarity in the benthic community structure at Mandapam.

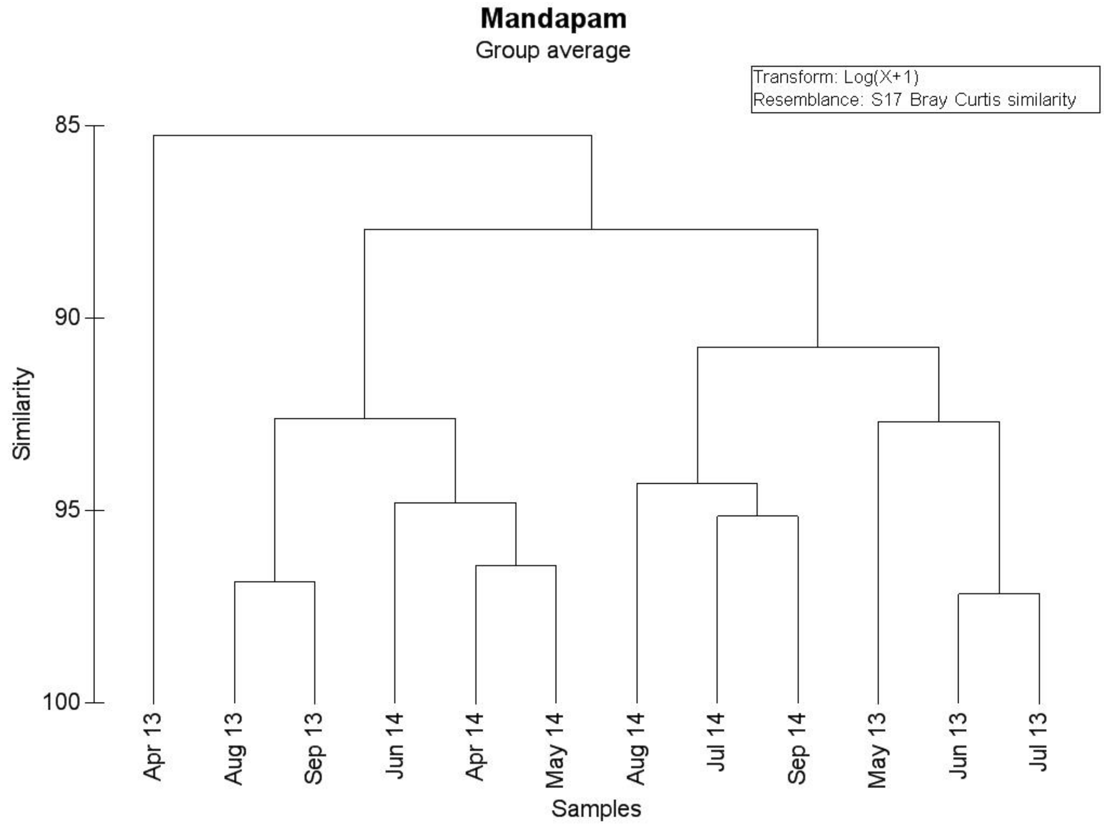


Fig 3.9. Bray-Curtis cluster analysis of the sampling months based on the average percent cover of different benthic components at Mandapam.

Table 8- Results of SIMPER analysis on the average percent cover of different benthic forms at Mandapam during the study period.

Mandapam 2013 vs 2014, Average Dissimilarity = 11.63 %					
Benthic component	**Average abundance**		**Average dissimilarity**	**% contribution**	**Cum %**
	2013	**2014**			
MA	2.68	2.02	3.96	34.09	34.09
DCCA	1.35	2.33	3.57	30.67	64.76
Halimeda	2.04	1.69	2.51	21.62	86.38
CCA	3.34	3.35	1.10	9.44	95.81

3.4. DISCUSSION

Observations on the dynamics of coral reef communities revealed occurrence of seasonal macroalgal blooms and their dominance over other benthic forms at the study sites of Vedhalai and Mandapam. The macroalgae was observed either to be attached or form a matrix covering all the available hard substrates including live corals, dead corals, CCA and rocks. The CCA population showed signs of recovery as their percent cover increased post the macroalgal bloom during the final observations. Whereas, the HLC population was unable to recover and their percent cover decreased. The short term proliferation of macroalgae is a normal reef process and considered to have no significant impacts on coral communities (Hughes et al. 2010). However, in this study the short term bloom of macroalgae reduced the HLC and CCA cover at the study sites of Vedhalai and Mandapam respectively over a period of two years.

The macroalgae *C. racemosa* grew luxuriantly during the summer months (April and May) at the study sites of both Vedhalai and Mandapam in Palk Bay. The specific causes of this seasonal bloom of macroalgae is not clear though it is likely to be associated with their life history traits, reproductive cycle and environmental conditions especially light, water temperature and day length (Hughes et al. 1999). Most macroalgae reproduce by means of producing spores and vegetative propagation. The spores of macroalgae remain in the reef ecosystem and it starts blooming upon the arrival of optimal environmental conditions which is highly variable for different species of macroalgae (Harley et al. 2012). Extensive blooms of macroalgae, such as *Chnoospora* and *Hydroclathrus* were reported in the shallow reef flats of Great Barrier Reef during winter (Diaz-Pulido and McCook 2008). Similarly, *Sargassum* sp was reported to bloom during the summer months (Diaz-Pulido and McCook 2005, Martin-Smith 1993, Vuki and Price 1998).

C. racemosa bloom resulted in partial mortality among the HLC colonies facilitating the settlement and growth of turf algae and increased the percent cover of LC/TA in Palk Bay. Mortality among the live coral colonies generally increases the availability of substratum for the attachment and subsequent growth of turf algae (Adjeroud et al. 2009). Normally, the live corals possess resistance mechanism against the attachment and growth of macroalgae, turf algae and borers (Bonaldo and Hay 2014, Rasher et al. 2011). However, the mechanism by which the macroalgae colonize the HLC remains unclear. Though corals and macroalgae compete for space in a reef ecosystem, corals are often successful against macroalgae under pristine environmental conditions (Nugues et al. 2004). However under extreme conditions like increased temperature and radiation, corals are stressed and their resistance potential is compromised enabling the algae to colonize them. In Palk Bay reef, the seasonal bloom of macroalgae occurred in the summer months during which the corals were reported to start bleaching. In general, bleaching is a stress response in corals due to increased sea water temperature and radiation. During bleaching, corals expel their symbiotic zooxanthellae due to oxidative stress, starve for nutrients and exist in a stressed condition (Gates et al. 1992) which could favored the colonization of turf algae and macroalgae.

Increase in the percent cover of turf and macroalgae and their persistence at the study sites of Palk Bay potentially reduced the availability of hard substratum for other reef processes such as coral larval settlement and recruitment. The reef ecosystem in Palk Bay is a potential fishing ground for small scale fishermen and the herbivore fishes are exploited in large quantity compared to fishes of other functional groups (Manikandan et al. 2014). Also, it has been reported that the damage incurred during reef fishing activities opens up the substratum for the attachment of turf algae and macroalgae and its subsequent growth. All these factors had contributed to the consistent presence of macroalgae and turf algae even after the bloom gets washed off from the study sites in Palk Bay. Increase in the level of dissolved nutrients especially that of nitrogen and phosphorus also increase the biomass of algae during this kind of seasonal macroalgal blooms (Lapointe 1999, Hughes et al. 1999).

The Successive macroalgal blooms in 2013 and the increase in the percent cover of *Halimeda* sp in 2014 had reduced the percent cover of CCA at the study sites of Mandapam. CCA are the important components of reef ecosystem and they promote the settlement and growth of coral larvae (Morse et al. 1988, Morse et al. 1996, Heyward and Negri 1999, Harrington et al. 2004). Reduction in CCA cover could substantially affect the coral recruitment and metamorphosis which has been one of the key to reef resilience. With enormous reproductive potential by vegetative propagation and propagules production, macroalgae can colonize the available hard substrates under favorable conditions. CCA has been reported to control the macroalgal population in a reef by providing shelter to micro-herbivores (Paine 1980, Steneck 1997) by shedding their thalli and preventing the establishment of macroalgae (Johnson and Mann 1986). Contrary to this, observations in this study revealed that during macroalgal bloom both *C. racemosa* and *E. flexuosa* were attached to the CCA substrate. Experimental evidences also indicate that CCA suppress the recruitment and the subsequent growth of macroalgae (Vermeij et al. 2011). However, these results are based on the experiments carried out using a single macroalgae *Ulva* sp and it cannot be generalized for other macroalgal species as the interaction of CCA may vary with different algal species and the prevailing environmental conditions.

Availability of hard substratum and the successful settlement and growth of coral larvae has been the key for recovery of any degraded reef (Shinn 1976, Gilmour et al. 2013). The live corals which turns dead due to an extreme event like bleaching, storm damage, predation, diseases etc. can still contribute to the recovery of a degraded reef by serving as a hard substrate for the settlement of new coral larvae (Wallace et al. 1986, Norstorm et al. 2007). Seasonal macroalgal blooms and gradual increase in the percent cover of calcareous algae *Halimeda* sp had reduced the availability of hard substratum such as dead corals and CCA cover to a large extent at the study sites of Vedhalai during the study period of 2 years. In addition, thick mat of turf algae was also observed over the dead corals which will trap the fine sediments in water column and inhibit the settlement of new coral larvae (Birrell et al. 2005). Presence of a healthy stock of herbivore fish population and grazing of turf algal substrate can reverse this scenario and favor the successful settlement and recruitment of corals (Hughes et al. 2007a). However, the herbivore fish population was assessed to be low in diversity and quantity and also exploited in large quantity along Palk Bay reef (Manikandan et al. 2014).

The rate of loss of HLC cover over the study period of two years was high in Palk Bay reef. The HLC colonized by macroalgae and turf algae continues to degrade without any signs of recovery. Recovery of corals post a stress event like macroalgal bloom is rare due to the persistence of macroalgae and exploitation of functionally important herbivore fish from the reef (Hughes 1994, Gardner et al. 2003). In Palk Bay reef, persistence of macroalgae bloom ranges between a maximum of 45 days to a minimum of 30 days and is capable of reducing the HLC cover. Natural recovery of corals under favorable conditions will take decades and also depends on the species composition of the reef (Hunter and Evans 1994, Idjadi et al. 2006). Recovery of corals was rapid in the reefs dominated by fast growing *Acropora* sp through rapid tissue regeneration (Diaz-Pulido et al. 2009). In Palk Bay, species diversity of corals was low and dominated by massive corals belonging *Porites*, *Favia* and *Favites* sp

(Unpublished data) and the chances of recovery by means of tissue regeneration appears remote.

In conclusion, the seasonal bloom of macroalgae, underestimated to be a normal reef process reduced the total cover of important reef components such as HLC and CCA in Palk Bay reef. The annual rate of loss of HLC and CCA is typically high and the persistence of macroalgae and calcareous algae reduced the chances of recovery of the corals though the CCA population showed signs of recovery. Increase in the percent cover of LC/TA and LC/MA further hinders the recovery of corals. With limited diversity of slow growing massive corals, it is likely that the Palk Bay reef will turn in to an algal reef in future with the continuing trend in the decline of HLC population. Experimental studies reported the relation of increased level of nitrogen and ammonia with the seasonal algal blooms (Stimson et al. 1996). However, in this study the threshold level of nutrients associated with the algal blooms was not investigated and the future research should focus on it.

Chapter 4

Bleaching and Recovery patterns of corals in Palk Bay

4.1. INTRODUCTION

Coral reef ecosystems are under serious threat due to the impacts generated by the processes of climate change. The frequency and severity of coral bleaching events increased in recent years affecting the resilience potential of the corals. Mass coral bleaching associated with increase in the Sea Surface Temperature (SST), Photosynthetically Active Radiation (PAR) and diseases drives the degradation of corals globally (Brown 1997). The coral bleaching phenomenon was characterized by the loss of color in the coral colonies due to expulsion of symbiotic zooxanthellae. Increase in SST often results in an oxidative stress resulting in the production and accumulation of reduced oxygen intermediates such as Superoxide radicals, singlet oxygen, hydrogen peroxide and hydroxyl radicals and damages the cellular components including DNA, lipids and proteins (Lesser 2011). The oxidative stress response of corals is exaggerated during the incidence of high irradiances damaging the photosystem of symbiotic zooxanthellae affecting their CO_2 fixation (Lesser 1997, Jones et al. 1998, Warner et al. 1999).

Coral bleaching was first reported by Vaughan (1914) and later described by Glynn (1984). Since then, the coral bleaching has become a common phenomena occurring in all the major reefs resulting in a significant loss of live coral cover (Spencer et al. 2000, Marshall and Baird 2000, Arthur 2000, McClanahan 2007). The frequency of coral bleaching events were predicted to increase in the upcoming years minimizing the time available for the recovery of corals and elevate their risk of extinction (Donner et al. 2005, Logan et al. 2014). Apart from this, coral bleaching has severe ecological implications including coral mortality, reduced coral growth, changes in community structure, decrease in species diversity and decrease in fish assemblage (Booth and Beretta 2002, Bellwood et al. 2006a, Baird and Marshall 2002, Glynn 1996, Ostrander et al. 2000). In addition, coral bleaching also weakens the reef frame work and its structural complexity resulting in the loss of critical habitats for the reef fishes (Baker et al. 2008).

Corals can mitigate the thermal stress through a variety of adaptive strategies including shuffling their zooxanthellae symbionts towards housing the thermo tolerant clades (Baker et al. 2004, Jones et al. 2008, Coffroth et al. 2010, Silverstein et al. 2012); by acquiring different types of symbionts from the environment in addition to the maternally inherited ones (Byler et al. 2013). Corals also increase the expression of heat shock proteins, photo protective proteins and antioxidants etc. during the bleaching period to make the coral symbiont more thermo tolerant (Robinson and Warner 2006, Coles and brown 2003, Sampayo et al. 2008, Van Woesik 2011). In addition to the adaptive mechanism evolved by the corals, there are numerous environmental factors that reduce the incidence and severity of bleaching by minimizing the temperature and radiation reaching the corals (Salm et al. 2001). Physical processes such as upwelling of cold waters and stronger currents mitigate the coral bleaching by reducing the sea water temperature (Chou 2000, Goreau et al. 2000) and flushing out the lethal oxygen radicals respectively (Nakamura and van Woesik 2001). On the other hand high levels of suspended particles and chromophoric dissolved organic materials in the water column attenuate the light reaching the corals and thereby minimize the impacts of coral bleaching (Goreau et al. 2000, Anderson et al. 2001).

Coral bleaching often resulted in mass mortality of corals enabling the other communities to dominate the reef. Macroalgal phase-shifts were common in the reefs that were severely affected by bleaching (Diaz-Pulido et al. 2009, Bruno et al. 2009). However, numerous studies reported the recovery of corals post major bleaching event (Golbuu et al. 2013, Rodrigues and Grottoli 2007, Gilmour et al. 2013). Recovery of corals post a bleaching event depends on food availability (Connolly et al. 2012); replenishment of energy reserves and tissue biomass by the corals (Rodrigues and Grottoli 2007); availability of new coral recruits (Hughes et al. 1999); reduced pressure from the local and regional stressors (Graham et al. 2011); presence of healthy stock of reef fishes (Mumby et al. 2007) and effective management through marine protected areas (Mumby and Harborne 2010). Berkelmans (2002) demonstrated the linkage between the dissolved inorganic nitrogen loading in the reef environment and the upper thermal bleaching thresholds of corals in inshore reefs. Improved coral reef management that minimizes the terrestrial inputs will help the corals resisting the bleaching related effects (Wooldridge 2009).

There were no records on coral bleaching in India till the 1998 major bleaching event. The 1998 bleaching event resulted in the significant loss of corals in all the major reef regions of India (Ravindran et al. 1999, Pet-Soede et al. 2000, Arthur 2000). Post bleaching recovery process was slow and was strongly influenced by the local processes (Arthur 2006). Post 1998, two other bleaching events were reported including the one in 2002 (Kumaraguru et al. 2003) and other in 2010 (Ravindran et al. 2012, Vinoth et al. 2012) which significantly reduced the live coral cover. Although, coral bleaching reported occasionally in the Indian reefs, it turned out to be an annual event as revealed by the local reef users. Under this objective, we present the results of bleaching and recovery patterns of corals in Palk Bay for two consecutive years 2013 and 2014. In addition, we monitored the temporal pattern of SST and PAR to analyze their effects on differential bleaching extent among various coral species.

4.2. MATERIALS AND METHODS

4.2.1. Study sites

Observations on the bleaching and recovery patterns of corals were carried out at Vedhalai and Mandapam along the Palk Bay reef. Location of the study sites was presented in the Fig 4.1.

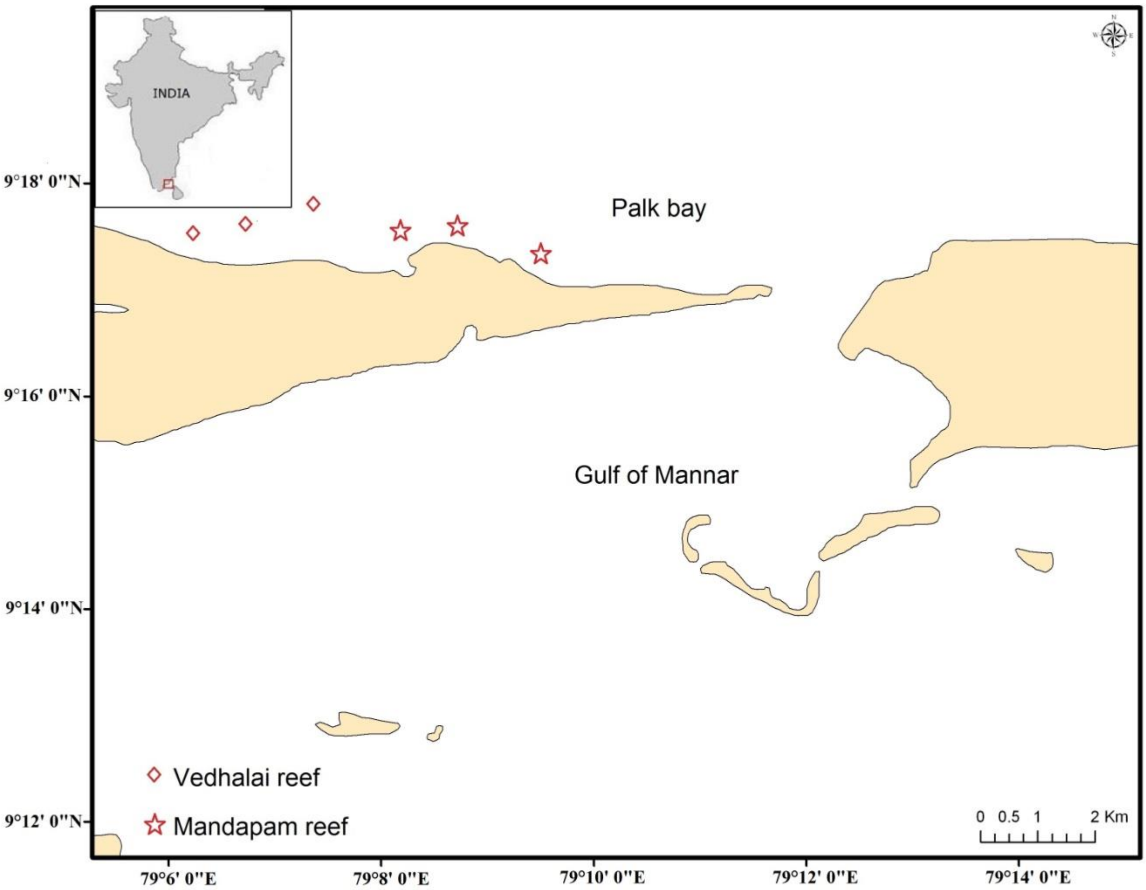


Fig 4.1. Location of the study sites observed for bleaching and recovery of corals.

4.2.2. Bleaching survey method

Observations on the bleaching and recovery response of corals were carried out following the permanent quadrat method (English et al. 1997) with slight modifications. An area of 100 m^2 was demarcated at 6 locations spanning both Vedhalai and Mandapam reefs as described in Manikandan et al. 2014 and fixed in permanence. All the coral colonies that falls within the effective area of the quadrat were tagged for continuous observations. The corals were photographed using Olympus µtough 8000 camera in underwater macro mode for identification. The corals were identified up to the genus level using high resolution photographs using the identification keys described by Veron (2000) and Venkataraman (2003). The corals couldn't be identified at species level due to the legal restrictions in collection of coral samples in India.

In-situ observations on bleaching, recovery and post bleaching mortality were carried out between March to September in 2013 and 2014 at weekly intervals. The corals upon bleaching were categorized in to four categories namely severely bleached (Corals that completely turned white); moderately bleached (Corals that turns pale in color); Unbleached (Corals that were unresponsive to bleaching) and Recovering (Corals that underwent bleaching and recovering to their normal state) (Fig 4.2). The bleaching response of corals was reported as the percentage of corals that exist in each different bleaching category relative to the total number of corals that were tagged. Observations on coral bleaching and recovery response were carried out at an interval of eight days between March to July during the study period. Thereafter, the observations were extended till September with same time interval to account for a potential post-bleaching mortality among tagged coral colonies.

Fig 4.2. Coral colonies in different bleaching category. (a) Severely bleached (b) Moderately bleached (c) Unresponsive/healthy; (d) Recovering.

4.2.3. Environmental conditions during bleaching

SST and PAR are the two critical factors responsible for the coral bleaching. The SST over the Palk Bay region was monitored continuously during the study period between March to July in 2013 and 2014. Data on SST was obtained from a daily 9km optimum interpolated global SST (MODIS+TMI) dataset (www.misst.org). The data was a merged product of both day and night in the Infrared and microwave wavelengths. From these data, average SST for every eight days was calculated and plotted since the *in-situ* observations on bleaching were carried out every 8 days.

PAR is one of the critical parameter determining bleaching. It is defined as the integration of the solar flux reaching the ocean surface and denoted as Einstein $m^{-2}d^{-1}$. It determines the type and amount of light needed for the growth of corals. In this study, PAR data at the ocean surface with a spatial resolution of 4 km was obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite. Similar to SST, the PAR values averaged for every 8 days was obtained for the period of March to September in 2013 and 2014. The data was downloaded from the website (http://oceandata.sci.gsfc.nasa.gov). MODIS-Aqua satellite has ocean bands 8, 9, 10, 11, 12, 13, 14 in the visible range and the PAR values are estimated using these bands with specific algorithms (Frouin 2002). Data was flagged off for few days within the study period due to its poor quality. The accuracy of PAR data from MODIS-Aqua has average errors in the order of 5-8%, with an individual estimation errors as high as 21% (Van Laake and Sanchez-Azofeifa 2005). This PAR data was used as the high resolution PAR measurements are not available in this region. Since the sampling depth is around 2m in clear waters, the PAR value on the surface may not change significantly during the downwelling. This PAR value must be giving representative information on the available light as the conditions remain same in the water column.

4.2.4. Analysis

Data from all the permanent quadrats were pooled and the bleaching and recovery response of corals is expressed as the average proportion of coral colonies in each bleaching category at the given time of *in-situ* observations. The proportion of coral colonies in different bleaching category was determined by summing up the number of corals that exist in each bleaching category at the time of observation relative to the total number of coral colonies tagged for continuous observation. One-way ANOVA was used to test the significance of monthly variation in the SST and PAR in 2013 and 2014 and the bleaching response among corals in 2013 and 2014. The data on the proportion of corals in different bleaching category at the given time interval was $\log_{10}(x+1)$ transformed to meet the assumptions of ANOVA. Multiple regression analysis was performed to analyze the relationship between the SST and PAR with the proportion of severely bleached coral colonies in 2013 and 2014. The proportion of severely bleached coral colonies were entered as the dependent variable and the values of SST and PAR were entered as the independent variables. The analysis was performed using SPSS statistical software Version 16.0.

4.3. RESULTS

A total of 256 coral colonies representing five genera of corals were recorded in the permanent quadrats setup in Palk Bay reef. *Leptastrea* sp was dominant (58.1%) followed by *Porites* (18.1%), *Favia* (12.7%), *Favites* (6.3%) and *Cyphastrea* sp (4.5%). The proportion of severely bleached coral colonies were high in 2014 compared to 2013 corresponding to the increase in the intensity of SST and PAR in 2014. Corals of different genera differ in their sensitivity to bleaching and the corals of *Favites* and *Leptastrea* sp were more sensitive being the first to bleach. *Cyphastrea* sp and few colonies of *Leptastrea* sp were unresponsive to bleaching.

4.3.1. Bleaching event 2013

The temporal pattern of SST and PAR during the study period in 2013 was presented in the Fig 4.3. There exist a statistically significant variation in the temporal pattern of SST during the study period in 2013 (One-way ANOVA, df= 4; F= 12.03; F_{crit}= 3.05; p value= 0.0001<0.05). However, the PAR values does not differ significantly during the study period (One-wayANOVA, df= 4; F= 2.21; F_{crit}= 3.05; p value= 0.11>0.05). The mean SST and PAR was below 30 °C and above 50 $Em^{-2}d^{-1}$ respectively during March 2013. The coral colonies within the permanent quadrats were healthy without any signs of bleaching during the first two weeks of March 2013. Bleaching was first witnessed among the *Favites* and *Leptastrea* colonies during the third week of March 2013. During this period, 2.7% of the corals of

Favites and *Leptastrea* sp were moderately bleached. The mean SST continued to increase above 30 °C and PAR values were stable >50 $Em^{-2}d^{-1}$. Correspondingly, the proportion of moderately bleached colonies increased to 10% by the end of March 2013.

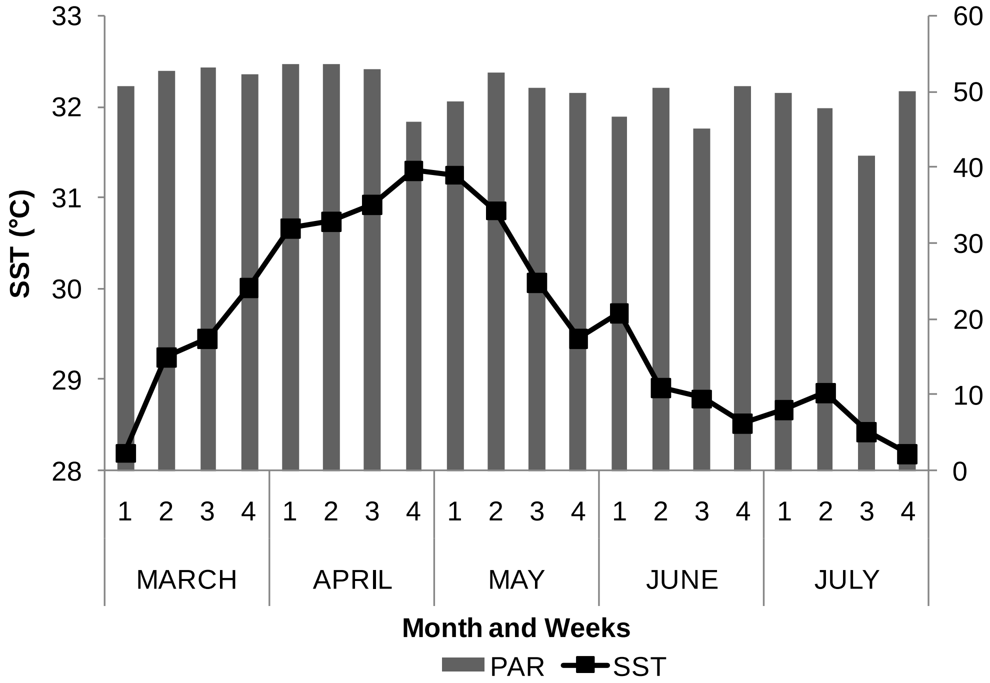


Fig 4.3. Temporal pattern of Sea Surface Temperature (SST) and Photosynthetically Active Radiation (PAR) during the bleaching event 2013.

The average SST and PAR was stable above 30 °C and 52 $Em^{-2}d^{-1}$ respectively during the first week of April. In total, 4.5% of the corals of *Favites* sp were severely bleached and 11.8% of the corals including *Favia* and *Leptastrea* sp were moderately bleached. The average SST and PAR values continued to increase to a maximum of 31 °C and 53 $Em^{-2}d^{-1}$ by the third week of April 2013. Correspondingly, the proportion of severely bleached and moderately bleached coral colonies including *Favites*, *Leptastrea* and *Favia* sp increased to 11.8% and 17.3% respectively. Though the average PAR drops below 50 $Em^{-2}d^{-1}$ by the last week of April 2013, the SST was high above 31 °C and increased the proportion of severely bleached colonies to 13.6%. The massive *Porites* sp started bleaching during this period and increased the proportion of moderately bleached colonies to 27.3%.

In May 2013, the average SST was stable above 30 °C and PAR values fluctuated between a maximum of 52.7 $Em^{-2}d^{-1}$ to a minimum of 48.9 $Em^{-2}d^{-1}$. Majority of the *Porites* sp turns pale in color and increased the proportion of moderately bleached coral colonies to 43.6% by the third week of May. In addition, a maximum of 13.6% of the corals represented by *Favia* and *Leptastrea* sp were severely bleached. However, 3.6% of the corals of the *Favites* sp that was severely bleached showed signs of recovery during this period. Further recovery was observed with *Favia* and *Leptastrea* coral colonies as the average SST and PAR values drops below 30 °C and 50 $Em^{-2}d^{-1}$ respectively by the end of May 2013. Corresponding to this, the proportion of recovering coral colonies increased to 8.2%.

Majority of the corals belonging to *Favia, Favites* and *Leptastrea* sp that were severely and moderately bleached were completely recovered as the average SST and PAR dropped below 30 °C and 48 $Em^{-2}d^{-1}$ respectively in the second week June 2013. However, 2.7% of the corals represented by the *Porites* sp were severely bleached; 26.3% comprising *Porites* and *Leptastrea* sp were moderately bleached; 22.7% of *Leptastrea* and *Favia* sp were recovering and 48% of the corals were healthy and it includes those corals that were recovered from bleaching by the end of June. Recovery signs were observed with *Porites* sp by the second week of July 2013 as the average SST and PAR values were stable below 29 °C and 48 $Em^{-2}d^{-1}$. Majority of the *Porites* sp had recovered and a total of 5.4% of the *Porites* sp were still recovering by the end of July. The bleaching and recovery response of corals in 2013 was summarized in the Fig 4.4. In total, 33.6% of the coral colonies comprising

Cyphastrea and few *Leptastrea* sp were unresponsive to bleaching and remains healthy during the entire bleaching episode. Subsequent observations in August and September 2013 revealed the recovery of all the bleached coral colonies without any mortality among the corals.

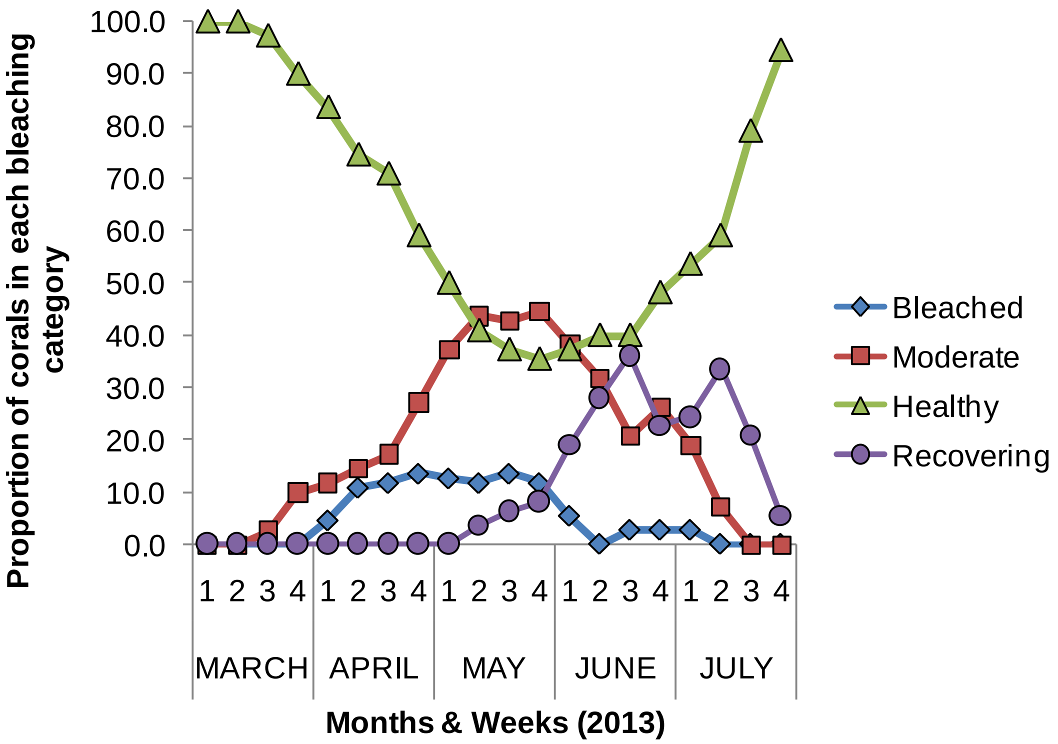


Fig 4.4. Bleaching and Recovery patterns of corals along the Palk Bay reef during the bleaching event in 2013.

4.3.2. Bleaching event 2014

Overall bleaching and recovery response among corals in Palk Bay differed significantly in 2014 compared to 2013 (One-way ANOVA, df= 1; F= 7.43; F_{crit}= 4.09; p value= 0.009<0.05). Similar to 2013, *in-situ* observations on coral bleaching was started in March 2014 and continued till September 2014. Unlike 2013, both SST (One-way ANOVA, df= 4; F= 12.5; F_{crit}= 3.05; p value= 0.0001<0.05) and PAR (One-way ANOVA, df= 4; F= 3.41; F_{crit}= 3.05; p value= 0.03<0.05) varied significantly in their temporal pattern during the study period in 2014.

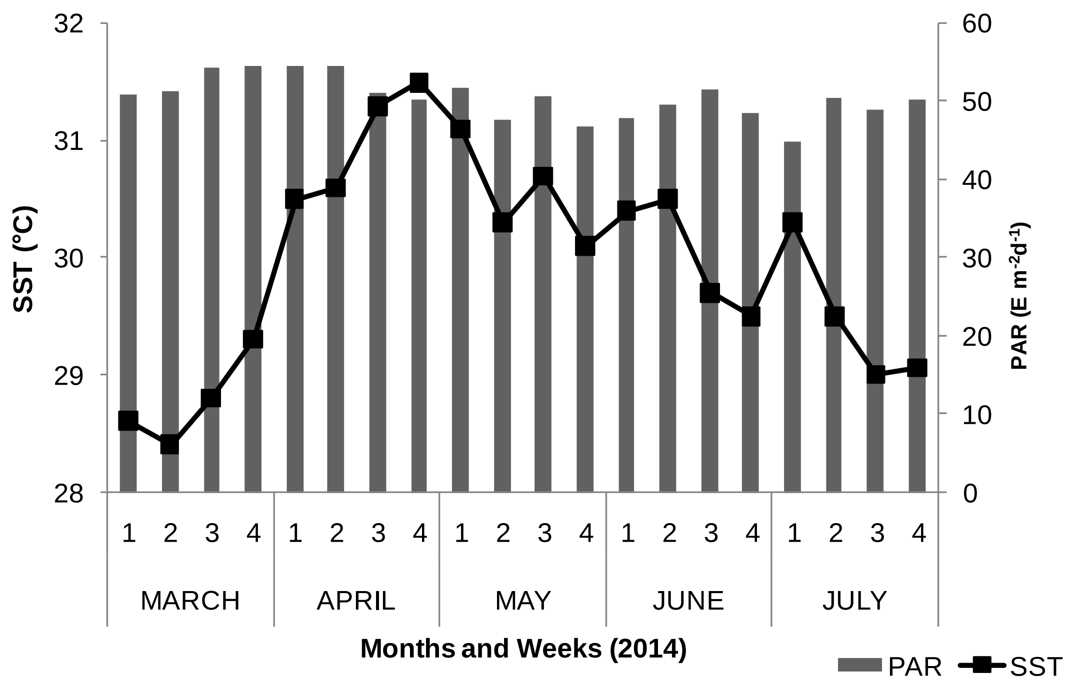


Fig 4.5. Temporal pattern of Sea Surface Temperature (SST) and Photosynthetically Active Radiation (PAR) during the bleaching event 2014.

The mean SST was <30 °C and the PAR values were high fluctuating between a minimum of 51.03 Em^{-2}d^{-1} to a maximum of 54.3 Em^{-2}d^{-1} in March 2014 (Fig 4.5). The first visible signs of bleaching were witnessed during the second week of March comparatively earlier than 2013. In total, 19.1% of the corals of *Leptastrea*, *Favia* and *Favites* sp were moderately bleached by the second week of March 2014. As the average PAR values were stable above 54 Em^{-2}d^{-1} during the third and fourth week of March 2014, 1.8% of the corals of *Favites* sp were severely bleached and 30.9% of the corals of *Favites*, *Leptastrea* and *Porites* sp were moderately bleached. Similar to 2013, *Cyphastrea* sp and few *Leptastrea* colonies were unresponsive to bleaching.

The proportion of severely and moderately bleached coral colonies increased up to 8.2% and 40% respectively by the second week of April 2014 (Fig 4.6). During this period, the average SST fluctuated between 30-31.5 °C and the average PAR values were stable above 54 Em^{-2}d^{-1}. Thereafter, the average PAR values dropped below 52 $Em^{-2}d^{-1}$ by the third week of April 2014. However, the average SST increased >31°C and increased the proportion of severely and moderately bleached coral colonies to 15.5% and 56.4% respectively by the last week of April 2014. As the average SST and PAR values were stable above 30°C and 50 $Em^{-2}d^{-1}$, 3.6% of the massive *Porites* sp was severely bleached and it increased the proportion of severely bleached coral colonies to 25.4% by the second week of May 2014. In addition, 62.7% of the corals of *Porites*, *Leptastrea* and *Favia* sp were moderately bleached during this period.

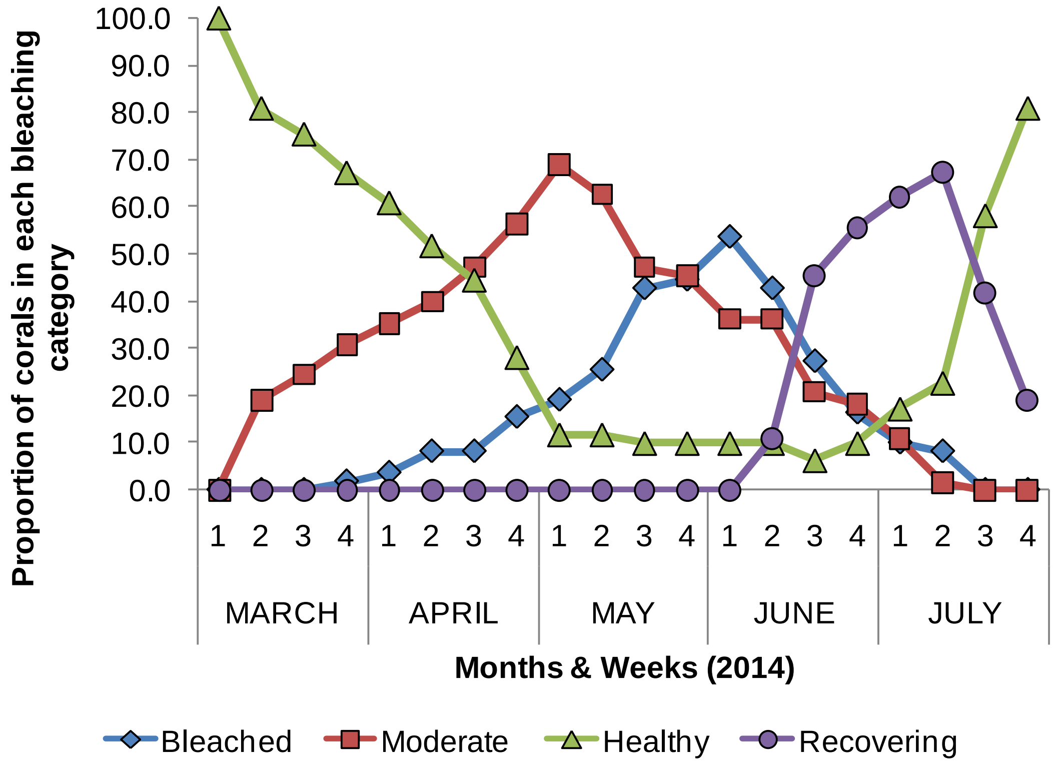


Fig 4.6. Bleaching and Recovery patterns of corals at the study sites of Palk Bay during the bleaching event in 2014.

The proportion of severely bleached coral colonies gradually increased and reached a maximum of 53.6% by the first week of June 2014. Though the average PAR values dropped below 50 $Em^{-2}d^{-1}$ during this period, the average SST was high (>30 °C). Recovery signs were observed among the coral colonies during the second week of June 2014 as the average SST and PAR values dropped below 30°C and 50 $Em^{-2}d^{-1}$ respectively. In total, 8.2% of the corals of *Leptastrea* and *Favites* sp showed signs of recovery during this period. Though the average PAR values fluctuated between a maximum of 51.5% to a minimum of 47.9%, the average SST was consistent below 30°C by the end of June 2014. Corresponding to this, the proportion of severely bleached coral colonies reduced to 16.4% with a simultaneous increase in the proportion of the recovering coral colonies to 55.5% by the end of June 2014.

Subsequent observations revealed the complete recovery of *Favia* and *Favites* colonies. However, the recovery was slow among the *Porites* sp and few *Leptastrea* colonies and they together added 19% to the total proportion of recovering coral colonies by the end of July 2013. Further observation in August and September revealed complete recovery of all the tagged coral colonies with zero percent mortality. As per the results of multiple regression analysis, 63% of the variation in the proportion of severely bleached coral colonies is explained by the variation in the SST and PAR values in 2013. Also, the variation in SST and PAR statistically significantly predicted the variation in the proportion of severely bleached coral colonies, $F(2, 17) = 14.4$, p value < 0.0005. However among the independent variables, only SST added statistical significance to the variation in the proportion of severely bleached coral colonies, $p<0.05$. In contrast, both SST and PAR contributed statistical significance to the variation in the proportion of severely bleached coral colonies in 2014, $p<0.05$. Variation in both SST and PAR together explained 39% of the variation in the proportion of severely bleached coral colonies and predicted the variation significantly, $F(2, 17) = 5.4$, p value < 0.0005 in 2014 (Table 9).

Table 9- Multiple regression analysis of the Sea Surface Temperature and Photosynthetically Active Radiation with the proportion of severely bleached coral colonies.

Parameter	Beta coefficients	R^2	F	p value
Bleaching 2013		0.63	14.4	<0.01
SST	0.827			<0.01
PAR	-0.148			>0.01
Bleaching 2014		0.39	5.48	<0.01
SST	0.415			<0.01
PAR	-0.424			<0.01

4.3.3. Differential susceptibilities among corals of different genera

Corals of different genera differed in their sensitivity to bleaching and subsequent recovery process. Based on continuous observations the entire bleaching and recovery episode of corals in Palk Bay reef were categorized into three phases. Phase I- Time period between the initial signs of bleaching to a severely bleached state; Phase II – Time period between the severely bleached state to Initial signs of recovery; Phase III – Time period between the Initial signs of recovery to complete recovered state. The time lag between the first signs of bleaching to a completely recovered state among corals increased in 2014 compared to 2013 (Fig 4.7).In 2013, the total time lag varied between a minimum of 50 days to a maximum of 91 days whereas, it increased to a minimum of 98 days to a maximum of 112 days in 2014. The variation in the bleaching time lag between 2013 and 2014 was high among the corals of *Favites* sp (48 days) followed by *Favia* sp (42 days).

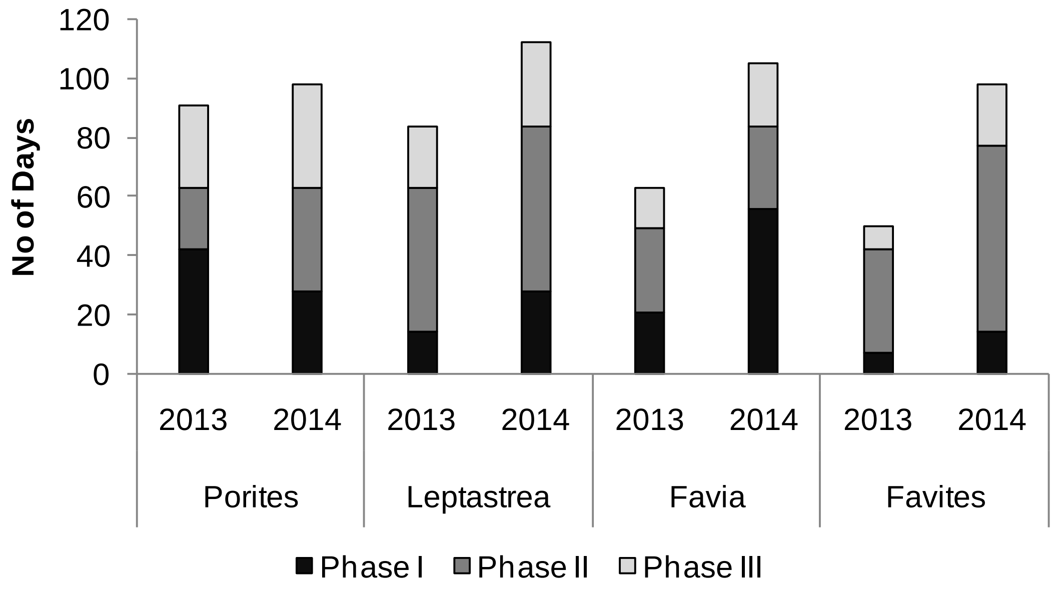


Fig 4.7. Time lag between different stages of bleaching between different genus of corals in 2013 and 2014.

4.4. DISCUSSION

Results of this study showed that the corals in Palk Bay possess the potential to recover back to their normal state without mortality despite an increase in the values of average SST and PAR during the study period. Elevated SST was considered to be the most common factor causing bleaching in corals (Jokiel and Coles 1990, Yee and Barron 2010, Krishnan et al. 2011). However, continuous observations on the bleaching and recovery patterns of corals in Palk Bay suggested that the PAR is the critical factor responsible for the onset of bleaching among the corals and SST further enhanced the bleaching response among the coral colonies. Production of Reactive oxygen species (ROS) by the symbiotic zooxanthellae in response to an increase in the PAR plays a critical role in triggering bleaching through photo-inhibition of photosynthesis among corals (Smith et al. 2005). Comparison of the climatic conditions preceding the previous bleaching events in 1998 and 2002 with that of 2013 and 2014 showed an increase in the level of bleaching thresholds of the corals in Palk Bay. An average PAR and SST of 47 $Em^{-2}d^{-1}$ and 30 °C resulted in severe bleaching among the corals in Gulf of Mannar (GoM) and Lakshadweep reefs (Sridhar et al. 2012) in 2002.Whereas, the initial signs of bleaching were observed only as the average PAR and SST exceeded 50 $Em^{-2}d^{-1}$ and 30 °C respectively during the bleaching events in 2013 and 2014 in this study. Increase in the bleaching threshold among corals might result from their adaptation and acclimatization patterns in response to the previous bleaching events. The ability of corals to shuffle their symbionts towards thermal and photo tolerant clades of zooxanthellae (Jones et al. 2000) will increase the resistance potential of corals against the increasing SST and PAR.

Comparison of the SST and PAR values revealed an increase in the values of both average SST and PAR in 2014 than 2013. Despite an increase in the intensity of bleaching conditions, all the corals recovered to their normal state without mortality. The corals existed in their severely bleached state for a prolonged period and also took more time to recover to their normal state in 2014 compared to 2013. The percentage of severely bleached corals was also higher in 2014 than 2013. This could be attributed to the prolonged increase in the SST in 2014 compared to 2013. Though the PAR fluctuated between their minimum and maximum values during bleaching, the SST was stable above 30 °C for a maximum of 8 and 11 weeks respectively in 2013 and 2014 and it increased the proportion of bleached coral colonies. Prolonged increase in the temperature could significantly affect the stability of symbiosis between the corals and zooxanthellae (Glynn and Croz 1990) resulting in their expulsion. However in Palk Bay, the prolonged increase in SST did not affect the survivability of corals. However, other impacts associated with the prolonged increase in SST needs to be investigated. Earlier, coral colonies were reported to exist in a bleached state for 7 months and recovered in Florida (Szmant and Gassman 1990). Though this had no effect on the survivability of coral colonies, it impaired the reproductive potential of the corals.

Corals of *Favites* and *Leptastrea* sp were more sensitive being the first to bleach though the average SST was <30 °C. On the other hand, no signs of bleaching were observed with the corals of *Porites*, *Favia* and *Cyphastrea* sp though the average PAR was >50 $Em^{-2}d^{-}1$ and the signs of bleaching were observed with these species only when the average SST rose above 30 °C. Corals belonging to the genus *Cyphastrea* are not affected by bleaching and remained healthy during the entire bleaching episode in both 2013 and 2014. Variations in the susceptibility of bleaching among different coral species were reported earlier in which the variation was determined by many factors including species assemblage (Marshall and Baird 2000); type of symbiont associated with corals (Rowan et al. 1997, Glynn 2001) and tissue thickness and colony growth morphology (Loya et al. 2001). Apart from the species specific characteristic of corals that aid to resist bleaching related stress, there were other external factors which found to be influencing the bleaching response of corals. West and Salm (2003) reviewed the external factors that contribute to the resistance potential of corals against bleaching. In addition, Ravindran et al. (2013) reported the presence of UV absorbing bacteria in the coral mucus which is suspected to produce UV absorbing compounds which is hypothesized to subsidize the effects of harmful UV radiation during the bleaching events.

The varied bleaching and recovery response among corals might be due to their size class. The thermal tolerance limit of individual coral colonies were often attributed to the symbiotic zooxanthellae clades associated with corals (Sampayo et al. 2008). Apart from the type of zooxanthellae clades, the size of coral colonies also determines the ability of corals to resist bleaching. Corals of large size class were highly resistant to bleaching (Harriot 1985) compared to the corals of other growth forms. Also, the massive corals like *Porites* sp protect the symbiotic algae by withdrawing their polyps to a deeper shaded region (Jones et al. 2000). However, the SST and PAR values increased continuously that could have compromised the resistance and defence potential of the massive coral forms and triggered bleaching response in them. Simultaneous recovery process was slow among the massive corals and the recovery signs were observed only after the SST drops below 29°C.

There was no post bleaching mortality among the corals in Palk Bay unlike the previous bleaching events observed during 2002 (Kumaraguru et al. 2003). Though this appears to be a positive sign of resilience, the zero mortality was largely due to the presence of thermal resistant coral species in abundance compared to the thermally sensitive ones. The reef area of Palk Bay has been largely reduced since 1996 with simultaneous increase in the area cover of seaweeds and sand (Sridhar et al. 2010). In connection to this, the species diversity of corals was reduced to a greater extent possibly due to natural selection of those species which could tolerate the stress prevailing in Palk Bay. Earlier, a total of 63 sp of corals of 23 genera was reported from Palk Bay (Pillai 1969). However, recent survey recorded a reduction in the species diversity of corals to 34 species of 15 genera (Venkataraman and Rajkumar 2013). Massive corals belonging to *Porites*, *Favia* and *Favites* sp were abundant in Palk Bay which was reported to be thermally tolerant (Baker et al. 2008). Though *Leptastrea* sp were abundant in terms of number of colonies compared to other massive forms, they occur as small encrusting colonies and occupied less area compared to other massive forms of corals. Their niche under the holes and crevices of the dead corals and rocks would have offered protection against the radiation and contributed to their success over bleaching induced stress. In general, the 1998 massive bleaching event resulted in a widespread coral mortality and community structural shift in majority of the reefs (Loya et al. 2001). The impacts of 1998 bleaching event and the subsequent recovery was not documented in Palk Bay reef and there was no clue about the factors responsible for an increase in the relative abundance of massive and encrusting coral species among other forms of corals.

Increase in the frequency of stress conditions such as bleaching can influence the corals by minimizing the time available for corals to recover from the stress and lead to their mortality. In contrary, Brown et al. (2002) stated that exposure of corals to frequent stressors reduce their susceptibility to bleaching. The bleaching events and their frequency were not well documented in Indian reefs due to the lack of intensive field research in the country. Three major bleaching events reported in the Indian reefs since 1998 (Ravindran et al. 1999, Arthur 2000, Kumaraguru et al. 2003, Ravindran et al. 2012). In reality, coral bleaching occurs every year in Palk Bay and Gulf of Mannar reefs as reported by fishermen and local reef users and it remains unnoticed by scientific communities. Frequent bleaching events and the presence of regular stress conditions render the coral host with the potential to resist the bleaching related stress by shuffling their symbiotic algal partner (Buddemeier et al. 2004) and acclimatization to the environmental stress respectively (West and Salm 2003). The reef environment in Palk Bay is often stressful mainly due to excessive sedimentation, increased anthropogenic activities (Manikandan et al. 2014) and high temperature during summer (Wilson et al. 2005, Ravindran et al. 2012). Though the corals in Palk Bay were unable to resist the bleaching stress despite the frequent stress conditions, they were able to recover back to their normal state. Survival and recovery of corals during and post a bleaching event was largely influenced by the prevalence of secondary stressors such as overgrowth of macroalgae, diseases and predator outbreaks (Miller et al. 2006, Carilli et al. 2009). Overgrowth of macro algae was reported to hinder the recovery of corals during the 2010 bleaching event in Palk Bay (Ravindran et al. 2012). Absence of such macroalgae overgrowth also aided the rapid recovery of corals post the bleaching event in 2013 and 2014.

In conclusion, the results of this study indicated an increase in the stress values that triggered bleaching among corals did not have a significant impact over the survivability of corals in a reef which is dominated by stress tolerant coral species. This in turn will enable the Palk Bay reef to be coral dominant and contribute to the recovery of coral populations. However, this study focused only on the survivability of the corals. The survival of corals post bleaching have the capacity to enhance the resilience potential of the reef by ensuring the presence of corals and its contribution towards the functional diversity of a reef and defend against the disturbances.

Chapter 5

Reef fish stock, exploitation and its implications on the corals of Palk Bay

5.1. INTRODUCTION

Reef fishes are the important components of coral reef ecosystem contributing to their community and functional structure. The complexity of the reef habitat and the availability of food favor the settlement of reef fishes and contribute to the abundance, diversity and distribution of the reef fish population in a coral reef ecosystem (Gratwicke and Speight 2005). The interaction between the corals and fishes has both positive and negative implications over corals. The reef fishes depend on corals for their food and shelter and feed on coral tissues and mucus affecting the coral growth. New coral recruits are removed by the grazing fishes affecting their distribution. Grazing fishes significantly reduce the algal population by feeding on them and prevents their overgrowth on corals (Ogden and Lobel 1978, O' Leary et al. 2013). Reef fishes contribute to the recycling of nutrients in the reef ecosystem through defecation (Meyer and Schultz 1985). Corallivore fishes produce sediment by feeding on the calcareous skeleton of corals which in turn contributes to the formation of reef and lagoon bases (Hixon 1997). Reef fishes excrete precipitated carbonate which contributes to the inorganic carbon cycle in the reef ecosystem.

Herbivory by reef fishes is an important reef process that maintains equilibrium between the corals and macroalgae (Mumby 2006). Diversity and abundance of the herbivore fish in a coral reef ecosystem provides numerous benefits that help in maintaining the community and functional structure of the reef (Burkepile and Hay 2008). Certain herbivore fishes regulate the algae population and other specific herbivores play an important role in reversing the phase-shifts. The herbivore reef fish are classified as scrapers, grazers and browsers based on their function in the reef (Bellwood 1994). Scrapers remove algae, sediment and other material by taking non-excavating bites and create a substrate for the settlement of new coral recruits. Similarly, the grazers feed on epilithic turf algae which in turn limit the growth of macroalgae (Bellwood and Choat 1990). Browsers feed on individual algal components and remove only the algae and its associated epiphytes. They play a critical role in controlling the algal population over corals and also in reversing the coral-algal phase shifts (Green et al. 2009). Absence of herbivore fishes due to overfishing enables the macroalgae to overtake corals affecting the reef structure and integrity (Done 1992, Hughes et al. 2007a).

Coral reef fishes are the major source of protein for at least 85% of the people living in the coastal areas (UNEP 2004). More than 80% of the world's shallow reefs were severely exploited (Wilkinson 2002) to meet the growing demand for reef fish. Herbivore reef fish exploitation strengthens the algal competition with corals leading to their mortality, and turns a coral dominant reef into an algal reef (Hughes et al. 2007b, Diaz-Pulido et al. 2009). The algae, based on their functional properties differ with their effect on corals (Jompa and McCook 2003). Recent studies showed the algae secrete toxic chemicals that killed live coral tissue (Rasher et al. 2011). The algal turfs killed the corals by trapping the sediments and smothering them. The corals were capable of recovering to their normal state after a major stress event like bleaching and it has been the key for reef resilience. Macroalgae and algal turfs in combination with sediment affect the coral resilience by preventing the settlement of new coral recruits (Birrell et al. 2005) and recovery of corals after a stress event like bleaching.

While exploitation of functionally important herbivore fish can have direct impact on corals, exploitation of predatory fishes resulted in trophic cascades and collapses the food web in a reef ecosystem (Wilson et al. 2008). Exploitation of reef fish had resulted in the outbreak of non-reef building taxa such as sea urchin *Echinometra mathaei* in Kenyan reefs (McClanahan and Shafir 1990) and crown of thorns star fish in Fiji (Dulvy et al. 2004). Structural complexity of the reef is critical to the biomass and species richness of the reef fish (Wilson et al. 2012). Mechanical damage to the corals during the reef fishing activities reduced the structural heterogeneity of the reef and decreased the shelter available for non-targeted herbivory fish making them vulnerable to predation (Dayton et al. 1995).

Palk Bay region which encompasses a narrow reef in the southeast coast of India is a potential fishing ground with an average annual production of 85000 tonnes (Kumaraguru et al. 2008). Scientific literature on the fishery potential of Palk Bay is limited and there are no reports on the contribution of coral reefs to the total fish production in Palk Bay. Reef fishing in Palk Bay was active throughout the year except during the Northeast (NE) monsoon that falls between October to December every year. The peak fishing season in Palk Bay is between January to September and the fishing effort ranges between 30 days boat^{-1} month^{-1} in the intensive reef fishing sites and 15 ± 4 days boat^{-1} month^{-1} in lightly fished reef sites. Reef fishing in Palk Bay employs artisanal fishing gears like hooks and cages. In addition, some destructive fishing methods were practiced including suspended trap net method. In this method, the net is deployed enclosing a particular patch of corals and the corals are beaten up using large wooden pestle to bring out the hidden fishes leading to their destruction.

Healthy stock of reef fish in a coral reef ecosystem is one of the key resilience indicators (McClanahan et al. 2012). Knowledge on the standing stock of reef fish and the quantity of reef fish being exploited is important to regulate the fishing activities inside a coral reef ecosystem and thereby to ensure the presence of healthy stock of reef fishes for performing the reef functions. Under this objective, the standing stock of reef fish (defined by the number of fishes 200 m^{-2} reef area) and their diversity was recorded from the selected study sites in Palk Bay reef. In addition, quantity of reef fish exploited (defined by wet weight in Kg) and their diversity was recorded from the Palk Bay reef. The percent cover of different benthic forms, their diversity and the abundance of healthy live corals, live corals smothered by turf and macroalgae were observed across the reef fishing sites of Palk Bay with varying fishing effort and it was compared with the control reef site in Gulf of Mannar (GoM) where the reef fishing was banned for more than three decades to evaluate the impacts of reef fishing over the coral communities in Palk Bay reef. In addition, the reef fish stock and diversity of reef fishes has been recorded in the control reef site.

5.2.MATERIALS AND METHODS

5.2.1. Study sites

In a snorkeling and SCUBA diving survey, two sites were observed each in Vedhalai (VDRF1 and VDRF2), Mandapam (MDRF1 and MDRF2) and Pamban (PBRF1 and PBRF 2) for their reef fish assemblage, coral community structure and coral status (Fig 5.1). A reef (MRC) near Manoli Island in the GoM was observed as a control site where reef fishing was banned for the more than three decades. The GoM reef encompasses 21 islands fringed with coral reefs and it was the first Marine

National Park in Southeast Asia. The fishing effort in Palk Bay reef was high in the western part comprising Vedhalai and Mandapam and low in the eastern part comprising Pamban and Rameshwaram. The reef fishing effort in the Vedhalai, Mandapam and Pamban locations were summarized in Table 10.

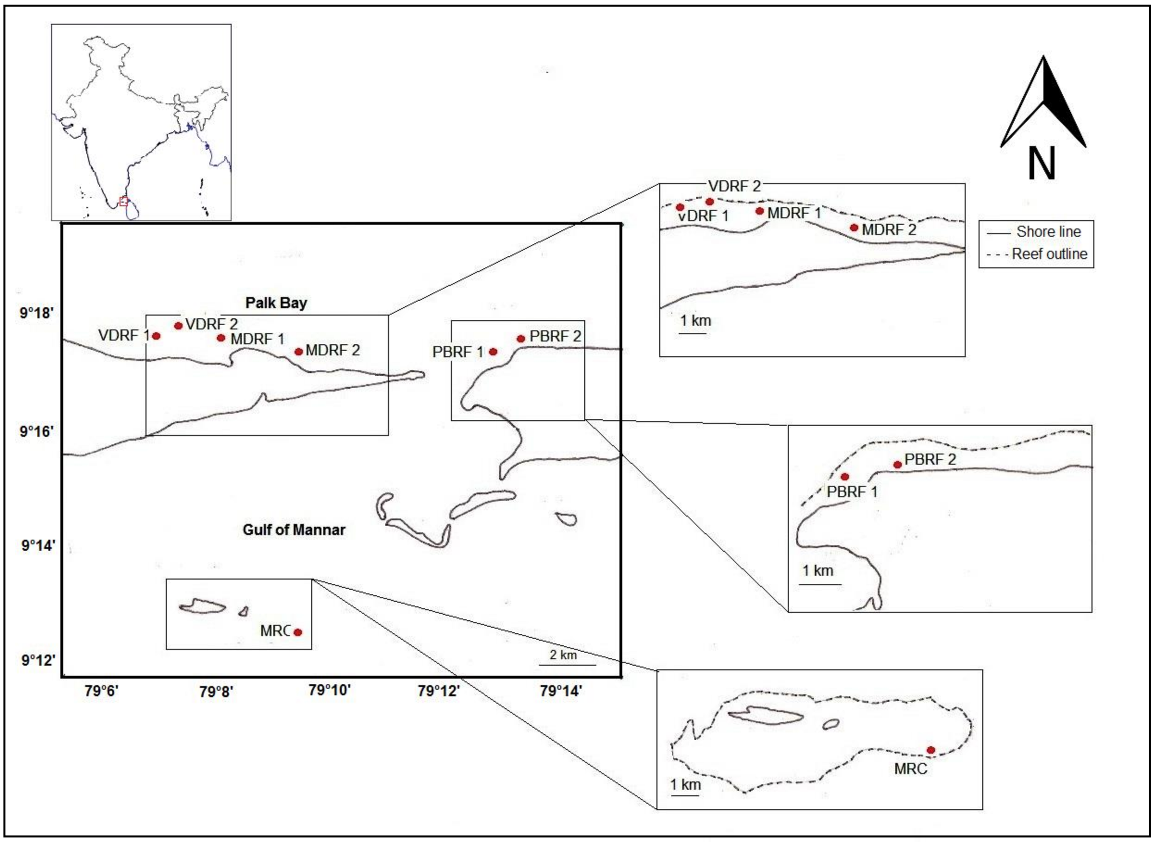


Fig 5.1. Map showing the study locations in the Palk Bay and Gulf of Mannar Reef, Southeast coast of India. (*VDRF 1* Vedhalai reef 1; *VDRF 2* Vedhalai reef 2; *MDRF 1* Mandapam reef 1; *MDRF 2* Mandapam reef 2; *PBRF 1* Pamban reef 1; *PBRF 2* Pamban reef 2; *MRC* Manoli Reef Complex).

Table 10- Reef fishing effort in the intensively fished and lightly fished reef sites of Palk Bay.

S. No	Details	Vedhalai and Mandapam reef	Pamban reef
1	Duration of Fishing	January-September	January- September
2	No. of Fishing days month^{-1}	30±1	15±4
3	Fishing methods	Cages, Shore seine, hooks, Trap nets	Shore seine, Hooks, hand picking
4	Hours of Operation	5±2 hours	3±1 hours
5	No. of Boats	20±5	15±5
6	No. of Fishermen's	45±10	30±10

5.2.2. Reef fish survey

The standing stock of reef fish at the study sites was assessed following the reef fish visual census method on a belt transect (English et al. 1997). Two permanent transects of 50 m length with a width of 2 m on either side of the transect were laid, one parallel to the shore and the other perpendicular to the shore on the selected study sites in each reef, giving a total of 4 transects at each reef. The effective width of the transect was 4 m and the total area covered was 200 m^2. The transect was left undisturbed for 15 minutes to enable the fishes to retain their normal behavior. The density of reef fishes was enumerated by swimming slowly along the transect and recorded as total number of fishes in 200 m^{-2} area. The fishes were identified to the highest taxonomic resolution possible in the field and identified up to species level using photographs and videos. Survey on the standing stock of reef fish was conducted between March – September in 2013 and 2014. Reef fish stock assessment was not done between October to February due to rough weather conditions and poor visibility.

5.2.3. Reef fish exploitation

The diversity and the quantity of commercially exploited reef fishes in the Palk Bay reef was surveyed through a questionnaire with fishermen involved in reef fishing, under water observations in the fish traps and at the fish landings in Palk Bay on daily basis during the active fishing season in the years 2013 and 2014. The quantity of reef fish being exploited was averaged over the number of fishing days and the number of fishermen involved in reef fishing. Since the diversity of fishes being exploited and their quantity differs every day, the fishes were categorized as Scrapers, Grazers and Carnivores based on their functional group and reported as average kilograms (wet weight) of fish exploited in each functional group per day per fisherman. The reef fishes being exploited were identified following the standard identification keys (Allen et al. 2003, Rao 2004).

5.2.4. Coral community assessment

The community structure of the corals was analyzed following the photo quadrat method described by English et al. (1997) with slight modifications. A square shaped area of 100 m^2 was demarcated using a 5 mm thick polypropylene rope consisting of 100 individual 1 m^2 grids at each study site. Each of the 1 m^2 quadrat was photographed using Olympus µ tough 8000 camera in an underwater macro mode. The quadrat images were processed manually by classifying different benthic forms including the abiotic forms like sand and rubbles and tracing them on a graph sheet. The area covered by each benthic form was measured with the factor of simple proportion relative to the total area of the quadrat in the graph sheet. The corals were identified to the genus level using the keys described by Veron (2000).

Status of the live coral colonies at the study sites was estimated following the belt transect method. A 50 m transect line was laid parallel to the shore at each study site and the observations were made following the belt transect survey, with a swath of 2.5 m on either side of the transect making the effective observed width as 5 m. The coral colonies, either live or partially live that falls within the transect were taken into consideration and categorized using a three point scale namely Healthy live coral (HLC), Live coral colonized by turf algae (LC/TA) and Live coral colonized by macroalgae (LC/MA).

5.2.5. Analysis

Shannon Index (H') ($\log_e$ based) was calculated for each study reef using the species richness and abundance (average density) of reef fish population for the years 2013 and 2014 and it has been compared. Further the diversity indices values (H') was converted in to Effective number of species (ENS) using the conversion ($\exp^{H'}$) described by Josts (2007) to observe the significance of differences between the annual variations in reef fish diversity during the study period. The reef fish density was averaged across the transects and study sites for each reef and is reported as average fish density of that particular reef. One way Analysis of Variance (ANOVA) was done to test for significant differences in reef fish density during the entire study period and for the contribution of herbivore and carnivore fishes to the total fish density. The values of reef fish density was log transformed to meet the assumptions of ANOVA. K-dominance curve was plotted using PRIMER statistical software V-6.1.2 for species abundance data to determine variation in reef fish density and diversity across the study sites.

The coral community data were compiled to form a matrix showcasing the percent cover of different benthic forms in the study sites. The data was subjected to the multivariate analyses to understand the present status of coral community structure. Principal component analyses (PCA) was done for different life-form categories observed in order to determine the most important benthic form contributing to the changes in the community structure. Bray-Curtis cluster analysis under the paired linkage was made to test the similarity between the intensive reef fishing sites, minimal reef fishing sites and control site. Principal Coordinate Analysis (PCoA) was done for segregating the study sites based on their similarity in the community structure. The relationship between the herbivore fish density and abundance of the healthy live corals was delineated using correlation analysis. All the statistical analysis was performed using the statistical software PAST, version 2.15.

5.3.RESULTS

5.3.1. Reef fish diversity

In total, 38 species of reef fish of 21 genera were recorded from the selected study sites of Palk Bay. Herbivore fishes were less diverse comprising 14 species of 7 genera compared to the carnivore fishes which comprise 24 species of 14 genera in Palk Bay. Diversity Index (H', $\log_e$ based) was typically high in Pamban measuring 2.96 followed by Vedhalai (2.80) and Mandapam (2.56) in 2013. However in 2014, the diversity index decreased to 2.93 in Pamban; 2.67 in Vedhalai and 2.53 in Mandapam. One way ANOVA showed significant differences between the annual variations in the effective number of species among the study sites (One-way ANOVA, df= 2; F= 33.1; F_{crit} = 9.5; p value = 0.009<0.05). The temporal pattern of the diversity index of the reef fishes during the study period in Palk Bay reef was presented in the Fig 5.2.

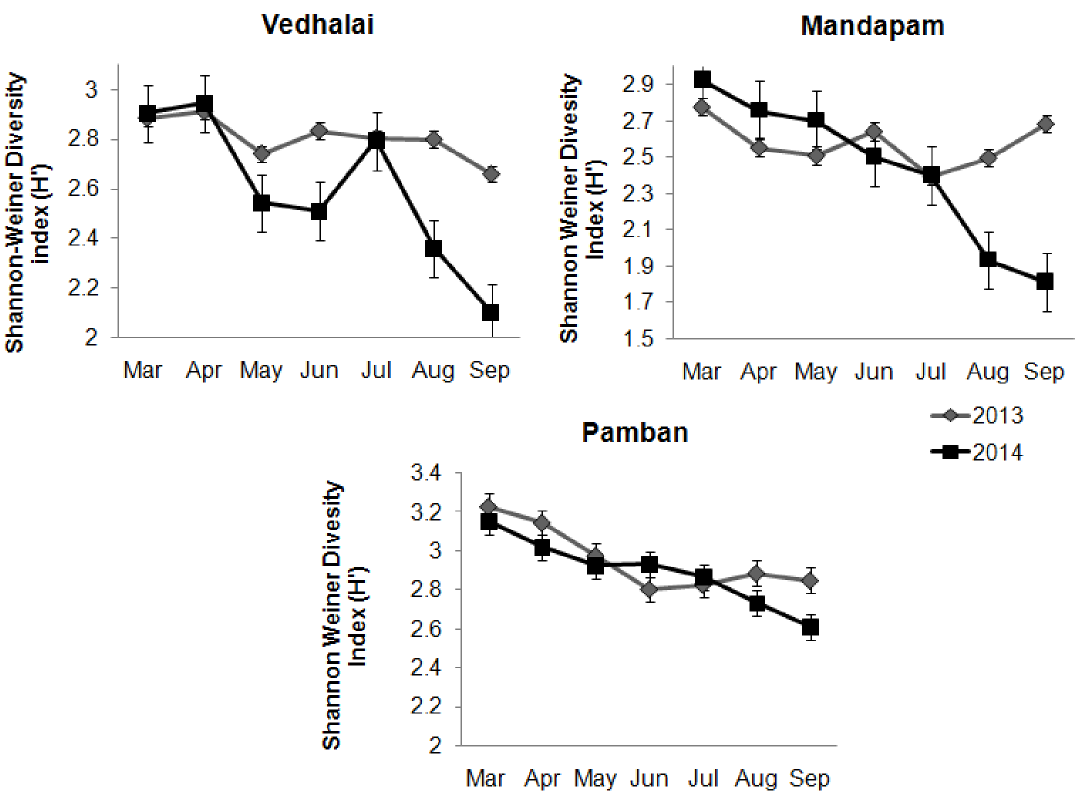


Fig 5.2. Temporal pattern of the Shannon Weiner Diversity index (H', $\log_e$ based)of the reef fish diversity at Palk Bay in 2013 and 2014.

In total, Pamban comprise 33 species of reef fish of 18 genera followed by Vedhalai and Mandapam each comprising 27 species of 17 genera. Carnivore fishes were dominant over the herbivore fishes in terms of abundance and diversity at all the study sites. Herbivore fishes of 8 species of 5 genera were recorded in the Vedhalai; 11 species of 7 genera in Mandapam and 13 species of 7 genera in Pamban. Herbivore fishes of *Scarus*, *Siganus* and *Canthigaster* sp were abundant at all the study sites compared to the other herbivore fishes. Vedhalai comprises 19 species of carnivore fishes belonging to 12 genera. Mandapam and Pamban comprise 16 species of 11 genera and 20 species of 12 genera respectively. *Apogon fasciatus*, *Synodus indicus* and *Terapon jarbua* were abundant compared to the other carnivore fishes at all the study sites.

The reef fish diversity was high in the control site at GoM with a diversity index (H’) of 3.57 compared to the study sites at Palk Bay. In total, 50 species of reef fish belonging to 36 genera were recorded in the control site. The species richness was high among the carnivore fishes and it comprises 37 species of 29 genera compared to herbivore fishes which comprise only 13 species of 7 genera. Herbivore fishes of *Scarus* sp were the major contributor to the total herbivore fish density and *Chaetodon collarae* was dominant among the carnivore fish population. The diversity index of reef fishes in the control site decreased from 3.57 in 2013 to 3.51 in 2014. The list of reef fishes recorded in the Palk Bay and GoM study sites were presented in the Table 11.

Table 11- List of reef fishes recorded in the study sites of Palk Bay and Gulf of Mannar. (+) indicates presence, (-) indicates absence.

S. No	Functional group	Species	Vedhalai	Mandapam	Pamban	GoM
1	**Herbivores**	*Acanthurus lineatus*	-	-	-	+
2		*Abudefduf septemfasciatus*	+	+	+	+
3		*Abudefduf vaigiensis*	+	-	-	+
4		*Acanthurus leucosternon*	-	+	+	+
5		*Acanthurus mata*	+	+	+	+
6		*Acanthurus nigrofuscus*	-	-	+	+
7		*Canthigaster solandri*	+	+	+	-
8		*Chaetodon deccusatus*	-	+	+	+
9		*Chlorurus gibbus*	-	+	+	+
10		*Scarus ghobban*	+	+	+	+
11		*Scarus gibbus*	+	+	+	-
12		*Scarus rubroviolaceous*	-	-	+	+
13		*Siganus canaliculatus*	+	+	+	-
14		*Siganus javus*	+	+	+	+
15		*Siganus lineatus*	-	+	+	+
16		Zebrasoma veliferum	-	-	-	+
	Carnivores					
17		*Acanthurus bleekeri*	-	-	+	-
18		*Apogon fasciatus*	+	+	+	+
19		*Apolemichthys xanthurus*	+	-	-	+
20		*Arothron immaculatus*	+	+	-	+
21		*Balistoides viridescens*	-	-	-	+

22	*caranx heberi*	-	-	-	+
23	*Chaetodon collarae*	+	-	+	+
24	*Chaetodon octofasciatus*	-	-	-	+
25	*Chaetodon pleubis*	-	+	+	+
26	*Chelinus undulatus*	-	-	+	+
27	*Chiloscyllium griseum*	-	-	-	+
28	*Dascyllus reticulatus*	-	-	-	+
29	*Diagramma pictum*	-	+	+	+
30	*Diodon holocanthus*	-	-	-	+
31	*Epinephalus arolatus*	-	-	-	+
32	*Epinephalus cocoides*	+	+	+	+
33	*Epinephalus fasciatus*	+	-	+	+
34	*Epinephalus malabaricus*	+	+	+	+
35	*Ghathodon speciosus*	-	-	-	+
36	*Halichoeres nigrescens*	-	-	-	+
37	*Hemigymmus melapterus*	-	-	-	+
38	*Heniochus acuminatus*	-	-	-	+
39	*Labyoides dimicliatus*	-	-	-	+
40	*Lutjanus deccusatus*	+	+	+	+
41	*Lutjanus ehrenbergii*	+	-	+	-
42	*Lutjanus fulviflamma*	+	+	+	+
43	*Lutjanus fulvus*	+	+	+	+
44	*Lutjanus malabaricus*	+	+	-	-
45	*Mulloidichthys vanicolensis*	-	-	-	+
46	*Paraupeneus macronema*	-	-	-	+
47	*Pempheris molucca*	-	-	-	+
48	*Plectorhincus lineatus*	+	-	-	+
49	*Plotorus lineatus*	-	-	-	+
50	*Pomacentrus caeruleus*	+	+	+	+
51	*Psammoperca waigiensis*	+	+	+	+
52	*Pterocaesio chrysozona*	-	-	-	+
53	*Pterois volitans*	-	-	+	+
54	*Sargocentron rubrum*	+	+	+	+
55	*Synodus indicus*	+	+	-	+
56	*Terapon jarbua*	+	+	+	-
57	*Terapon puta*	+	+	+	-
58	*Upeneus vittatus*	-	-	-	+

The diversity and density of reef fishes varied along the study sites with varied fishing effort. Reef fishes of very few genera belonging to the *Abudefduf, Scarus, Siganus, Apogon, Epinephalus, Lutjanus, Pomacentrus* and *Psammoperca* were recorded from all the study sites. Rest of the species showed discrepancy in their distribution between the study sites. The difference in species richness and density during 2013 and 2014 was shown in the Fig 5.3 where the cumulative percentage of dominance of species is ranked on a logarithmic scale. The highest species diversity was evident in the control site at GoM followed by the Pamban at Palk Bay.

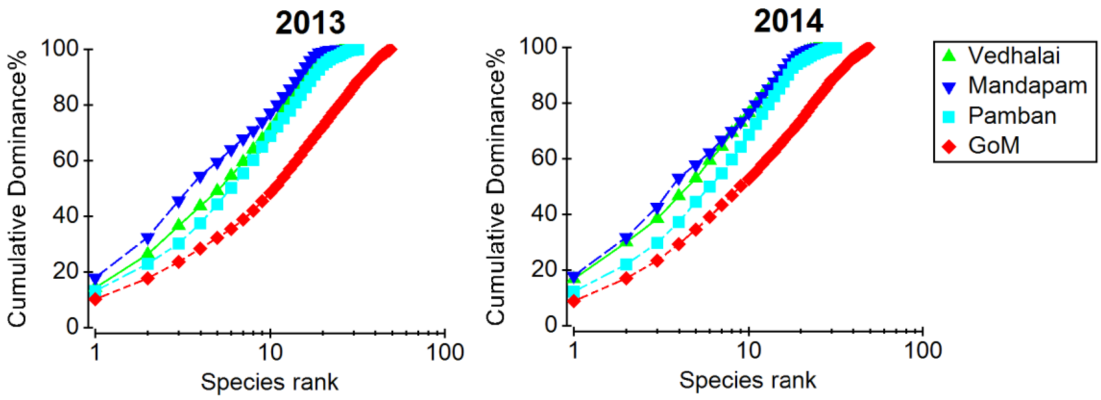


Fig 5.3. K-dominance curve showing variation in the species richness of the reef fish population at the study sites of Palk Bay and Gulf of Mannar in 2013 and 2014.

5.3.2. Reef fish density

Density of reef fishes in Palk Bay during the study period was presented in the Fig 5.4. The mean density of reef fish (200 m^{-2} area) in 2013 was 55.28 ± 1.73 (Mean ± SD) in Vedhalai; 39.64 ± 13.90 in Mandapam and 65.71 ± 12.1 in Pamban. Carnivore fishes were the major contributors to the total fish density accounting for 77.5% in Vedhalai reef; 80% in Mandapam reef and 67.2% in Pamban reef. The mean density of carnivore fish population differs between a maximum of 50.5 ± 7.6 to a minimum of 39 ± 3.8 fishes 200 m^{-2} in Vedhalai; 38.5 ± 6.7 to 24.5 ± 0.9 in Mandapam; 46 ± 2.3 to 41.5 ± 2.14 in Pamban between the subsequent observations. Herbivore fishes contribute less to the total fish density accounting for 22.48% in Vedhalai; 20% in Mandapam and 32.7% in Pamban. The mean density of the herbivore reef fish population differs between a minimum of 9.5 ± 2.9 to a maximum of 15.5 ± 3.02 fishes 200 m^{-2} in Vedhalai; 6.5 ± 1.4 to 10 ± 2.07 fishes 200 m^{-2} in

Mandapam; 16.5 ± 5 to 29.5 ± 8 fishes 200 m^{-2} in Pamban. Changes in the reef fish density does not differ significantly between the subsequent observations in a particular year at all the study sites (p value = 0.9>0.05, 2013; p value = 0.8 >0.05, 2014).

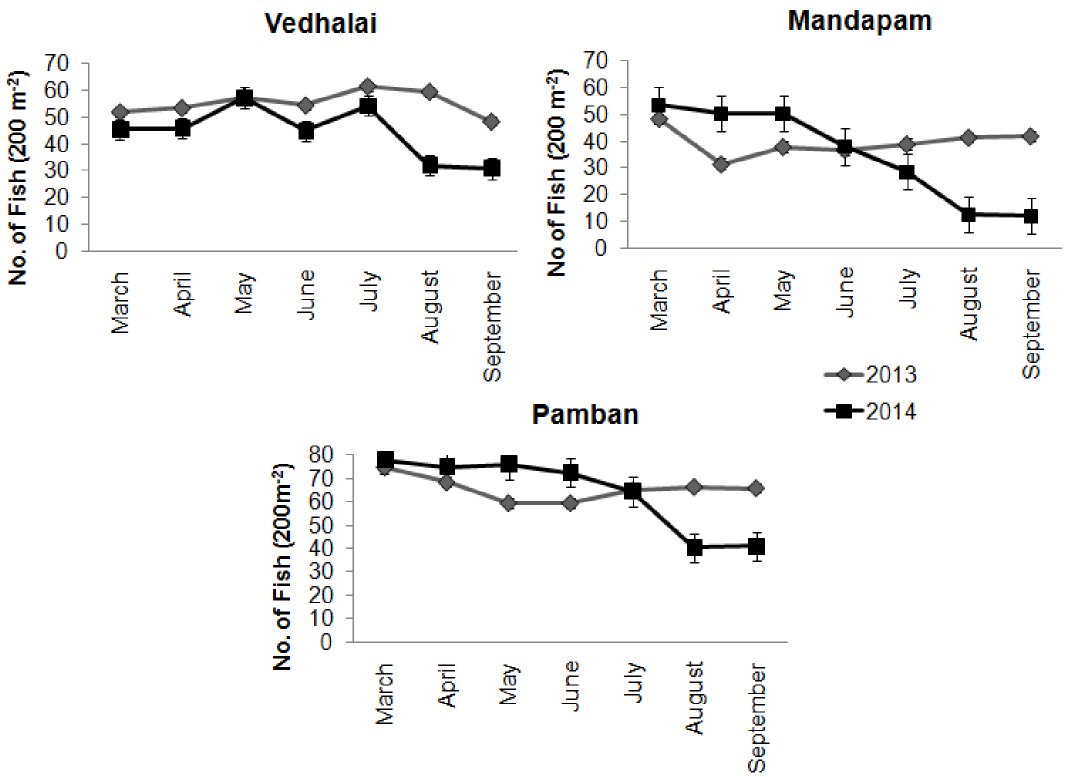


Fig 5.4. Average density of Reef fishes at the study sites of Palk Bay during the study period.

Observations in 2014 revealed decline in the total mean fish density at the study sites of Palk Bay. The mean reef fish density declined to 46.75 ± 4.3 in Vedhalai; 38.91 ± 12.2 in Mandapam and 62.75 ± 13.27 in Pamban. The decline in the total fish density between 2013 and 2014 was not statistically significant (One-way ANOVA, df= 1; F= 0.15; F_{crit}= 7.7; p value = 0.7>0.05). However, the contribution of herbivore fish to the total fish density increased up to 33.3% in Vedhalai ; 23.55% in Mandapam and 33.2% in Pamban in 2014 (Fig 5.5). The mean density of the herbivore fish population in 2014 ranges between 10 ± 5.5 to 19 ± 3.4

fishes 200 m^{-2} in the Vedhalai; 2 ± 7.1 to 15.5 ± 6.3 fishes 200 m^{-2} in Mandapam and 13 ± 0.6 to 23 ± 2.1 fishes 200 m^{-2} in Pamban. Similarly the carnivore fish population ranges between 22 ± 6.3 to 38.5 ± 7.3 fishes 200 m^{-2} in Vedhalai; 10.5 ± 19.25 to 39 ± 9.2 fishes 200 m^{-2} in Mandapam and 27.5 ± 14.41 to 50.5 ± 8.5 fishes 200 m^{-2}. In general, the contribution of carnivore fishes towards total fish density differs significantly from that of herbivore fishes (p value <0.05) during the entire study period (Table 12).

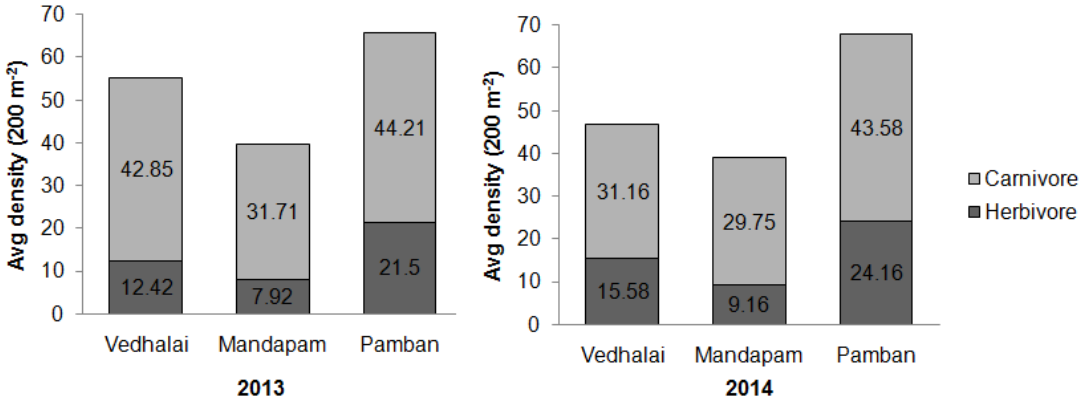


Fig 5.5. Contribution of herbivore and carnivore fishes to the total fish density at the study sites of Palk Bay in 2013 and 2014.

Table 12- One way ANOVA revealing significant differences between the contribution of carnivore and herbivore fishes towards total fish density.

Year	Study site	df	F value	F_{crit}	p value (0.05)
2013	Vedhalai	1	242.1	4.7	2.5×10^{-9}
	Mandapam	1	188.3	4.7	0.1×10^{-9}
	Pamban	1	128.4	4.7	0.9×10^{-9}
2014	Vedhalai	1	31.3	4.9	0.0002
	Mandapam	1	16.6	4.9	0.002
	Pamban	1	34.1	4.9	0.0001

The average density of reef fish in the control site was several times higher compared to the other study sites in Palk Bay which are influenced by reef fishing. The mean density of reef fishes ranges a maximum of 242 ± 4.5 in 2013 and 233 ± 4.5 in 2014. Similar to Palk Bay, carnivore fishes were abundant contributing 63.2% and 59.2% to the total fish density in 2013 and 2014 respectively. However, the percentage of contribution of herbivore fishes had increased to 40.7% in 2014 compared to 36.7% in 2013.

5.3.3. Reef fish exploitation

The list of commercially exploited reef fishes and their functional group were presented in the Table 13. An average of 8.9 ± 3.5 kg of Scrapers; 3.21 ± 2.1 kg of Grazers and 3.89 ± 1.4 kg of carnivores were exploited day^{-1} fisherman^{-1} in 2013. The average catch rate of scraper fishes including *Scarus ghobban, Scarus ruboviolaceous* and *Scarus gibbus* differs between a minimum of 5.75 ± 3.17 kg to a maximum of 14.71 ± 5.78 kg day^{-1} fisherman^{-1}. The average catch rate of scrapers differed significantly compared to that of grazers and carnivores (One-way ANOVA, df= 2; F= 14.7; F_{crit}= 3.5; p-value = 0.0001<0.05). Among grazing fishes *Signaus javus, Siganus canaliculatus* and *Siganus lineatus* were targeted in large quantity and the catch rate differs between 2.08 ± 1.13 to a maximum of 5.4 ± 2.18 kg day^{-1} fisherman^{-1}. Similarly, among carnivore fishes *Epinephalus, Lutjanus, Lethrinus* and *Psammoperca* sp were maximum targeted and the catch rate differs between 1.91 ± 1.98 to 5.1 ± 1.20 kg day^{-1} fisherman^{-1}.

The average catch rate of scrapers increased to 11.08 ± 5.2 kg in 2014 comparatively higher than their average catch rate in 2013. However, increase in average catch rate of scrapers was not statistically significant (One-way ANOVA, df= 1; F value = 1.98; F_{crit}= 4.74; p value = 0.18 > 0.05). In 2014, the average catch rate of scrapers ranged between a minimum of 8.3 ± 2.78 to a maximum of 14.98 ± 3.89 kg day^{-1} fisherman^{-1}. Similarly, the average catch rate of grazers and carnivores ranged between 2 ± 0.96 to 3.89 ± 0.92 kg day^{-1} fisherman^{-1} and 6.81 ± 3.34 to 1.06 ± 2.4 kg day^{-1} fisherman^{-1} respectively (Fig 5.6).

Table 13- List of commercially exploited reef fishes from Palk Bay reef.

S. No	Species	Functional group
1	*Acanthurus bleekeri*	Zooplanktivore
2	*Acanthurus mata*	Zooplanktivore
3	*Acanthurus xanthopterus*	Grazer
4	*Epinephalus sp*	Carnivore
5	*Lutjanus deccusatus*	Carnivore
6	*Lutjanus fulviflamma*	Carnivore
7	*Lutjanus malabaricus*	Carnivore
8	*Lutjanus rivulatus*	Carnivore
9	*Psammoperca waigiensis*	Carnivore
10	*Scarus ghobban*	Scraper
11	*Scarus gibbus*	Scraper
12	*Scarus riboviolaceous*	Scraper
13	*Siganus canaliculatus*	Grazer
14	*Siganus javus*	Grazer
15	*Siganus lineatus*	Grazer

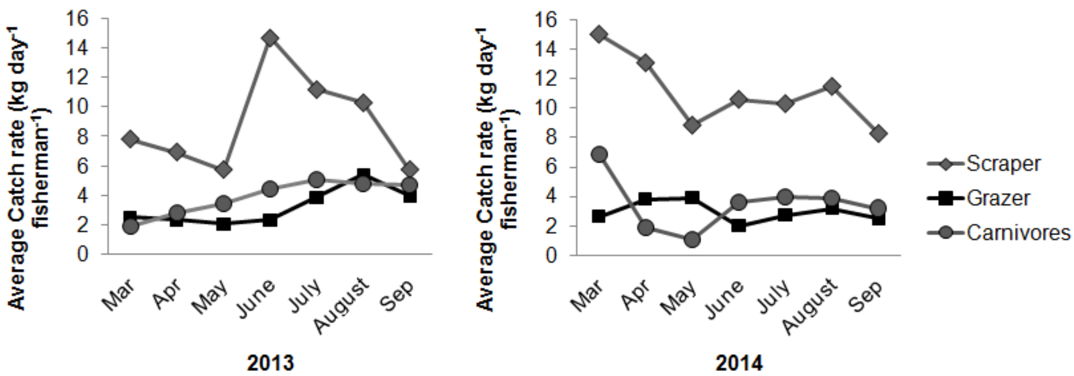


Fig 5.6. Temporal pattern of exploitation of reef fishes of different functional groups at Palk Bay in 2013 and 2014.

5.3.4. Coral community structure

Corals at the study sites of intensively fished Vedhalai and Mandapam were severely degraded owing to the mechanical damage, algal turf and macro algal colonization. Community structure analysis revealed majority of the corals were dead and the existing live corals exhibited partial mortality due to the colonization of turf and macroalgae. The percent cover of different benthic forms at the study sites were presented in Fig 5.7. Dead corals colonized by turf algae (DC/TA) predominates VDRF 2 and MDRF 1 accounting for 56.2% and 33.1% respectively. Whereas, VDRF 1 and MDRF 2 was dominated by LC/TA which contributes 26.7% and 30.4% respectively. The rubbles cover was noteworthy in the intensive reef fishing sites compared to the control site MRC, as they provide direct evidence for the mechanical damage that arose due to the drifting activities of the fishermen in the reef fishing sites. The percent cover of LC/H was less than 3% in the intensive reef fishing sites except VDRF 1 (7.8 %). Algal competition by macro and turf algal assemblages on live corals were noticed more in intensively fished Mandapam reef sites than the other sites. More than 8% of live corals in the intensive reef fishing sites were colonized by the macro algal species like *Caluerpa racemosa, Padina* and *Sargassum* sp. Diversity of the live corals were dominated by massive colonies of *Porites*, *Favites* and *Favia* sp, whereas corals of other genera such as *Acropora* sp were dead due to turf algal colonization. Six species of corals belonging to four genera were recorded from the study sites of intensively fished Vedhalai and Mandapam.

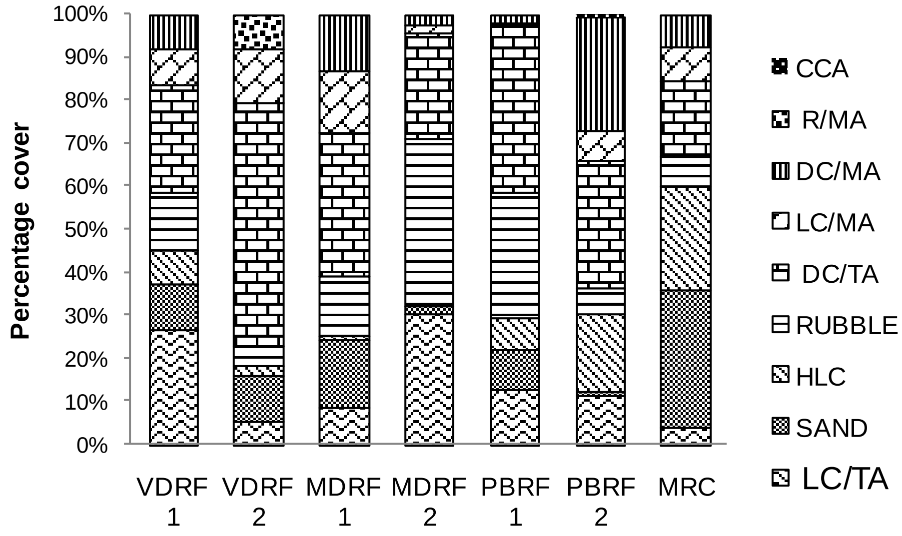


Fig 5.7. Area cover of different reef community forms along the intensive reef fishing (VDRF 1, VDRF 2, MDRF 1 and MDRF 2) and mild reef fishing sites (PBRF 1 and PBRF 2) of Palk Bay and control site (MRC). CCA - Crustose coralline algae; R/MA - macroalgae attached to rubbles; DC/MA- dead coral colonized by macroalgae; LC/MA- live coral colonized by macroalgae; DC/TA- dead coral colonized by turf algal assemblage; LC/H- healthy live coral; LC/TA- live coral colonized by turf algal assemblage).

The impacts of intensive reef fishing at Vedhalai and Mandapam reefs spreaded out to the Pamban reef (PBRF 1 and PBRF 2) despite the minimal fishing pressure. Live corals of 12.8% and 18.4% exhibited partial mortality due to turf and macro algal colonization in PBRF 1 and PBRF 2 respectively. Similar to the intensive reef fishing sites, DC/TA was dominant in both PBRF 1 (39.3%) and PBRF 2 (29.6%) reducing the availability of bare substrate for coral recruitment. The impacts of reef fishing were low in PBRF 2 compared to PBRF 1. It can be attributed to the level of proximity of these sites from the intensive fishing sites. The live coral cover was high in PBRF 2 (17.9%) compared to PBRF 1 (7.1%). The taxonomic composition of corals was higher in the Pamban reef compared to the Vedhalai and Mandapam reefs. Ten species of corals of six genera were recorded in PBRF 1 and PBRF 2. Massive

Porites sp was abundant followed by *Favia* and *Favites* sp in these study sites. The Principal component analysis (PCA) revealed that the MRC and PBRF 2 contributed more live corals, according to the observation made in this study (Fig 5.8). The percent cover of LC/H was high in MRC and it accounts for 24%. However, LC/TA and LC/MA together contributes 12% and DC/TA contributes 17.3% to the total benthic community composition. Ten species of corals from seven genera was recorded in MRC, comparatively higher than the study sites influenced by reef fishing at Palk Bay. The diversity of corals at the study sites were summarized in the Table 14.

As per the results of Bray-Curtis cluster analysis under paired linkage the study sites were grouped into three major groups with more than 60% similarity, based on the benthic forms observed in this study (Fig 5.9). The Mandapam reef site (MDRF 1) was merged with Vedhalai reef sites (VDRF 1 and VDRF 2) due to similar composition of benthic life-form categories. Similarly, the Mandapam reef site (MDRF 2) was merged with Pamban reef site (PBRF 1). Due to similar composition of LC/H and LC/MA, PBRF 2 and MRC were merged in one single group. Hence, these two sites were separated from other sites in the Principal Coordinate analysis (PCoA) (Fig 5.10). It also showed a clear difference between intensive fishing reef and Non-fishing reef sites.

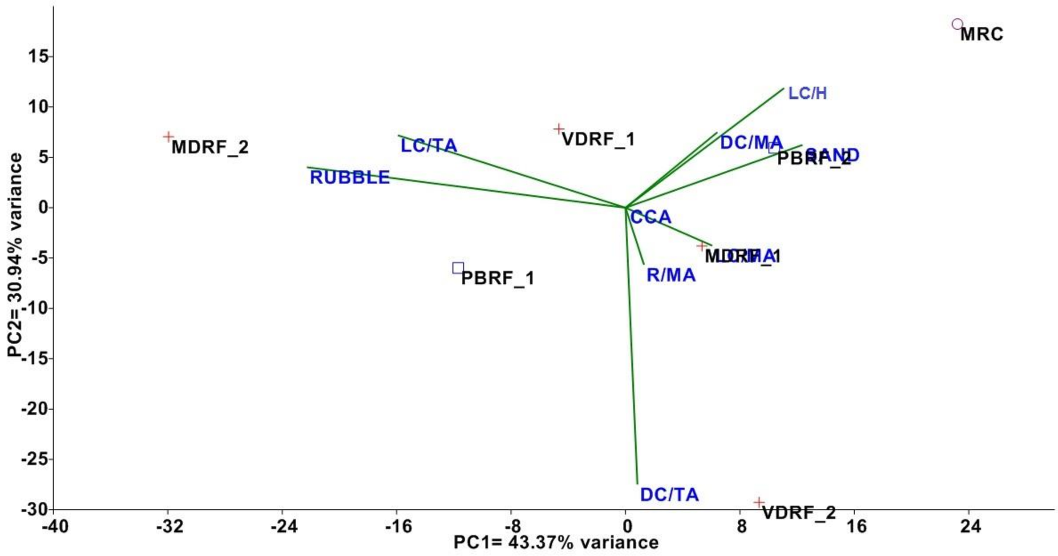


Fig 5.8. Principal component analysis (PCA) of the reef communities at the study sites of Palk Bay and Gulf of Mannar.

Table 14- List of coral species recorded at the study sites of Palk Bay and Gulf of Mannar. ('+' indicates presence and '-' indicates absence).

Coral sp	MRC	VDRF 1	VDRF 2	MDRF 1	MDRF 2	PBRF 1	PBRF 2
Acropora cyatherea	-	-	-	-	-	+	+
Acropora formosa	-	-	-	-	-	+	+
Cyphastrea microphthalma	-	+	+	-	-	-	-
Echinopora lamellosa	+		-	-	-	-	-
Favia pallida	+	+	+	+	+	+	+
Favia speciosa	+	+	+	+	+	+	+
Favites halicora	+	+	+	+	+	+	+
Goniastrea sp	+	-	-	-	-	-	-
Montipora foliosa	+	-	-	-	-	-	-
Porites annae	+	-	-	-	-	+	+
Porites lobata	+	+	+	+	+	+	+
Porites lutea	+	+	+	+	+	+	+
Symphyllia radians	-	-	-	-	-	+	+
Turbinaria peltata	+	-	-	-	-	-	-
Platygyra sp	-	-	-	-	-	+	+

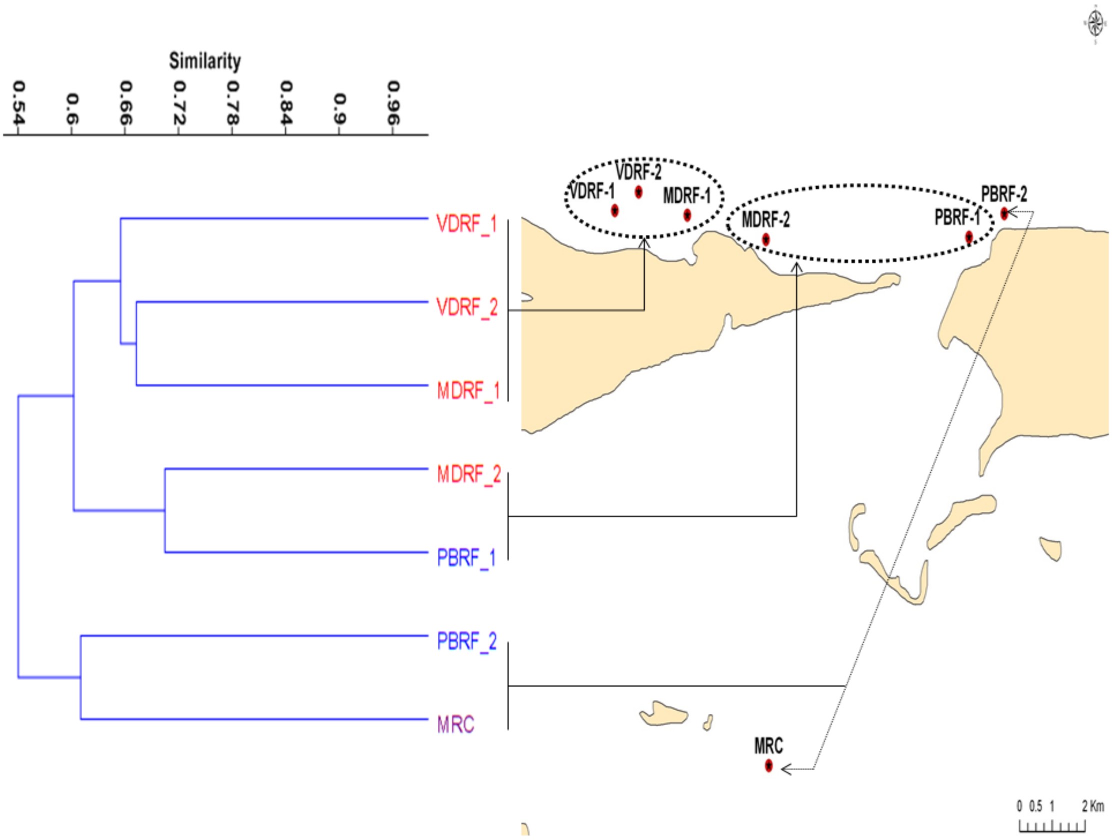


Fig 5.9. Bray-Curtis cluster analysis of the study sites at Palk Bay and Gulf of Mannar.

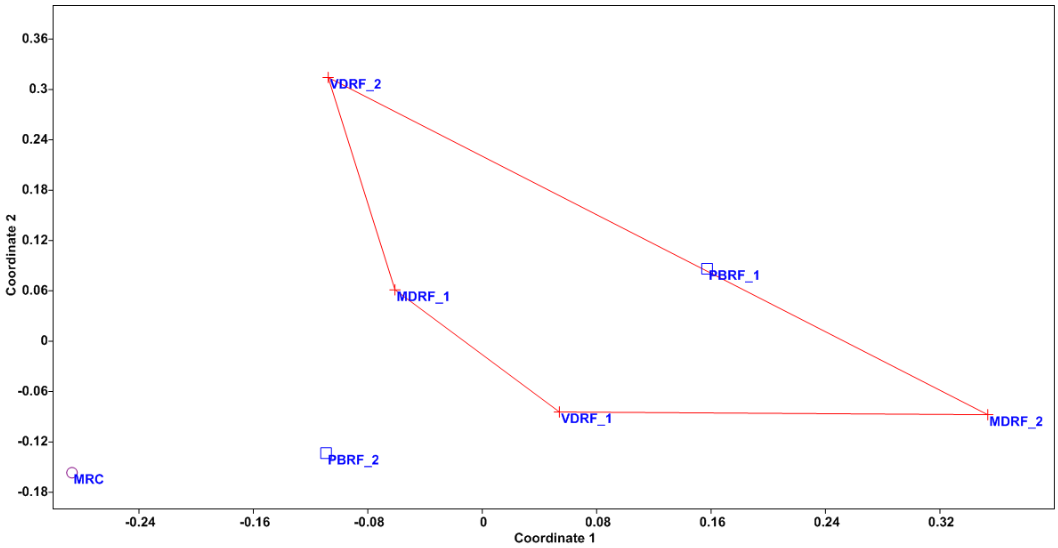
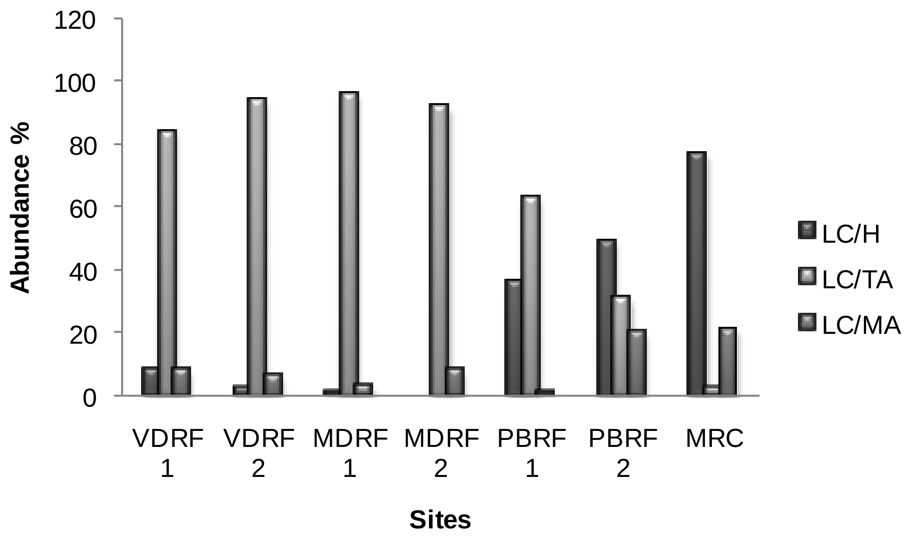


Fig 5.10. Principal Coordinate analysis of the study sites at Palk Bay and Gulf of Mannar with varied fishing efforts.

5.3.5. Status of live corals

The percent cover of LC/H varied compared to LC/TA and LC/MA across the study sites which are free and influenced by reef fishing pressure (Fig 5.11). The percent cover of LC/TA ranges between a maximum of 96% to a minimum of 84% and LC/H accounts for <10% at the study sites of intensively fished Vedhalai and Mandapam. *Porites* sp was largely affected by turf algae compared to the other coral species. The percent cover of LC/H to that of LC/TA at the two sites of Pamban varied with their proximity to the intensively fished Vedhalai and Mandapam. PBRF 1 lies in close proximity to the intensive reef fishing sites and hosts 63% and 36% of LC/TA and LC/H respectively. Whereas PBRF 2 lies far from the Vedhalai and Mandapam and encompass 31% and 49% of LC/TA and LC/H respectively. The control site hosts high LC/H (77%) compared to those sites influenced by reef fishing in Palk Bay. However the percent composition of LC/MA was high in MRC (21%) and PBRF 2 (20%) compared to the intensively fished Vedhalai and Mandapam. A significant positive correlation exists between the herbivore fish density and the percent cover of healthy live corals. Based on the coefficient of determination value (r^2=0.840), it was evident that almost 84% of the variance in the dependent variable (i.e. Herbivore fish count) is explained by the derived regression equation, and mere 16% is unexplained (Fig. 5.12).



5.11. Percent cover of live corals of different states in the study sites (LC/H healthy live coral; LC/TA live coral colonized by turf algae, LC/MA live coral colonized by macroalgae).

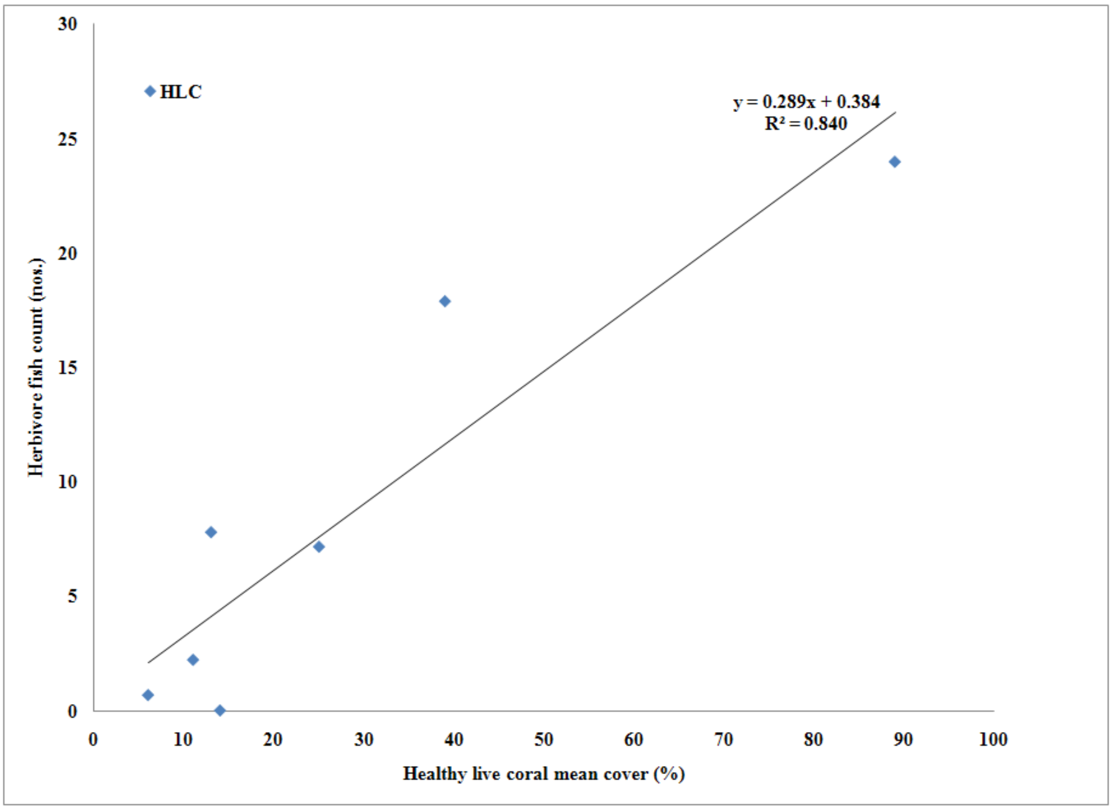


Fig 5.12. Regression analysis of herbivore fish count with percent cover of healthy live corals in the study sites.

5.4.DISCUSSION

The Gulf of Mannar Marine Biosphere Reserve (GOMBR) comprises both GoM and Palk Bay reefs. However, they have been offered different levels of protection. In GoM, reef fishing and the other human activities around the coral islands are strictly regulated. No such regulations were imposed on Palk Bay and eventually reef fishing turns out to be a potential life source for small scale fishermans. Comparison of the diversity and the numerical density of reef fishes in Palk Bay and GoM reveal the potential of the conservation status. The reef fish density in GoM was several times higher than the study sites at Palk Bay. Part of this high diversity of reef fishes can be attributed to the conservation status, live coral cover and habitat type. Maintenance of high diversity and density of reef fishes is essential for normal reef functions (Hixon 1997).

The western part of the Palk Bay that includes Vedhalai and Mandapam reefs spans a reef area of 4.85 km^2. Observations revealed that the diversity and density of the herbivore reef fishes within this area was low than the reef fishes of other functional groups. The ratio of exploitation of functionally important herbivore fish was high compared to the carnivore fish owing to their commercial value. With a little diversity of the large herbivore fishes in Palk Bay, the *Scarus* and *Siganus* species plays an important role in regulating the algal population. However these fishes are the primary targets of fishermen and were exploited in larger quantities compared to other carnivore fishes. Exploitation of a particular group of fishes in large number can result in the outbreak of a single species which can exert unforeseen effects on the ecosystem.

While exploitation of functionally important herbivore fishes can have direct impact on corals, exploitation of non-functional groups and predatory fishes may exert unpredicted catastrophes affecting the ecosystem function (Dulvy et al. 2004). Most fishing techniques and fishermen target the larger individuals in populations to yield maximum biomass and this reduced the proportion of large and matured individuals in a population. Reef fish exploitation have severe ecological implications affecting the inorganic carbon cycle in reef ecosystems (Jennings and Wilson 2009), collapse the food web (Wilson et al. 2008), outbreak of non reef building taxa such as sea urchin (McClanahan and Shafir 1990) and crown of thorns star fish (Dulvy et al. 2004). The consequences of reef fishing were restricted to the loss of corals and no such outbreaks of non-reef building taxa were observed in Palk Bay reef.

It is obvious from the results that turf and macroalgal colonization that arised out of the existing fishing practices was the major factor driving the degradation of corals in the reef fishing sites of Palk Bay. The competition between the corals and algal communities was seen as a vital process in structuring the reef community (McCook et al. 2001). However, the dominance of one form over the other due to external stress results in severe catastrophes that will affect the entire ecosystem. Current fishing practices such as deployment of trap nets and cages around the healthy coral colonies resulted in mechanical damage of corals. All these practices created dead patches on the surface of the healthy coral colonies which facilitated the settlement of borers and algal spores and their subsequent colonization over corals (Fig 5.13). These actions coupled with removal of herbivore reef fishes exacerbated the development of algae over the corals. It was noticed that >90% of the live corals existing in the intensive reef fishing sites were mechanically damaged, either partly or wholly, and colonized by the algal turf and macroalgae. The impacts of reef fish exploitation were not solely restricted to the intensive fishing sites, but also to its neighboring coral ecosystems despite the minimal fishing pressure. Of the 100 m^2

area analyzed in the Pamban (PBRF 1 and PBRF 2), >40m^2 of area spanning live corals and dead corals were colonized by algal turfs. Added to this, the abundance of herbivore and other reef fishes were comparatively low in the Pamban reef.

Fig 5.13. Colonization of turf algae over corals. (a) Dead patch on the coral *Favia pallid* formed due to the drifting activity of the boat; (b) turf algal colonization over the dead patch of the coral; (c) turf algae spreads to the healthy portion of coral thereby affecting the entire colony.

The impact of algal communities over corals has been widely described (Tanner 1995, McCook et al. 2001, Kuffner et al. 2006). The reefs with high terrestrial inputs are often dominated by algal turfs. Birrell et al. (2005) proved that algal turfs in combination with sediments prevent the settlement of coral recruits. In addition, the filamentous turf algae upon interaction with corals results in a chronic stress, overgrowth and mortality (Cetz-Navvaro et al. 2013). The macroalgae can negatively influence the corals by smothering, shading, overgrowth, enhancing the coral microbial activity (Smith et al. 2006), being a vector harbouring potential pathogens and affecting the regeneration of tissues (Bender et al. 2012). The calcium carbonate deposition during an incidence of high algal biomass is solely attributable to the algal deposition and the so formed reef structure is inappropriate for fish habitat and shore line protection (McClanahan 1995). Nutrient enrichment due to pollution and reduction in herbivory fish has been considered as prime factors triggering the algal dominance in reefs. Experimental evidence indicate that exploitation of large herbivory fish have profound impacts in a coral ecosystem than nutrient enrichment (Miller et al. 1999). The exploitation of reef herbivory fish may exacerbate the effects of turf algal assemblage over the corals by affecting their recruitment and resilience potential.

Herbivore fishes are highly susceptible to the gears used in artisanal fishing practice (McClanahan and Cinner 2008). The reef fishing practices that exist in Palk Bay include deploying underwater cages, shore seine, trap nets, bait fishing and throw nets. Reef fishing using these artisanal fishing gears is largely seen as a harmless and effective method while their indirect effects have been ignored. Of these practices, trap net fishing and cage fishing methods are followed by majority of the fishermen in Palk Bay which incur mechanical damage to the corals. In addition, the other activities associated with reef fishing such as drifting of boat over the reef to locate the cages, anchoring of boats over corals and beating up of corals using large wooden logs to disturb the fishes that hides under the holes and crevices to lure them into the traps adds up to the mechanical destruction of corals affecting their structural complexity. Structural complexity of a reef is critical to the biomass and species richness of the reef fish (Wilson et al. 2012). Mechanical damage to the corals during the reef fishing activities could reduce the structural heterogeneity of the reef thereby decreasing the shelter available for non-targeted herbivory fishes making them vulnerable to predation (Dayton et al. 1995).

Connectivity between the coral ecosystems plays a critical role in the resilience of degraded reef ecosystems by means of larvae and nutrients supply from one reef to the another (Mumby and Hastings 2008). Connectivity between the coral ecosystems will be affected by the reduction in the density of reef fishes. The mobile organisms like fishes play an important role in connecting the ecosystems (Nystorm and Folke 2001, Lundberg and Moberg 2003) by transferring the essential and limiting nutrients and minerals from the adjacent ecosystems to the other coral ecosystems under stress (Geesey et al. 1984, Meyer and Schultz 1985) thereby enhancing the resilience potential of the reef. In addition, they also prevent the phase shifts in the disturbed coral ecosystems through grazing (Hughes 1994). Apart from the neighbouring coral ecosystems, the mangroves and sea grass also plays a vital role in maintaining the reef resilience as these ecosystems were used as nursery habitats by the herbivory fishes. However these ecosystems are also threatened to a greater extent due to reef fish exploitation (Waycott et al. 2009, Alongi 2008).

Palk Bay, being an area of biological significance and species richness was less conserved compared to the adjacent Gulf of Mannar Marine National Park (GOMNP). Establishment of a Marine Protected Area (MPAs) similar to GOMNP ensures the conservation of Palk Bay. However, the profound impacts of human activities inside an ecosystem have diluted the conservation efforts of the MPAs. Fishing activities inside a protected area is regulated by imposing strict fish catch regulations and encouraging the use of traditional fishing gears. However, there are no standards describing the threshold limit of fishing intensity that may disrupt the reef resilience (Mumby et al. 2007). Knowledge on the abundance of herbivory fish populations in an ecosystem of concern and a long term data on the amount of reef fish being exploited is important, as it can help the managers to avoid ecosystem catastrophes (Lokrantz et al. 2009, Nystrom et al. 2008) by devising a resilience based management strategy (Graham et al. 2011) . At present there is no resilience based management system limiting the exploitation of reef fish in Palk Bay. It is important to devise a local management strategy that focuses on the fisheries management, limitations of terrestrial input and offering protection to the core and adjacent ecosystems (Adam et al. 2011) in order to maintain their connectivity and achieve the coral reef resilience in the face of global climate change.

In conclusion, continuous observations on the reef fish density, diversity and exploitation in Palk Bay does not reveal statistically significant differences during the study period. However comparison of the above parameters with GoM revealed very high variations in reef fish density and diversity proving the potential of conservation status. The coral status and their community structure showed marked differences along the reef fishing intensity gradients. Sustainability in the rate of exploitation of reef fishes in Palk Bay despite the low standing stock of reef fishes demands an explanation. The rate of production of reef fishes in Palk Bay is not known. It is hypothesized that the required number of fishes for performing the ecosystem functions was not available in Palk Bay as both the processes of reef fish production and exploitation compensate for each other and keeps the standing stock of reef fishes consistently low in the ecosystem.

Removal of the herbivore reef fish exert severe impact over reef building corals leading to their mortality mainly due to lack of control over macroalgal and turf algal propagation over live corals. Moreover, continuous exploitation of reef fish in the adjacent reefs also rules out the replenishment of the reef fish stock in the study area. Reef fish being a connector between communities makes their absence, a delink of trophic dynamics in the reef environment and makes the communities especially the corals vulnerable for various stressors. Since the resilience potential of an affected reef largely depends on the supply of new recruits of the depleted communities from the neighboring reefs, it becomes important to maintain a no fishing zones of reef fish in the neighborhood of reef fishing hotspots. In addition, long term data on diversity, quantity, age, size structure and sex of the reef fishes exploited and the associated changes with the coral community is essential to develop standards that aids in evolving an effective management practice. In order to minimize the damages caused by current fishing practices, refined methods involving fish luring devices (FLDs) or fish aggregating devices (FADs) has to be used. In a long term, as the demand for reef fish increases, the exploitation also will increase. So, it is essential to promote alternative livelihood for the fishermen in Palk Bay in the cultivation of seaweeds of nutraceutical and pharmaceutical interests. This not only conserves the natural resources but also minimizes or prevents the damages to the reef.

Chapter 6

Final Summary & Conclusions

6.1. Current scenario of Palk Bay reef

The ecological footprint of both climatic and anthropogenic activities was evident in the Palk Bay reef through this study. The climatic factors included bleaching, monsoon triggered sedimentation, seasonal bloom of macroalgae and the anthropogenic activities such as reef fishing activities and exploitation of herbivore fishes in large quantity influenced the corals of Palk Bay. Through this study, it is inferred that the seasonal bloom of macroalgae and reef fishing activities are the two major disturbances to the corals in the Palk Bay reef. Scientific literature on the coral reef ecosystem of Palk Bay is limited to diversity and the status of corals and its associated flora and fauna. There are no comprehensive reports on the reef processes and its functions in Palk Bay except for that of bleaching and sedimentation (Ravindran et al. 2012; Wilson et al. 2005). The live coral cover in Palk Bay reef was reduced to a larger extent post the 1998 and 2002 bleaching event (Kumaraguru et al. 2003). Recovery of corals post 1998 bleaching event was also slow and hindered by the bleaching events that occurred in 2002 and 2010. All these events collectively decreased the live coral cover and their diversity in Palk Bay reef. In total, 34 species of Scleractinian corals was recorded recently in Palk Bay reef (Venkatraman and Rajkumar 2013) comparatively lower than the earlier report of 63 species (Pillai 1969). Diversity and density of the corals also varied spatially across the Palk Bay reef.

Though the Palk Bay reef forms a part of Gulf of Mannar Marine Biosphere reserve (GoMBR), it is less protected compared to the Gulf of Mannar (GoM). The reef in GoM is separated from the Palk Bay reef by the Mandapam peninsula and Rameshwaram Island. Moreover, GoM comprises Islands fringed by reefs up to a depth of about 12 m that serve as a suitable habitat for the corals to settle and grow whereas, Palk Bay lacks such a vast substratum and comprise a narrow discontinuous fringing shallow reef of not more than 200 m wide that runs parallel to the shore. The reef ecosystem of Palk Bay serves as a potential fishing ground for small scale fishermen. The reef fishing activities were highly active between January to September in a year though the fishing effort varied between the different time period. The average annual production of fishes in Palk Bay accounts for 85000 tonnes (Kumaraguru et al. 2008). However, there are no reports on the contribution of reef fishes to the total production of fishes in Palk Bay.

6.2.What factors drive the degradation of corals in Palk Bay?

Results of this study showed that the seasonal bloom of macroalgae that occurred during the summer months at the study sites of Palk Bay reef significantly reduced the healthy live coral cover during the study period of two years. The annual rate of loss of healthy live corals accounts for 4% yr^{-1}. The macroalgae, upon interaction with healthy live corals had resulted in partial mortality among them and lead to subsequent turf algal colonization. The macroalgae kills the coral tissues through various mechanisms such as smothering, secretion of toxins and allelopathic chemicals (Rasher et al. 2011) and mediation of pathogens (Smith et al. 2006). Corals also possess resistance mechanism against algal colonization through variety of mechanisms including shading, stinging, secretion of allelopathic chemicals and mucus secretion (McCook et al. 2001). However, their resistance mechanism was compromised under variable environmental conditions especially during an increase in seawater temperature (Ward et al. 2007). In this study, the macro algal bloom was reported to occur during summer months in which the Sea Surface Temperature rose above 30 °C. This could probably surpassed the resistance potential of corals against macroalgae.

The macroalgae bloom concomitantly increased the percent cover of live corals colonized by turf algae and macroalgae during the study period. The rapid growth rate of turf algae often contributed to their success over the corals under enriched nutrient conditions (Vermeij et al. 2011). The role of nutrients in enhancing the growth of turf algae over corals in Palk Bay reef has not been addressed in this study. However, higher concentration of Phosphate and Nitrate was reported in the Palk Bay reef especially during the northeast and southwest monsoon period (Sridhar et al. 2008). Turf algae affected the corals by trapping more sediments from the water column which in turn will smothers the corals and cause tissue mortality (Nugues and Roberts 2003). The Palk Bay reef environment is characterized by high level of suspended sediments during NE monsoon and generally the rate of sedimentation over corals was also high (Wilson et al. 2005). Abundant presence of reef fishes especially that of grazers and scrapers can control the turf algae by scraping the coral substrates with turf algae and by taking non-excavating bites of the coral skeletons (Bellwood and Choat 1990). This in turn will create a bare substrate facilitating the settlement of new coral recruits. However the reef fish population in Palk Bay was consistently low and the available fishes of scraper (*Scarus* sp) and grazer (*Siganus* sp) functional groups are exploited in larger quantity. Increased exploitation kept the standing stock of reef fishes consistently low and the quantity of fishes that are required for performing the normal reef functions are not available in Palk Bay. This further promoted the colonization of turf algae over corals in Palk Bay leading to their degradation.

Reef fishing in Palk Bay was based on artisanal fishing gears like hooks and cages. In addition, some destructive fishing methods were practiced including suspended trap net method. In this method, the net was deployed enclosing a particular patch of corals and the corals were disturbed by banging them using a large wooden pestle to bring out the fishes from their shelters that lead to the destruction of corals. A healthy coral colony was mechanically damaged due to drifting of the boat by the fishermen over the corals to locate the fish cages deployed under water. This in turn creates a dead patch over the healthy corals which facilitate the colonization of turf algae and its subsequent colonization of the entire colony.

The macroalgae and calcareous algae continuously increased in their cover and colonized the hard substrates such as dead coral skeleton and crustose coralline algae at the study sites of Palk Bay. This lead to the reduced diversity and density of the juvenile corals at the study sites of Vedhalai and Mandapam. Low stock of reef herbivore fishes aided the proliferation of the macroalgae over the available hard substrates without being grazed upon. The Seasonal bloom of Macroalgae, persistence of macroalgae in the system, Reef fish exploitation and the destructive reef fishing methods collectively contributed to the degradation of corals in Palk Bay reef.

6.3. Promising factors of Resilience in Palk Bay reef

The evidence of connectivity, survivability of juvenile corals in response to the prevailing stress conditions and the ability of corals to recover from bleaching despite an increase in the bleaching thresholds without mortality will contribute to the resilience potential of Palk Bay reef. Presence of the juvenile corals of *Acropora, Goniastrea*, *Galaxea* and *Hydnophora* and the absence of adult coral colonies of the same species suggested that the larvae of these particular species of corals might be transported from other reef and settled in Palk Bay reef. This phenomenon of larval transport from a parent reef and its subsequent settlement in a distant reef is termed as connectivity (Chia et al. 1984) and it is largely influenced by the local and regional hydrodynamics. The phenomenon of sea water exchange between Gulf of Mannar and Palk Bay (Shankar et al. 2002, NIO 2012) and rich diversity of corals around the Gulf of Mannar Islands might be a possible source of coral larvae to the Palk Bay reef. The species diversity of corals was largely reduced in Palk Bay post the bleaching events in 1998 and 2002. Only, 34 species of 15 genera exist in Palk Bay at present (Venkataraman and Rajkumar 2013) compared to their earlier records of 63 species of 23 genera (Pillai 1969). The current recruitment pattern of corals will help in restoring the lost species diversity of corals in Palk Bay to some extent.

Though the recruitment pattern varied spatially across the Palk Bay reef, the increased survival rate of the juvenile corals will aid in the restoration of lost live coral cover in Palk Bay. The successful settlement of the new coral larvae and the survival of juvenile corals up to their reproductive age withstanding the stress conditions were yet other critical factors determining the resilience potential of the reef. In Palk Bay, >90% of the juvenile corals were able to survive the stress associated with high level of sedimentation during NE monsoon and bleaching during the summer. The increased survival rate of juvenile corals will enable themselves to be the source of larvae in another few years and subsequently lead to the establishment of coral population and its dominance in the reef ecosystems of Palk Bay.

The bleaching and recovery patterns of corals in Palk Bay showed that the corals were able to recover to their normal state post bleaching without mortality.

Comparison of the environmental conditions during bleaching showed an increase in the level of bleaching thresholds among the corals in Palk Bay. The success of corals over bleaching related stress can be attributed to the absence of secondary stressors post bleaching which are the main reason for the beaching related mortality in Palk bay (Ravindran et al. 2012) and natural selection of the species in Palk Bay which are more thermal tolerant. Five genera of corals belonging to *Porites, Favia, Favites, Leptastrea* and *Cyphastrea* were predominantly present along the Palk Bay reef all of which were reported to be thermo tolerant (Baker et al. 2008). *Cyphastrea* sp was unresponsive to bleaching and other genera of corals exhibited a differential bleaching response. The differential response among corals of different genera might be due to their different thermal tolerant limits which is determined by the type of zooxanthellae clades associated with the corals (Sampayo et al. 2008), regulating their genes and expression of heat shock proteins (Palaumbi et al. 2014) and their frequent exposure to bleaching stress conditions (Brown et al. 2002). The wide spread prevalence of stress tolerant juveniles and adult coral colonies and their ability to withstand the stress is a positive sign of resilience which will contribute to the coral dominance in the Palk Bay reef despite the prevailing disturbances.

6.4. Future Research focus

The coral recruitment pattern in Palk Bay suggested the presence of connectivity in the eastern part and its absence in the western part of the reef. The exact time of coral spawning, the success rate of the coral larvae and the water current conditions that influence the transport of larvae is not known. Further research addressing these parameters will help in identifying the source of coral larvae to Palk Bay reef and pave way for its effective conservation. Though the new coral recruits in Palk Bay were able to survive the stress conditions associated with bleaching and sedimentation, their impact on the reproductive potential and the physiological processes of coral recruits needs further investigation. Seasonal bloom of macroalgae is identified as one of the potential threat to the corals in Palk Bay. However, the causative factor for the seasonal bloom of macroalgae was not identified. Though the literature supports the enrichment of nutrients as a main reason behind macroalgal blooms, it is essential to focus on the other parameters such as light and temperature which is suspected to play a critical role in triggering macroalgal blooms. The exploitation rate of reef fishes was increasing between years though the standing stock of reef fishes was consistently low. The average annual production of reef fishes in Palk Bay is not known. From this study, it is hypothesized that the average production of reef fishes was high enough to compensate for its exploitation so as to maintain the stable low standing stock by which the reef functions could not be performed normally. Though the bleaching process did not affect the survivability of the corals, its impacts on the physiology and reproductive potential of the coral needs further investigation.

6.5. Strategy for enhancing the resilience of Palk Bay reef

An effective management strategy and tools are essential to combat the decline of coral population and to enhance the resilience potential of the Palk Bay reef.

6.5.1. Monitoring

Long term monitoring of the biophysical status and environmental parameters was essential to assess the condition of the Palk Bay reef periodically and to check the efficiency of the conservation measures introduced to conserve the reef. Long term monitoring will give early signals regarding disease outbreaks, bleaching and other stress events which in turn help to mitigate them effectively. Continuous monitoring will also help in assessing the adaptive potential of the corals to the stress events like bleaching and sedimentation. In addition, effective monitoring will help in identifying the potential source of coral larvae, its conservation and connectivity patterns among corals.

6.5.2. Reef management

The Palk bay reef can be managed for resilience by the following ways.

- Training the local communities and involving them in monitoring the reef health.
- Promoting research activities focusing on reef processes, functions and reef response to the changing climate and local stressors
- Regulating the human activities by strengthening and effective enforcement of the laws
- Creating no fishing zones and promoting alternate livelihood for fishermen thereby to reduce the fishing pressure and ensure the availability of healthy stock of reef fishes
- Minimizing the land based activities which will reduce the sediment and nutrient input in to the reef ecosystem.
- Through ecological restoration whenever the natural recovery process is slow and impeded.

LITERATURE CITED

- Adam TC, Schmitt RJ, Holbrook SJ, Brooks AJ, Edmunds PJ, Carpenter RC, Bernardi G (2011) Herbivory, connectivity, and ecosystem resilience: response of a coral reef to a large-scale perturbation. PloS one 6(8): e23717.
- Adjeroud M, Michonneau F, Edmunds PJ, Chancerelle Y, De Loma TL, Penin L, ... Galzin R (2009) Recurrent disturbances, recovery trajectories, and resilience of coral assemblages on a South Central Pacific reef. Coral Reefs 28(3): 775-780.
- Adjeroud M, Penin L, Carroll A (2007) Spatio-temporal heterogeneity in coral recruitment around Moorea, French Polynesia: Implications for population maintenance. Journal of Experimental Marine Biology and Ecology 341(2): 204-218.
- Ainsworth TD, Thurber RV, Gates RD (2010) The future of coral reefs: a microbial perspective. Trends in Ecology and Evolution 25(4): 233-240.
- Albright R, Mason B, Miller M, Langdon C (2010) Ocean acidification compromises recruitment success of the threatened Caribbean coral *Acropora palmata*. Proceedings of the National Academy of Sciences 107(47): 20400-20404.
- Allen G, Steene R, Humann P, Deloach N (2003) Reef fish identification. California: Tropical pacific, New world publications, Jacksonville, Florida and Odyssey publications, El cajon.
- Alongi DM (2008) Mangrove forests: Resilience, protection from tsunamis and responses to global climate change. Estuarine Coastal Shelf Science 76 (1): 1-13.
- Alvarado JJ, Cortes JO, Salas E (2004) Population densities of *Diadema antillarum* Philippi at Cahuita National Park (1997-2003), Coasta Rica. Carribbean Journal of Sciences 40: 257-259.
- Anderson S, Zepp R, Machula J, Santavy D, Hansen L, Mueller E (2001) Indicators of UV exposure in corals and their relevance to global climate change and coral bleaching. Human and Ecological Risk Assessment: An International Journal7(5): 1271-1282.
- Anthony KR, Kline DI, Diaz-Pulido G, Dove S, Hoegh-Guldberg O (2008) Ocean acidification causes bleaching and productivity loss in coral reef builders. Proceedings of the National Academy of Sciences105(45): 17442-17446.
- Appukuttan KK (1972) Coral-boring bivalves of Gulf of Mannar and Palk Bay. In: C Mukundam. CS Gopinatha Pillai (Eds). Proceedings of the symposium of corals and Coral reefs. Marine Biological Association of India, pp-379-398.
- Arnold SN, Steneck R, Mumby PJ (2010) Running the gauntlet: inhibitory effects of algal turfs on the processes of coral recruitment. Marine Ecology Progress Series 414: 91-105.

- Arthur R (2000) Coral bleaching and mortality in three Indian reef regions during an El Niño southern oscillation event. Current Science 79(12): 1723-1729.
- Arthur R, Done TJ, Marsh H, Harriot V (2006) Local processes strongly influence post-bleaching benthic recovery in the Lakshadweep Islands. Coral Reefs25(3): 427-440.
- Baird AH, Marshall PA (2002) Mortality, growth and reproduction in scleractinian corals following bleaching on the Great Barrier Reef. Marine Ecology Progress Series237: 133-141.
- Bak RPM, Carpay MJE, De Ruyter, Van Steveninck ED (1984) Densities of the sea urchin Diadema antillarum before and after mass mortalities on the coral reefs on Curacao. Marine Ecology Progress Series 17(1): 105-108.
- Bak RPM, Engel MS (1979) Distribution, abundance and survival of juvenile hermatypic corals (Scleractinia) and the importance of life history strategies in the parent coral community. Marine Biology 54(4): 341-352.
- Baker AC, Glynn PW, Riegl B (2008) Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. Estuarine, Coastal and Shelf Science 80(4): 435-471.
- Baker AC, Starger CJ, McClanahan TR, Glynn PW (2004) Coral reefs: corals adaptive response to climate change. Nature430(7001): 741-741.
- Baker CA, Glynn PW, Riegl B (2008) Climate change and coral reef bleaching: An ecological assessment of long term impacts, recovery trends and future outlook. Estuarine, Coastal and Shelf Science80(4): 435-471.
- Bellwood DR (1994) A phylogenetic study of the parrotfishes family Scaridae (Pisces: Labroidei), with a revision of genera. Records of the Australian Museum, Supplement 20: 1–86.
- Bellwood DR, Choat JH (1990) A functional analysis of grazing in parrot fishes (family Scaridae): the ecological implications. Environmental Biology of Fishes 28(1–4): 189–214.
- Bellwood DR, Hoey AS, Ackerman JL, Depczynski M (2006a) Coral bleaching, reef fish community phase shifts and the resilience of coral reefs. Global Change Biology 12(9): 1587-1594.
- Bellwood DR, Hughes TP, Hoey AS (2006b) Sleeping functional group drives coral-reef recovery. Current Biology 16(24): 2434-2439.
- Bender D, Diaz-Pulido G, Dove S (2012) Effects of macroalgae on corals recovering from disturbance. Journal of Experimental Marine Biology and Ecology 429: 15-19.
- Berkelmans R (2002) Time-integrated thermal bleaching thresholds of reefs and their variation on the Great Barrier Reef. Marine Ecology Progress Series229: 73-82.

- Berkelmans R, Van Oppen MJ (2006) The role of zooxanthellae in the thermal tolerance of corals: a 'nugget of hope' for coral reefs in an era of climate change. Proceedings of the Royal Society B: Biological Sciences 273(1599): 2305-2312.
- Birkeland C (1985) Ecological interactions between mangroves, seagrass beds, and coral reefs. In: Birkeland C, Grosenbaugh D (Eds). Ecological Interactions between Tropical Coastal Ecosystems. UNEP Regional Seas Reports and Studies No.73, pp 1–26.
- Birrell CL, McCook LJ, Willis BL (2005) Effects of algal turfs and sediment on coral settlement. Marine Pollution Bulletin 51(1): 408-414.
- Bonaldo RM, Hay ME (2014) Seaweed-coral interactions: variance in seaweed allelopathy, coral susceptibility, and potential effects on coral resilience. PLoS One 9(1): e85786.
- Booth DJ, Beretta GA (2002) Changes in a fish assemblage after a coral bleaching event. Marine Ecology Progress Series 245: 205-212.
- Bourne DG, Garren M, Work TM, Rosenberg E, Smith GW, Harvell, CD (2009) Microbial disease and the coral holobiont. Trends in Microbiology 17(12): 554-562.
- Brown B, Dunne R, Goodson M, Douglas A (2002) Experience shapes the susceptibility of a reef coral to bleaching. Coral Reefs21(2): 119-126.
- Brown BE (1997) Coral bleaching: causes and consequences. Coral reefs 16(1): S129-S138.
- Bruno JF, Sweatman H, Precht WF, Selig ER, Schutte VG (2009) Assessing evidence of phase shifts from coral to macroalgal dominance on coral reefs. Ecology 90(6): 1478-1484.
- Bryant D, Burke L, McManus J, Spalding M (1998). Reefs at risk: a map-based indicator of the threats to the worlds coral reefs. World Resources Institute, International Center for Living Aquatic Resources Management, World Conservation Monitoring Centre, and United Nations Environment Programme, Washington DC.
- Buddemeier RW, Baker AC, Fautin DG, Jacobs JR (2004) The adaptive hypothesis of bleaching. In: Rosenberg E, Loya Y (Eds). Coral health and disease, Springer, Berlin, Heidelberg, p 427-444.
- Burke L, Selig E, Spalding M (2006) Reefs at risk in Southeast Asia. World resources Institute, Washington DC.
- Burkepile DE, Hay ME (2008) Herbivore species Richness and feeding complementarity affect community structure and function on a coral reef. Proceedings of National Academy of Sciences 105(42): 16201-16206.

- Byler KA, Carmi-Veal M, Fine M, Goulet TL (2013) Multiple symbiont acquisition strategies as an adaptive mechanism in the coral *Stylophora pistillata*. PloS one8(3): e59596.
- Carilli JE, Norris RD, Black BA, Walsh SM, McField M (2009) Local stressors reduce coral resilience to bleaching. PLoS One4(7): e6324.
- Carpenter KE, Abrar M, Aeby G, Aronson RB, Banks S, Bruckner A ...Wood E (2008) One-third of reef-building corals face elevated extinction risk from climate change and local impacts. Science 321(5888): 560-563.
- Carpenter RC, Edmunds PJ (2006) Local and regional scale recovery of *Diadema* promotes recruitment of scleractinian corals. Ecology letters 9(3): 271-280.
- Castro P, Huber ME (2003) Coral Reefs. In: Castro P, Huber ME (Ed). Marine Biology, 4th edn, pp 297-320.
- Cesar H, Burke L, Pet-Soede L (2003) The economics of worldwide coral reef degradation. Cesar Environmental Economics Consulting, the Netherlands.
- Cetz-Navarro NP, Espinoza-Avalos J, Hernández-Arana HA, Carricart-Ganivet JP (2013) Biological Responses of the Coral *Montastraea annularis* to the Removal of Filamentous Turf Algae. PloS one8(1): e54810.
- Chelliah A, Amar HB, Hyde J, Yewdall K, Steinberg PD, Guest JR (2014) First record of multi-species synchronous coral spawning from Malaysia. Peer J 3: e777.
- Chia FS, Buckland-Nicks J, Young CM (1984) Locomotion of marine invertebrate larvae- A review. Canadian Journal of Zoology 62(7): 1205-1222.
- Chiappone M, Swanson D, Miller SL (2002) Density, spatial distribution and size structure of sea urchins in Florida Keys coral reef and hard bottom habitats. Marine Ecology Progress Series 235: 117-126.
- Chou LM (2000) Southeast Asian Reefs-Status update: Cambodia, Indonesia, Malaysia, Philippines, Singapore, Thailand and Viet Nam. Status of coral reefs of the world, 117-129.
- Clarke KR (1993) Non-parametric multivariate analyses of changes in community structure. Australian Journal of Ecology 18: 117-117.
- Coffroth MA, Poland DM, Petrou EL, Brazeau DA, Holmberg JC (2010) Environmental symbiont acquisition may not be the solution to warming seas for reef-building corals. PLoS One5: e13258.
- Coles SL, Brown BE (2003) Coral bleaching- capacity for acclimatization and adaptation. Advances in Marine Biology 46: 183-223.
- Connolly SR, Lopez-Yglesias MA, Anthony KRN (2012) Food availability promotes rapid recovery from thermal stress in a scleractinian coral. Coral reefs 31(4): 951-960.

- Cowen RK, Sponaugle S (2009) Larval dispersal and marine population connectivity. Annual Review of Marine Science 1: 443-466.
- D'Elia CF (1988) The cycling of essential elements in coral reefs. In: Pomeroy LR, Alberts JJ (Eds). Concepts of ecosystem ecology. Springer New York. pp 195-230.
- Dayton PK, Thrush SF, Agardy MT, Hofman RJ (1995) Environmental effects of Marine fishing. Aquatic Conservation: Marine and Freshwater ecosystems 5(3): 205-232.
- Diaz-Pulido G, McCook L J (2008) Environmental Status: Macroalgae (Seaweeds). In: Chin A (Ed). The state of the Great barrier Reef. Online, Great Barrier Reef Marine Park Authority, Townsville, Australia.
- Diaz-Pulido G, McCook LJ (2005) Effects of nutrient enhancement on the fecundity of a coral reef macroalga. Journal of Experimental Marine Biology and Ecology 317(1): 13-24.
- Diaz-Pulido G, McCook LJ, Dove S, Berkelmans R, Roff G, Kline DI, Weeks S, Evans RD, Williamson DH, Hoegh-Guldberg O (2009) Doom and Boom on a Resilient Reef: Climate Change, Algal Overgrowth and Coral Recovery. PLOS one 4(4): e5239.
- Done TJ (1992) Phase shifts in coral reef communities and their ecological significance. In: Jaccarini V, Martens E (Eds). The Ecology of Mangrove and Related Ecosystems, Springer, Netherlands, pp 121-132.
- Donner SD, Skirving WJ, Little CM, Oppenheimer M, Hoegh-Guldberg O (2005) Global assessment of coral bleaching and required rates of adaptation under climate change. Global Change Biology11(12):2251-2265.
- Doropoulos C, Ward S, Diaz-Pulido G, Hoegh-Guldberg O, Mumby PJ (2012) Ocean acidification reduces coral recruitment by disrupting intimate larval-algal settlement interactions. Ecology Letters 15(4): 338-346.
- Dubinsky ZVY, Stambler N (1996) Marine pollution and coral reefs. Global change biology 2(6): 511-526.
- Dulvy NK, Freckleton RP, Polunin NVC (2004) Coral reef cascades and the indirect effects of predator removal by exploitation. Ecology letters 7(5): 410-416.
- Dunstan PK, Johnson CR (1998) Spatio-temporal variation in coral recruitment at different scales on Heron reef, southern Great Barrier Reef. Coral Reefs 17(1): 71-81.
- Edmunds PJ (2000) Patterns in the distribution of juvenile corals and coral reef community structure in St. John, US Virgin Islands. Marine Ecology Progress Series 202: 113-124

- Edmunds PJ, Carpenter RC (2001) Recovery of *Diadema antillarum* reduces macroalgal cover and increases abundance of juvenile corals on a Caribbean reef. Proceedings of National Academy of Sciences 98(9): 5067-5071.
- Edmunds PJ, Gray SC (2014) The effects of storms, heavy rain, and sedimentation on the shallow coral reefs of St. John, US Virgin Islands. Hydrobiologia 734(1): 143-158.
- Elmhirst T, Connolly SR, Hughes TP (2009) Connectivity, regime shifts and the resilience of coral reefs. Coral Reefs 28(4): 949-957.
- English S, Wilkinson C, Baker V (1997) Survey Manual for Tropical Marine Resources 2nd ed. Australian Institute of Marine Science, Townsville, Australia.
- Erftemeijer PL, Hagedorn M, Laterveer M, Craggs J, Guest JR (2012) Effect of suspended sediment on fertilization success in the scleractinian coral *Pectinia lactuca*. Journal of Marine Biological Association of UK 92(04): 741-745.
- Feely RA, Sabine CL, Lee K, Berelson W, Kleypas J, Fabry VJ, Millero FJ (2004) Impact of anthropogenic CO2 on the CaCO3 system in the oceans. Science 305(5682): 362-366.
- Fisk DA, Harriott VJ (1990) Spatial and temporal variation in coral recruitment on the great barrier Reef: implications for dispersal hypotheses. Marine Biology 107(3): 485-490.
- Fitt Wk, Brown BE, Warner ME, Dunne RP (2001) Coral bleaching: interpretation of thermal tolerance limits and thermal thresholds in tropical corals. Coral Reefs 20(1): 51-56.
- Fung T, Seymour RM, Johnson CR (2011) Alternative stable states and phase shifts in coral reefs under anthropogenic stress. Ecology 92(4): 967-982.
- Gardner TA, Cote IM, Gill JA, Grant A, Watkinson AR (2005) Hurricanes and Caribbean coral reefs: impacts, recovery patterns, and role in long-term decline. Ecology 86(1): 174-184.
- Gardner TA, Cote IM, Gill JA, Grant A, Watkinson, A. R. (2003). Long-term region-wide declines in Caribbean corals. Science 301(5635): 958-960.
- Gates RD, Baghdasarian G, Muscatine L (1992) Temperature stress causes host cell detachment in symbiotic cnidarians: implications for coral bleaching. Biological Bulletin 182(3): 324-332.
- Geesey GG, Alexander GV, Bray RN, Miller AC (1984) Fish fecal pellets are a source of minerals for inshore reef communities. Marine ecology progress series *Olendorf* 15(1): 19-25.
- Gilmour JP, Smith LD, Heyward AJ, Baird AH, Pratchett MS (2013) Recovery of an isolated coral reef system following severe disturbance. Science 340(6128): 69-71.

- Glassom D, Zakai D, Chadwick-Furman NE (2004) Coral recruitment: a spatio-temporal analysis along the coastline of Eilat, northern Red Sea. Marine Biology144(4): 641-651.
- Glynn PW (1984) Widespread coral mortality and the 1982-83 El Nino warming event. Environmental Conservation 11(02): 133-146.
- Glynn PW (1996) Coral reef bleaching: facts, hypotheses and implications. Global Change Biology 2(6): 495-509.
- Glynn PW (1997) Bioerosion and coral-reef growth: a dynamic balance. In: C Birkeland (Ed). Life and death of coral reefs, Chapman and Hall, New York. pp 68-95.
- Glynn PW, D'croz L (1990) Experimental evidence for high temperature stress as the cause of El Nino-coincident coral mortality. Coral reefs8(4): 181-191.
- Glynn PW, Mate JL, Baker AC, Calderon MO (2001) Coral bleaching and mortality in panama and Ecuador during the 1997/1998 El Nino Southern Oscillation Event: spatial/temporal patterns and comparisons with the 19821983 event. Bulletin of Marine Science69(1): 79-109.
- Golbuu Y, Andrew J, Mereb G, van Woesik R (2013) Recovery of Coral Populations at Helen-Reef Atoll after a Major Bleaching Event. PICRC technical report, Palau International coral reef center, Florida Institute of Technology
- Goreau T, McClanahan T, Hayes R, Strong AI (2000) Conservation of coral reefs after the 1998 Global bleaching event. Conservation Biology 14(1): 5-15.
- Graham NAJ, Nash KL, Kool JT (2011) Coral reef recovery dynamics in a changing world. Coral Reefs 30(2): 283-294.
- Graham NJ, Chabanet P, Evans RD, Jennings S, Letourneur Y, MacNeil MA, McClanahan TR, Ohman MC, Polunin NV, Wilson SK (2011) Extinction Vulnerability of coral reef fishes. Ecology Letters 14(4): 341-348.
- Gratwicke B, Speight MR (2005). The relationship between fish species richness, abundance and habitat complexity in a range of shallow tropical marine habitats. Journal of Fish Biology 66(3): 650-667.
- Green AL, Bellwood DR, Choat H (2009) Monitoring functional groups of herbivorous reef fishes as indicators of coral reef resilience. A practical guide for coral reef managers in the Asia Pacific Region. IUCN, Gland, Switzerland.
- Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, ... Watson R. (2008) A global map of human impact on marine ecosystems. Science 319(5865): 948-952.

- Harley CD, Randall Hughes A, Hultgren KM, Miner BG, Sorte CJ, Thornber CS, ... Williams SL (2006) The impacts of climate change in coastal marine systems. Ecology letters 9(2): 228-241.
- Harley CDG, Anderson K.M, Demes KW, Jorve JP, Kordas RL, Coyle TA (2012) Effects of climate change on global seaweed communities. Journal of Phycology 48(5): 1064-1078.
- Harrington L, Fabricius K, De'Ath G, Negri A (2004) Recognition and selection of settlement substrata determine post-settlement survival in corals. Ecology 85(12): 3428-3437.
- Harriott VJ (1985) Mortality rates of scleractinian corals before and during a mass bleaching event. Marine ecology progress series21: 81-88.
- Harriott VJ, Fisk DA (1998) Recruitment patterns of scleractinian corals: a study of Three Reefs. Australian Journal of Marine and Freshwater Research 39(4): 409-416.
- Heyward AJ, Negri AP (1999) Natural inducers for coral larval metamorphosis. Coral Reefs 18(3): 273-279.
- Hixon M A (1997) Effects of reef fishes on Corals and Algae. In: Birkeland C (Ed). Life and Death of Coral Reefs, Chapman and Hall Publishing, pp 230-248.
- Hodgson G (1999) A global assessment of human effects on coral reefs. Marine Pollution Bulletin 38(5): 345-355.
- Hoegh-Guldberg O (1999) Climate change, coral bleaching and the future of the world's coral reefs. Marine and freshwater research 50(8): 839-866.
- Hoey AS, Pratchett MS, Cvitanovic C (2011) High macroalgal cover and low coral recruitment undermines the potential resilience of the world's southernmost coral reef assemblages. Plos One 6(10): e25824.
- Hughes T, Szmant AM, Steneck R, Carpenter R, Miller S (1999). Algal blooms on coral reefs: what are the causes?. Limnology and Oceanography 44(6): 1583-1586.
- Hughes TP (1994) Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. Science-AAAS-Weekly Paper Edition 265(5178): 1547-1551.
- Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, ... Roughgarden J (2003) Climate change, human impacts, and the resilience of coral reefs. Science 301(5635): 929-933.
- Hughes TP, Bellwood DR, Folke CS, McCook LJ, Pandolfi JM (2007a) No-take areas, herbivory and coral reef resilience. Trends in ecology & evolution 22(1): 1-3.
- Hughes TP, Graham NA, Jackson JB, Mumby PJ, Steneck RS (2010) Rising to the challenge of sustaining coral reef resilience. Trends in Ecology and Evolution 25(11): 633-642.

- Hughes TP, Rodrigues MJ, Bellwood DR, Ceccarelli D, Hoegh-Guldberg O, McCook L, Moltschaniwskyj N, Pratchett MS, Steneck RS, Willis B (2007b) Phase shifts, Herbivory, and the Resilience of Coral Reefs to Climate Change. Current Biology 17(4): 360-365.
- Hughes TP, Tanner JE (2000) Recruitment failure, life histories, and long-term decline of Caribbean corals. Ecology 81(8): 2250-2263.
- Hunter CL, Evans CW (1994) Reefs in Kaneohe Bay, Hawaii: two centuries of western influence and two decades of data. In: Ginzburg RM (Ed). Proceedings of the Colloquium on Global Aspects of Coral Reefs: Health, Hazards and History, University of Miami, Florida, pp 339–345.
- Idjadi JA, Lee SC, Bruno JF, Precht WF, Allen-Requa L, Edmunds P J (2006) Rapid phase-shift reversal on a Jamaican coral reef. Coral reefs 25(2): 209-211.
- IPCC 2001: Climate Change 2001: Synthesis report. Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom, New York, USA, Cambridge University Press.
- Jasmine S (2013) Mass spawning of Scleractinian corals in the Lakshadweep Archipelago. http://eprints.cmfri.org.in/9365/1/147.pdf (accessed 30 May 2015).
- Jennings S, Kaiser MJ (1998) The effects of fishing on marine ecosystems. Advances in Marine biology 34: 201-352.
- Jennings S, Polunin NV (1996) Impacts of fishing on tropical reef ecosystems. Ambio 25(1): 44-49.
- Jennings S, Wilson RW (2009) Fishing impacts on the marine inorganic carbon cycle. Journal of Applied Ecology 46(5): 976-982.
- Johnson CR, Mann KH (1986) The crustose coralline alga, Phymatolithon Foslie, inhibits the overgrowth of seaweeds without relying on herbivores. Journal of Experimental Marine Biology and Ecology 96(2): 127-146.
- Jokiel PL, Coles SL (1990) Response of Hawaiian and other Indo-Pacific reef corals to elevated temperature. Coral reefs8(4)**:** 155-162.
- Jompa J, McCook LJ (2002) Effects of competition and herbivory on interactions between a hard coral and a brown alga. Journal of Experimental Marine Biology and Ecology 271(1): 25-39.
- Jompa J, McCook LJ (2003) Coral-algal competition: macroalgae with different properties have different effects on corals. Marine Ecology Progress Series 258: 87-95.
- Jones AM, Berkelmans R, van Oppen MJ, Mieog JC, Sinclair W (2008) A community change in the algal endosymbionts of a scleractinian coral following a

natural bleaching event: field evidence of acclimatization. Proceedings of the Royal Society B: Biological Sciences275(1641): 1359-1365.

- Jones RJ, Hoegh-Guldberg O, Larkum AWD, Schreiber U (1998) Temperature-induced bleaching of corals begins with impairment of the CO2 fixation mechanism in zooxanthellae. Plant, Cell & Environment21(12): 1219-1230.
- Jones RJ, Ward S, Amri AY, Hoegh-Guldberg O (2000) Changes in quantum efficiency of Photosystem II of symbiotic dinoflagellates of corals after heat stress, and of bleached corals sampled after the 1998 Great Barrier Reef mass bleaching event. Marine and Freshwater Research51(1): 63-71.
- Jost L (2007) Partitioning diversity into independent alpha and beta components. Ecology88(10): 2427-2439.
- Kinzie RA, Takayama M, Santos SR, Coffroth MA (2001) The adaptive bleaching hypothesis: experimental tests of critical assumptions. The Biological Bulletin 200(1): 51-58.
- Knowlton N (2001) The future of coral reefs. Proceedings of the National Academy of Sciences 98(10): 5419-5425.
- Komyakova V, Munday PL, Jones GP (2013) Relative importance of coral cover, habitat complexity and diversity in determining the structure of reef fish communities. PLoS One 8: e83178.
- Koop K., Booth D, Broadbent A, Brodie J, Bucher D, Capone D, ... Yellowlees D (2001) ENCORE: the effect of nutrient enrichment on coral reefs. Synthesis of results and conclusions. Marine pollution bulletin 42(2): 91-120.
- Krishnan P, Dam Roy S, George G, Srivastava RC, Anand A, Murugesan S, ... Soundararajan R (2011) Elevated sea surface temperature during May 2010 induces mass bleaching of corals in the Andaman. Current Science100(1): 111-117.
- Kuffner IB, Walters LJ, Becerro MA, Paul VJ, Ritson Williams R, Beach KS (2006) Inhibition of coral recruitment by macroalgae and cyanobacteria. Marine Ecology Progress Series 323: 107-117.
- Kumaraguru AK, Edwin Joseph V, Rajee M, Balasubramanian T (2008) Palk Bay – Information and Bibliography, CAS in Marine Biology, Annamalai University, Parangipettai and Center for marine and coastal studies, Madurai kamraj University, Madurai, 227 pp.
- Kumaraguru AK, Jayakumar K, Ramakritinan CM (2003) Coral bleaching 2002 in the Palk Bay, southeast coast of India. Current Science85(12): 1787-1792.
- Kumaraguru AK, Jayakumar K, Wilson JJ, Ramakritinan CM (2005). Impact of the tsunami of 26 December 2004 on the coral reef environment of Gulf of Mannar and Palk Bay in the southeast coast of India. Current Science89(10): 1729-1741.

- Kumaraguru AK, Joseph VE, Rajee M, Balasubramanian T (2008) Palk Bay – Information and Bibliography. CAS in Marine Biology, Annamalai University and Centre for Marine and Coastal Studies, Madurai Kamaraj University, 227 pp.
- Lapointe BE (1999) Simultaneous top-down and bottom-up forces control macroalgal blooms on coral reefs. Limnology and Oceanography 44(6): 1586-1592.
- Ledlie MH, Graham NAJ, Bythell JC, Wilson SK, Jennings S, Polunin NVC, Hardcastle J (2007) Phase shifts and the role of herbivory in the resilience of coral reefs. Coral Reefs 26(3): 641-653.
- Lee TN, Rooth C, Williams E, McGowan M, Szmant AF, Clarke ME (1992) Influence of Florida Current, gyres and wind-driven circulation on transport of larvae and recruitment in the Florida Keys coral reefs. Continental Shelf Research 12(7): 971-1002.
- Lesser MP (1997) Oxidative stress causes coral bleaching during exposure to elevated temperatures. Coral reefs16(3): 187-192.
- Lesser MP (2011) Coral bleaching: causes and mechanisms. In: Dubinsky Z, Stambler N (Eds). Coral reefs: an ecosystem in transition. Springer, Netherlands: 405-419.
- Logan CA, Dunne JP, Eakin CM, Donner SD (2014) Incorporating adaptive responses into future projections of coral bleaching. Global change biology20(1): 125-139.
- Lokrantz J, Nystrom M, Norstrom AV, Folke C, Cinner JE (2009) Impacts of artisanal fishing on key functional groups and the potential vulnerability of coral reefs. Environmental conservation 36(4): 327-337.
- Lough JM (2008) 10th anniversary review: a changing climate for coral reefs. Journal of Environmental Monitoring 10(1): 21-29.
- Loya Y, Sakai K., Yamazato K., Nakano Y, Sambali H, Van Woesik R (2001) Coral bleaching: the winners and the losers. Ecology Letters4(2): 122-131.
- Lundberg J, Moberg F (2003) Mobile link organisms and Ecosystem functioning: Implications for ecosystem resilience and Management. Ecosystems 6(1): 87-98.
- Mahadevan S, Nayar KN (1972) Distribution of coral reefs in the Gulf of Mannar and Palk Bay and their exploitation and utilization. Proceedings of the 1st international coral reef symposium, Mandapam, India, pp 181-190.
- Manikandan B, Ravindran J, Shrinivaasu S, Marimuthu N, Paramasivam K (2014) Community structure and coral status across reef fishing intensity gradients in Palkbay, Southeast coast of India. Environmental Monitoring and Assessment 186(10): 5989-6002.

- Maragos JE, Crosby MP, McManus JW (1996) Coral reefs and biodiversity: a critical and threatened relationship. Oceanography 9: 83-99.
- Marshall AT (1996) Calcification in hermatypic and ahermatypic corals. SCIENCE-NEW YORK THEN WASHINGTON 271(5249): 637-639.
- Marshall PA, Baird AH (2000) Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. Coral reefs 19(2): 155-163.
- Martin-Smith KM (1993) The phenology of four species of *Sargassum* at magnetic Island, Australia. Botanica Marina 36(4): 327-334.
- McAllister DE, Schueler FW, Roberts CM, Hawkins JP (1994). Mapping and GIS analysis of the global distribution of coral reef fishes on an equal-area grid. In: Miller RI (Ed). Mapping the diversity of nature, Springer, Netherlands. pp. 155-175.
- McClanahan TR (1995) A coral reef ecosystem-fisheries model: impacts of fishing intensity and catch selection on reef structure and processes. Ecological Modelling 80(1): 1-19.
- McClanahan TR, Ateweberhan M, Graham NAJ, Wilson SK, Sebastian C, Guillaume MM, Bruggemann, JH (2007a) Western Indian Ocean coral communities: bleaching responses and susceptibility to extinction.
- McClanahan TR, Ateweberhan M, Muhando CA, Maina J, Mohammed MS (2007) Effects of climate and seawater temperature variation on coral bleaching and mortality. Ecological monographs77(4): 503-525.
- McClanahan TR, Cinner JE (2008) A framework for adaptive gear and ecosystem-based management in artisanal coral reef fishery of Papua New Guinea. Aquatic conservation: Marine and Freshwater Ecosystems 18(5): 493-507.
- McClanahan TR, Donner SD, Maynard JA, MacNeil MA, Graham NA, Maina J, ... van Woesik R (2012) Prioritizing key resilience indicators to support coral reef management in a changing climate. PloS one 7(8): e42884.
- McClanahan TR, Shafir SH (1990) Causes and consequences of sea urchin abundance and diversity in Kenyan coral reef lagoons. Oceologia 83(3): 362-370.
- McCook L, Jompa J, Diaz-Pulido G (2001) Competition between corals and algae on coral reefs: a review of evidence and mechanisms. Coral Reefs 19(4): 400-417.
- McCook LJ (1999) Macroalgae, nutrients and phase shifts on coral reefs: scientific issues and management consequences for the Great Barrier Reef. Coral reefs18(4): 357-367.
- McCook LJ, Jompa J, Diaz-Pulido G (2001) Competition between corals and algae on coral reefs: a review of evidence and mechanisms. Coral reefs 19(4): 400-417.

- McCulloch M, Falter J, Trotter J, Montagna P (2012) Coral resilience to ocean acidification and global warming through pH up-regulation. Nature Climate Change2(8): 623-627.
- McManus JW, Meñez LA, Kesner-Reyes KN, Vergara SG, Ablan MC (2000) Coral reef fishing and coral-algal phase shifts: implications for global reef status. ICES Journal of Marine Science: Journal du Conseil 57(3): 572-578.
- Meyer JL, Schultz ET (1985) Migrating haemulid fishes as a source of nutrients and organic matter on coral reefs. Limnology and Oceanography 30(1): 146-156.
- Miller J, Waara R, Muller E, Rogers C (2006) Coral bleaching and disease combine to cause extensive mortality on reefs in US Virgin Islands. Coral Reefs25(3): 418-418.
- Miller MW, Hay ME, Miller SL, Malone D, Sotka EE, Szmant AM (1999). Effects of nutrients versus herbivores on reef algae: A new method for manipulating nutrients on coral reefs. Limnology and Oceanography 44(8): 1847-1861.
- Miller MW, Weil E, Szmant AM (2000) Coral recruitment and juvenile mortality as structuring factors for the reef benthic communities in Biscayne National Park, USA. Coral Reefs 19(2): 115-123.
- Moberg F, Folke C (1999) Ecological goods and services of coral reef ecosystems. Ecological economics29(2): 215-233.
- Morse AN, Iwao K, Baba M, Shimoike K, Hayashibara T, Omori MAKOTO (1996) An ancient chemosensory mechanism brings new life to coral reefs. Biological Bulletin 191(12): 149-154.
- Morse DE, Hooker N, Morse AN, Jensen RA (1988) Control of larval metamorphosis and recruitment in sympatric Agariciid corals. Journal of Experimental Marine Biology Ecology 116(3): 193-217.
- Moulding AL (2005) Coral recruitment patterns in the Florida Keys. Revista de biología tropical 53: 75-82.
- Muhammad Faiz MH, Shahbudin S, Yukinori M (2015) Biannual coral spawning in Timon Island, Malaysia. http://www.academia.eddu/8781803/Biannual Coral Spawning in Timon Island Malaysia (accessed 30 May 2015).
- Mumby PJ (2006) The impact of exploiting grazers (Scaride) on the dynamics of Caribbean coral reefs. Ecological Applications 16(2): 747-769.
- Mumby PJ, Harborne AR (2010) Marine reserves enhance the recovery of corals on Caribbean reefs. PLoS ONE 5(1): e8657.
- Mumby PJ, Harborne AR, Williams J, Kappel CV, Brumbaugh DR, Micheli F, ... Blackwell PG (2007) Trophic cascade facilitates coral recruitment in a marine reserve. Proceedings of the National Academy of Sciences 104(20): 8362-8367.

- Mumby PJ, Hastings A (2008) The impact of ecosystem connectivity on the coral reef resilience. Journal of Applied Ecology 45(3): 854-862.
- Mumby PJ, Hastings A, Edwards HJ (2007) Thresholds and the resilience of Caribbean coral reefs. Nature 450(7166): 98-101.
- Nakamura T, Van Woesik R (2001) Water-flow rates and passive diffusion partially explain differential survival of corals during the 1998 bleaching event. Marine Ecology Progress Series212:301-304.
- NIO (National Institute of Oceanography) (2012) Environmental Impact Assessment for alignment 4A of Sethu Samudram Channel. NIO, Donapaula, Goa.
- Norstrom AV, Lokrantz J, Nystrom M, Yap HT (2007) Influence of dead coral substrate morphology on patterns of juvenile coral distribution. Marine Biology 150(6): 1145-1152.
- Norstrom AV, Nystrom M, Lokrantz J, Folke C (2009) Alternative states on coral reef: beyond coral – macroalgal phase shifts. Marine Ecology Progress Series 376: 295-306.
- Nugues MM, Delvoye L, Bak RPM (2004) Coral defence against macroalgae: differential effects of mesenterial filaments on the green alga *Halimeda opuntia*. Marine Ecology Progress Series 278: 103-114.
- Nugues MM, Roberts CM (2003) Coral mortality and interaction with algae in relation to sedimentation. Coral reefs22(4): 507-516.
- Nystrom M, Folke C (2001) Spatial resilience of coral reefs. Ecosystems 4(5): 406-17.
- Nystrom M, Graham NAJ, Lokrantz J, Norstrom AV (2008) Capturing the cornerstones of coral reef resilience: linking theory to practice. Coral Reefs 27(4): 795-809.
- O'Leary JK, Potts D, Schoenrock KM, McClanahan TR (2013) Fish and sea urchin grazing opens settlement space equally but urchins reduce survival of coral recruits. Marine Ecology Progress Series 493: 165-177.
- O'Leary JK, Potts DC, Braga JC, McClanahan TR (2012) Indirect consequences of fishing: reduction of coralline algae suppresses juvenile coral abundance. Coral Reefs 31(2): 547-559.
- Obura DO (2005) Resilience and climate change: lessons from coral reefs and bleaching in the Western Indian Ocean. Estuarine Coastal Shelf Science 63(3): 353-372.
- Odum HT, Odum EP (1955) Trophic structure and productivity of a windward coral reef community on Eniwetok Atoll. Ecological Monographs25(3): 291-320.

- Ogden JC (1988) The influence of adjacent systems on the structure and function of coral reefs. Proceedings of the 2nd International Coral Reef Symposium 1: 123-129.
- Ogden JC, Lobel PS (1978) The role of herbivorous fishes and urchins in coral reef communities. Environmental biology of fishes 3(1): 49-63.
- Ormond RFG, Campbell AC, Head SH, Moore RJ, Rainbow PR, Saunders AP (1973) Formation and breakdown of aggregations of the crown-of-thorns starfish, Acanthaster planci (L.). in the Red Sea. Nature 246: 167-169.
- Ostrander GK, Armstrong KM, Knobbe ET, Gerace D, Scully EP (2000). Rapid transition in the structure of a coral reef community: the effects of coral bleaching and physical disturbance. Proceedings of the National Academy of Sciences 97(10): 5297-5302.
- Owen AW, Doyle P, Harper DA, Britt BB (2012) Corals and other reef-builders. Lethaia 45(1): 1-1.
- Padillo-Gamiña JL, Hédouin L, Waller RG, Smith D, Truong W, Gates RD (2014) Sedimentation and the Reproductive Biology of the Hawaiian Reef-Building Coral Montipora capitata. Biological Bulletin 226(1): 8-18.
- Paine RT (1980) Food webs: linkage, interaction strength and community infrastructure. Journal of Animal Ecology 89: 667-685.
- Palumbi SR, Barshis DJ, Traylor-Knowles N, Bay RA (2014) Mechanisms of reef coral resistance to future climate change. Science344(6186): 895-898.
- Perez K, Rodgers KS, Jokiel PL, Lager CV, Lager DJ (2014) Effects of terrigenous sediment on settlement and survival of the reef coral *Pocillopora damicornis*. Peer Journal 2: e387
- Pet-Soede LIDA, Wafar MVM, Venkaaraman K, Rajan PT, Wilhelmsson D (2000) The status of the coral reefs of India following the bleaching event of 1998. CORDIO Status Report.
- Philips NE, Shima JS, Osenberg CW (2014) Live coral cover may provide resilience to damage from the veremetid gastropod *Dendropoma maximum* by preventing larval settlement. Coral Reefs 33(4): 1137-1144.
- Pillai CG (1969) The distribution of corals on a reef at Mandapam (Palk Bay), S. India. Journal of the Marine Biological Association of India 11(1&2): 62-72.
- Pillai CG (1975) An assessment of the effects of environment and human interference on the coral reefs of Palk Bay and Gulf of Mannar along the Indian Coast. Seafood Export Journal 7(12): 9-21.
- Porter JW, Kosmynin V, Patterson KL, Porter KG, Jaap WC, Wheaton JL ... Dustan P (2002) In: Porter JW, Porter KG (Eds). Detection of coral reef change by the

Florida Keys coral reef monitoring project. The Everglades, Florida Bay, and coral reefs of the Florida Keys: An ecosystem sourcebook, CRC press, USA, p 749-769.

- Raj KD, Patterson J (2010) Observations on the reproduction of *Acropora* corals along the Tuticorin coast of the Gulf of Mannar, Southeastern India. Indian Journal of Marine Science39(2): 219-226.
- Rao DV (2004) Guide to reef fishes of Andaman and Nicobar Islands. India: Zoological survey of India.
- Rao MU (1972) Coral reef flora of the Gulf of Mannar and Palk Bay. CMFRI Report, Mandapam.
- Rao P (2002) Sediment transport and exchange around Rameswaram Island between Gulf of Mannar and Palkbay. PhD dissertation, Berhampur University, INDIA.
- Rasher DB, Stout EP, Engel S, Kubanek J, Hay ME (2011) Macroalgal terpenes function as allelopathic agents against reef corals. Proceedings of the National Academy of Sciences 108(43): 17726-17731.
- Ravindran J, Kannapiran E, Manikandan B, Francis K., Arora S, Karunya E, ... Jose J (2013) UV-absorbing bacteria in coral mucus and their response to simulated temperature elevations. Coral reefs 32(4): 1043-1050.
- Ravindran J, Kannapiran E, Manikandan B, ManiMurali R, Joseph A (2012) Bleaching and secondary threats on the corals of Palk Bay: A survey and Proactive conservation needs. Indian Journal of Geo Marine Sciences 41(1): 19-26.
- Ravindran J, Raghukumar C, Raghukumar S (1999) Disease and stress-induced mortality of corals in Indian reefs and observations on bleaching of corals in the Andamans. Current Science76: 233-237.
- Richmond RH (1987) Energetics, competency and long-distance dispersal of planula larvae of the coral *Pocillopora damicornis.* Marine Biology 93(4): 527-533.
- Richmond RH (1993) Coral Reefs: present problems and future concerns resulting from anthropogenic disturbance. American Zoologist 33(6): 524-536.
- Riegl BM, Sheppard CR, Purkis SJ (2012) Human impact on atolls leads to coral loss and community homogenisation: a modeling study. PloS one 7(6): e36921.
- Ritson-Williams R, Arnold SN, Fogarty ND, Steneck RS, Vermeij MJ, Paul VJ (2009) New perspectives on ecological mechanisms affecting coral recruitment on reefs. Smithson Contribution Marine Science 38: 437-457.
- Robinson JD, Warner ME (2006) Differential impacts of photoacclimation and thermal stress on the photobiology of four different phylotypes of Symbiodinium (pyrrhophyta) 1. Journal of phycology42(3): 568-579.
- Rodrigues LJ, Grottoloi AG (2007) Energy reserves and metabolism as indicators of coral recovery from bleaching. Limnology & Oceanography52(5):1874-1882.

- Roth MS, Knowlton N (2009) Distribution, abundance and microhabitat characterization of small juvenile corals at Palymra atoll. Marine Ecology Progress Series 376: 133-142.
- Rowan R (2004) Coral bleaching: thermal adaptation in reef coral symbionts. Nature 430(7001): 742-742.
- Rowan R, Knowlton N, Baker AC, Jara J (1997) Landscape ecology of algal symbiont communities explains variation in episodes of coral bleaching. Nature388(6639): 265-69.
- Ruiz-Zarate MA, Arias Gonzalez JE (2004) Spatial study of juvenile corals in the Northern region of the Mesoamerican Barrier Reef System (MBRS). Coral Reefs 23(4): 584-594.
- Salm R, Smith SE, Llewelyn G (2001) Mitigating the impact of coral bleaching through Marine Protected area design. In: HZ Schuttenberg (Ed). Coral Bleaching: Causes, Consequences and Response. 9th International coral reef symposium on coral reef bleaching: Assessing and linking ecological and socioeconomic impacts, future trends and mitigation planning. Coastal Management Report2230: 81-88.
- Sampayo EM, Ridgway T, Bongaerts P, Hoegh-Guldberg O (2008) Bleaching susceptibility and mortality of corals are determined by fine-scale differences in symbiont type. Proceedings of the National Academy of Sciences105(30): 10444-10449.
- Sawall Y, Jompa J, Litaay M, Maddusila A, Richter C (2013) Coral recruitment and potential recovery of eutrophied and blast fishing impacted reefs in Spermonde Archipelago, Indonesia. Marine Pollution Bulletin 74(1): 374-382.
- Shankar D, Vinayachandran PN, Unnikrishnan AS (2002) The monsoon currents in the north Indian Ocean. Progress in Oceanography 52(1): 63-20.
- Sheppard CCR, Harris A, Sheppard ALS (2008) Archipelago-wide coral recovery patterns since 1998 in the Chagos Archipelago, Central Indian Ocean. Marine Ecology Progress Series 362: 109-117.
- Shinn EA (1976) Coral reef recovery in Florida and the Persian Gulf. Environmental Geology 1(4): 241-254.
- Shinn EA, Smith GW, Prospero JM, Betzer P, Hayes ML, Garrison V, Barber RT (2000) African dust and the demise of Caribbean coral reefs. Geophysical Research Letters27(19): 3029-3032.
- Silverstein RN, Correa AM, Baker AC (2012) Specificity is rarely absolute in coral–algal symbiosis: implications for coral response to climate change. Proceedings of the Royal Society B: Biological Sciences 279(1738): 2609-2618.

- Smith DJ, Suggett DJ, Baker NR (2005) Is photoinhibition of zooxanthellae photosynthesis the primary cause of thermal bleaching in corals?.Global Change Biology11(1): 1-11.
- Smith JE, Shaw M, Edwards RA, Obura D, Pantos O, Sala E, Sandin SA, Smriga S, Hatay M, Rohwer FL (2006) Indirect effects of algae on coral: algae-mediated microbe induced coral mortality. Ecology letters 9(7): 835-845.
- Smith SV (1983) Coral reef calcification. In: Barnes DJ (Ed). Perspectives on coral reefs. Clouston, Manuka, ACT, Australia, pp 240-247.
- Sorokin YI (1990) Aspects of trophic relations, productivity and energy balance in coral-reef ecosystems. Ecosystems of the world25: 401-418.
- Sorokin YI (1993) (Ed). Coral Reef Ecology. Ecological Studies 102. Springer Verlag, Berlin.
- Spalding MD, Ravilious C, Green EP (2001) World Atlas of Coral Reefs. Prepared at the UNEP World Conservation Monitoring Centre. Berkeley.
- Spencer T, Teleki KA, Bradshaw C, Spalding MD (2000) Coral bleaching in the southern Seychelles during the 1997-1998 Indian Ocean warm event. Marine Pollution Bulletin40(7): 569-586.
- Sridhar PN, Ali MM, Rao MV, Nagamani PV (2012) Photosynthetically active radiation, a critical parameter for mass coral bleaching in the North Indian Ocean. Current Science102(1): 114-118.
- Sridhar R, Thangaradjou T, Kannan L (2008) Comparative investigation on physicochemical properties of the coral reef and seagrass ecosystems of the Palk Bay. Indian Journal of Marine Sciences37(2): 207.
- Sridhar R, Thangaradjou T, Kannan L, Astalakshmi S (2010) Assessment of coastal bio-resources of the Palk Bay, India, using IRS-LISS-III data. Journal of the Indian Society of Remote Sensing38(3): 565-575.
- Steneck RS (1997) Crustose corallines, other algal functional groups, herbivores and sediments: complex interactions along reef productivity gradients. Proceedings of the 8th International Coral Reef Symposium 1: 695–700.
- Stimson J, Larned S, McDermid K (1996) Seasonal growth of the coral reef macroalga *Dictyosphaeria cavernosa* (Forskal) Borgesen and the effects of nutrient availability, temperature and herbivory on growth rate. Journal of Experimental Marine Biology and Ecology 196(1): 53-77.
- Stoddart DR (1973) Coral reefs: the last two million years. Geography 58(4): 313-323.

- Szmant A, Gassman NJ (1990) The effects of prolonged “bleaching” on the tissue biomass and reproduction of the reef coral *Montastrea annularis*. Coral reefs8(4): 217-224.
- Szmant AM (2002) Nutrient enrichment on coral reefs: is it a major cause of coral reef decline?. Estuaries 25(4): 743-766.
- Tanner JE (1995) Competition between Scleractinian corals and macroalgae: An experimental investigation of coral growth, survival and reproduction. Journal of Experimental Marine Biology and Ecology 190(2): 151-168.
- Thacker R, Ginsburg D, Paul V (2001). Effects of herbivore exclusion and nutrient enrichment on coral reef macroalgae and cyanobacteria. Coral reefs 19(4): 318-329.
- Thomas PA (1972) Boring sponges of the reefs of Gulf of Mannar and Palk Bay. In: Mukundam C Gopinatha Pillai CS (Eds). Proceedings of the symposium of corals and Coral reefs. Marine Biological Association of India, pp-333-362.
- Tomascik T, Mah AJ, Nontji A, Moosa K (1997) The Ecology of the Indonesian seas. Vol 1, Periplus Editions (HK) Ltd, Hongkong.
- Trapon ML, Pratchett MS, Hoey AS, Baird AH (2013) Influence of fish grazing and sedimentation on the early post-settlement survival of the tabular coral *Acropora cytherea*. Coral reefs 32(4): 1051-1059.
- Underwood AJ, Keough MJ (2001) Supply-side ecology: the nature and consequences of variations in recruitment of intertidal organisms. Marine community Ecology, Sinauer Associates Inc, Sunderland, p 183-200.
- UNEP (2004) People and Reefs: Successes and challenges in the management of coral reef marine protected areas. UNEP Regional seas reports and Studies No. 176
- Van Laake PE, Sanchez-Azofeifa GA (2005) Mapping PAR using MODIS atmosphere products. Remote Sensing and Environment94(4): 554-563.
- Van Woesik R, Sakai K, Ganase A, Loya Y (2011) Revisiting the winners and the losers a decade after coral bleaching. Marine Ecology Progress Series434: 67-76.
- Vaughan TW (1914) Reef corals of the Bahamas and South Florida. Carnegie Inst Wash Yearbook13: 222-226.
- Venkataraman K (2007) Marine ecosystems of India. Indian Journal of Environmental Education 7: 7-26.
- Venkataraman K, Rajkumar R (2013) Status of coral reefs in Palk Bay. Records of Zoological Survey India 113: 1-11.
- Venkataraman K, Sathyanarayana CH, Alfred JRB, Wolstenhome J (2003) Handbook on hard corals of India. Zoological Survey of India, Kolkatta, India.

- Vermeij MJA, Dailer ML, Smith CM (2011) Crustose coralline algae can suppress macroalgal growth and recruitment on Hawaiian coral reefs. Marine Ecology Progress Series 422: 1-7.
- Veron JEN (2000) Corals of the world. In: M Stafford-Smith (Ed). Australian Institute of Marine Science, Townsville, Australia.
- Vineeta Hoon (1998) Coral reef of India: review of their extent, condition research and management status. In: Vineeta Hoon (Ed). Proceedings of the regional Workshop on the Conservation, Sustainability and Management of Coral Reefs, M.S. Swaminathan Research Foundation and BOBP of FAO/UN, 1-27.
- Vinoth R, Gopi M, Kumar TTA, Thangaradjou T, Balasubramanian T (2012) Coral reef bleaching at Agatti Island of Lakshadweep atolls, India. Journal of Ocean University of China 11(1): 105-110.
- Vuki VC, Price IR (1998) Seasonal changes in the *Sargassum* populations on a fringing coral reef, Magnetic Island, Great Barrier Reef region, Australia. Aquatic Botany 48(2): 153-166.
- Wallace CC, Watt A, Bull GD (1986) Recruitment of juvenile corals onto coral tables preyed upon by *Acanthaster planci*. Marine Ecology Progress Series 32: 299-306.
- Ward JR, Kim K, Harvell C (2007) Temperature affects coral disease resistance and pathogen growth. Marine Ecology Progress Series329: 115-121.
- Warner ME, Fitt WK, Schmidt GW (1999) Damage to photosystem II in symbiotic dinoflagellates: a determinant of coral bleaching. Proceedings of the National Academy of Sciences96(14): 8007-8012.
- Warwick RM, Clarke KR (1991) A comparison of some methods for analyzing changes in benthic community structure. Journal of Marine Biological Association of UK 71(01): 225-244.
- Waycott M, Duarte CM, Carruthers TJB, Orth RJ, Dennison WC, Olyarnik S….. (2009) Accelerating loss of sea grasses across the globe threatens coastal ecosystems. Proceedings of National Academy of Sciences USA 106(30): 12377-12381.
- West JM, Salm RV (2003) Resistance and resilience to coral bleaching: implications for coral reef conservation and management. Conservation Biology 17(4): 956-967.
- Wilkinson C (2002) Status of Coral Reefs of the World. Townsville, Australia: Australian Institute of Marine Science.
- Wilkinson C (2008) Status of Coral Reefs of the World: 2008. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia.

- Wilkinson C (2000) World-wide coral reef bleaching and mortality during 1998: A global climate change warning for the new millennium?. In: Sheppard CRC (Ed). Seas at the millennium: an environmental evaluation 3. Global Issues and Processes, Elseiver Science, Amsterdam, p 43-57.
- Wilkinson CR (1999) Global and local threats to coral reef functioning and existence: review and predictions. Marine and Freshwater Research 50(8): 867-878.
- Williams DE, Miller MW, Kramer KL (2008) Recruitment failure in Florida Keys *Acropora palmata*, a threatened Caribbean coral. Coral Reefs 27(3): 697-705.
- Wilson JJ, Marimuthu N, Kumaraguru AK (2005) Sedimentation of silt in the coral reef environment of Palk Bay, India. Journal of Marine Biological Association of India 47(1): 83-87.
- Wilson SK, Babcock RC, Fisher R, Holmes TH, Moore JAY, Thomson DP (2012) Relative and combined effects of habitat and fishing on reef fish communities across a limited fishing gradient at Ningaloo. Marine Environmental Research 81: 1-11.
- Wilson SK, Fisher R, Pratchett MS, Graham NAJ, Dulvy NK, Turner RA, Cakacaka A, Polunin NVC, Rushton SP (2008) Exploitation and habitat degradation as agents of change within coral reef fish communities. Global Change Biology 14(12): 2796-2809.
- Wooldridge SA (2009) Water quality and coral bleaching thresholds: Formalising the linkage for the inshore reefs of the Great Barrier Reef, Australia. Marine Pollution Bulletin58(5): 745-751.
- Yee SH, Barron MG (2010) Predicting coral bleaching in response to environmental stressors using 8 years of global-scale data. Environmental monitoring and assessment161(1-4): 423-438.
- Yeemin T, Saenghaisuk C, Sutthacheep M, Pengsakun S, Klinthong W, Saengmanee K (2009) Conditions of coral communities in the Gulf of Thailand: a decade after the 1998 bleaching event. Galaxea, Journal of coral reef studies 11(2): 207-217.

APPENDIX

List of Publications

From Thesis

- **Manikandan B**, Ravindran J, Shrinivaasu S, Marimuthu N, Paramasivam K (2014) Community structure and coral status across reef fishing intensity gradients in Palk Bay reef, southeast coast of India. Environmental monitoring and assessment, 186(10), 5989-6002.
- **Manikandan B**, Ravindran J, Vidya PJ, ManiMurali R, Shrinivaasu S, Paramasivam K. Recruitment pattern and survivability of juvenile corals amid recurrent stress events at Palk Bay, India. (*Communicated-Under Review*)
- **Manikandan B, Ravindran J.** Macroalgal bloom influenced the benthic community dynamics at Palk Bay reef, India.(*Communicated-Under Review*)
- **Manikandan B**, Ravindran J, Vidya PJ, Manimurali R. Evaluation of bleaching prespective and recovery pattern in Palk Bay, India for the assessment of reef resilience. (*Communicated-Under Review*).

Other Publications

- Ravindran J, Kannapiran E, **Manikandan B**, Mani Murali R, Anthony Joseph (2012) Bleaching and secondary threats on the corals of Palk Bay: A survey and Proactive conservation needs. Indian Journal of Geo-Marine sciences 41(1): 19-26.
- Ravindran J, Kannapiran E, **Manikandan B**, Francis K, Arora S, Karunya E, Amit Kumar, Jose J (2013) UV- absorbing bacteria in coral mucus and their response to simulated temperature elevations. Coral Reefs 32(4): 1043-1050.

- Shrinivaasu S, Venkataraman k, Venkataraman C, **Manikandan B** (2013) Pleurobranchus forskalii (Ruppell & Leuckart, 1828)- A new record for Indian Coastal Waters. Global Journal of Bioscience and Biotechnology 2(3): 456-457.
- Ravindran J, **Manikandan B**, Venkatesh M, Murali RM, Marimuthu N, Wafar MVM (2014) Repercussions of embarkation wharves in Lakshadweep islands on coral communities and their ecology. Indian Journal of Marine Sciences 43(7): 7.
- Ravindran J, **Manikandan B**, Shirodkar PV, Francis KX, Mani Murali R, Vethamony P (2014) Bacterial bioluminescence response to long-term exposure to reverse osmosis treated effluents from dye industries. Canadian journal of microbiology 60(10): 661-668.
- Ravindran J, Raghukumar C, **Manikandan B (**2015) Pink line syndrome. In: Woodley C, Downs CA, Bruckner AW, Porter JW, Galloway SB (Eds). Diseases of Coral, 1st Edition, John Wiley & Sons (***In press***).