CHAPTER 1: INTRODUCTION

1.1 CORAL AND CORAL REEFS

Planet earth's surface is covered by around 71% of water and various geomorphological structures and benthic morphology give rise to different types of biome and ecosystems beneath our oceans. One such ecosystem is known as coral reefs. Coral reefs are one of the important ecosystems on the earth, with high biological production and complicated environmental conditions. Coral reefs can be found along the shore and off the shores of islands and continents in tropical waters (Buchheim, 1998). They can also be seen from space as spectacular colour patterns tracing the borders of coastlines and spreading far out into the oceans (Spalding *et al.,* 2001). Reefs are teeming with life and are as rich as tropical rainforests in terms of diversity. They are home to a diversity of colourful exotic fish, corals, and countless other marine flora and fauna. They provide food and shelter to the many species that live in reefs (Meesters *et al.,* 1998). Coral reefs are expected to be home to 25% of all marine species, with as many as one million unique species (Davidson, 1998).

Marine animals with sedentary and primarily colonial behavior are referred to as corals (Joshi, 2016). Corals are marine invertebrates living in colonies of tiny structured polyps. As per the taxonomic classification, the corals are members of the class Anthozoa in the phylum Cnidaria. Corals have polyps with tentacles having stinging cells (cnidoblast), which are frequently utilized to paralyze the tiny invertebrates (plankton) that they consume (Goreau *et al.,*1979). These polyps have radial symmetry forming a crown of tentacles on the upper side and the other end is connected with the hard substrate, much like a sea anemone. The size of a polyp can vary from species to species. Since they are very thin and fragile, the delicate polyps retreat for protection within a skeleton made up of calcium carbonate that polyps secrete around the body. This type of coral is known as Hermatypic corals and Scleractinia corals (Sreekumaran and Gogate, 1972), which are estimated to be formed around 245 million years ago in Mesozoic Era (Stanley, 2003) are the pioneers of the reef-building process.

1.2 REPRODUCTIVE MECHANISM OF CORALS

Many corals have developed throughout the ages to have the capacity for both asexual and sexual reproduction. During asexual reproduction, new clonal polyps bud off from parent polyps to grow by generating new colonies (Sumich, 1996). When the parent polyp reaches a specific size and divides, this phenomenon occurs. Sometimes corals also reproduce asexually through the fragmentation process, which occurs when a section of the colony, like a branch, separates from the colony and lands on another suitable substrate. This can occur either naturally, such as when a coral piece is broken off by a storm's wave movement and falls somewhere else, or intentionally, such as when people take coral fragments and place them in another substrate (Highsmith, 1982). Throughout the span of life, the process is repeated to form continuously expanding coral colonies (Barnes and Hughes, 1999). The colony may develop in any species-specific growth form, including massive, sub-massive, encrusting, foliose, plate-like, or branching, as a result of asexual reproduction (Joshi, 2016).

When it comes to sexual reproduction, different coral species have different modes of sexual reproduction. Around 75 percent of stony corals generate hermaphroditic colonies which can produce both male and female gametes. The remaining individuals create gonochoristic colonies that can only generate either male or female gametes. Most of these stony corals perform a broadcast spawning to disperse their eggs over vast geographic areas (Veron, 2000). Through the fusion of gametes, planulae get created. These planulae will float in the water until they find a suitable substratum to settle and metamorphose into polyps and form colonies. Since corals can experience an abnormally high rate of mortality during the period between planulae formation and settlement (Barnes and Hughes, 1999), thousands of planulae are produced annually by coral colonies. Whereas, there are some species that spawn planulae within their bodies after internal fertilization. This procedure produces fewer, larger, and more developed planulae than spawning, which is associated with huge quantities of eggs and planulae (Veron, 2000).

1.3 SYMBIOTIC BEHAVIOR OF CORALS

The primary factor influencing the establishment, expansion, and productivity of coral reefs is the special mutualism between hermatypic corals and their photosynthetic zooxanthellae (Levinton, 1995).

The endodermal tissues of stony coral polyps are home to the photosynthetic, single-celled dinoflagellates known as zooxanthellae (intracellularly). Frequently, the gastrodermis cells and tentacles of the polyps are densely packed with zooxanthellae (Levinton, 1995).

The majority of corals that form reefs have zooxanthellae, unlike deep-water and some cold-water species (Lalli and Parsons, 1995).

Large amounts of carbon are "fixed" by zooxanthellae during photosynthesis, and some of this carbon is transferred to their host polyp. Glycerol makes up the majority of this carbon, but it also contains glucose and alanine. The polyp uses these chemical substances for its metabolic processes or as raw materials to create proteins, lipids, and carbs. Additionally, the symbiotic algae improve the coral's capacity to produce calcium carbonate (Lalli and Parsons, 1995).

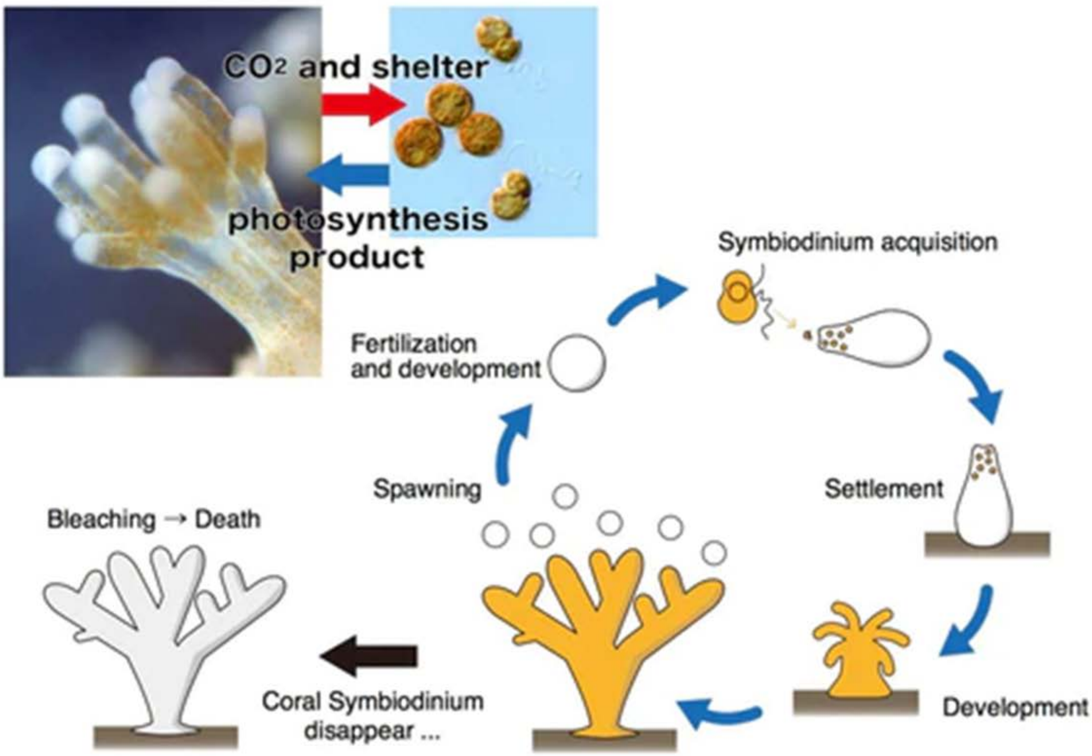

Figure 1: symbiotic behavior of corals

(Source: https://phys.org/news/2013-07-coral-symbiont-genome-decoded.html)

Hermatypic corals behave in many ways that are similar to plants because of their close association with zooxanthellae. As a result, both the distribution and growth of corals, as well as the development of the reef as a whole, are highly dependent on light (Levinton, 1995). The depth of light penetration limits the vertical distribution of living coral reefs, which is why the majority of coral reefs are found in shallow waters with a depth range of 60 to 70 meters. In deeper water, the hermatypic coral species diversity on a reef rapidly decreases; the curve closely resembles that of the extinction of light species (Barnes, 1987).

Clear water is necessary for reef corals because of their need for light. As a result, coral reefs are typically only found in waters with a tiny number of suspended debris, or in waters with low turbidity and poor productivity. As a result, corals prefer nutrient-poor seas, which paradoxically make for some of the most productive marine ecosystems (Barnes, 1987).

While a significant portion of their energy requirements are met by zooxanthellae, most corals also need zooplankton prey. Most corals feed at night, with a few exceptions (Barnes, 1987). Corals eat similarly to sea anemones by catching food particles. In order to capture prey, polyps extend their tentacles, sting the prey with poisonous nematocyst cells, and then draw the prey to their mouths. Many corals also gather tiny particles in mucous film or strands, which are then pulled by cilia into the mouth of the polyp in addition to zooplankton. Some species, like the foliaceous ("leafy") agariciids, which have few or no tentacles, are solely mucous suspension feeders. Depending on the size of the coral polyps, prey can be anything from tiny fish to tiny zooplankton (Barnes and Hughes, 1999). Nitrogen, a component that is necessary to both the coral and its zooxanthellae but is not produced in sufficient quantities by either, is provided by prey. A tight cycle of nutrients between corals and zooxanthellae is made possible by their symbiotic interaction (Barnes, 1987). Specific to each species, the coral's reliance on zooxanthellae varies (Barnes, 1987). Branching corals have a multi-layered growth type that enables for a larger surface area to intercept light both horizontally and vertically, making them appear to be more self-nourishing (autotrophic) than some of the enormous corals. This enables corals to utilize incident and dispersed light to their full potential. In addition to these skeletal changes, branching corals frequently have small polyps that expose the greatest number of zooxanthellae to light (Barnes and Hughes, 1999).

Heterotrophic corals, which require external sources of nutrition, are generally spheroidal and have a single-layered skeletal structure (Barnes, 1987). The thicker tissues of gigantic corals also contain less plant matter. Larger, thicker polyps on heterotrophic corals enable them to catch more plankton. Additionally, their shape maximizes the surface area of tissue that captures plankton (Barnes and Hughes, 1999).

Depending on the species and conditions, corals can obtain different amounts of energy through autotrophic and heterotrophic processes. According to estimations, photosynthesis accounts for a fraction of energy that ranges from over 95% in autotrophic corals to roughly 50% in the more extreme heterotrophic species (Barnes and Hughes, 1999). Evidence suggests that a complex interaction of light capture systems, effective nutrient recycling, and hydrodynamic processes is responsible for the extraordinarily high productivity found on coral reefs.

1.4 EVOLUTION HISTORY OF CORALS AND CORAL REEFS

There was a protracted Early Triassic period following the world's biggest mass extinction at the end of the Permian (Erwin, 2015), defined by the absence of metazoan reefs and a general reduction of carbonate production, with South China serving as a prominent exception (Lehrmann, 1999). Thus, the Early Triassic was an entire geologic epoch that lasted 8-10 million years without corals or large metazoan reefs. Modern corals first appeared in the Tethys Sea during the Middle Triassic, a time of mild weather and expanding carbonate shelves. Corals and other shallow-water calcified Middle Triassic animals were a part of a delayed comeback from the biggest mass extinction at the end of the Permian (Chen and Benton, 2012). Sponge, bryozoan, calcified algae, and non-colonial invertebrates built the earliest reef-like characteristics. The Middle Triassic period saw the global emergence of scleractinians, which were unrelated to the older orders of Paleozoic corals that all perished during the end-Permian extinction. Thus, scleractinians are a large amount of time apart from the final Paleozoic corals. They also have distinct symmetry, septal insertion patterns, and composition (Paleozoic corals secreted calcite rather than aragonite). Because of their distinct morphologies and their chronological separation from Paleozoic corals (Fine and Tchernov, 2007; Stanley, 2007)., scleractinians are thought to have existed as soft-bodied, anemone-like species that did not leave a fossil record during the Early Triassic period. The "naked coral" theory was that (Stanley and Fautin, 2001). It was backed by decalcification studies performed on living corals and by molecular analysis (Medina *et al.,*2006).

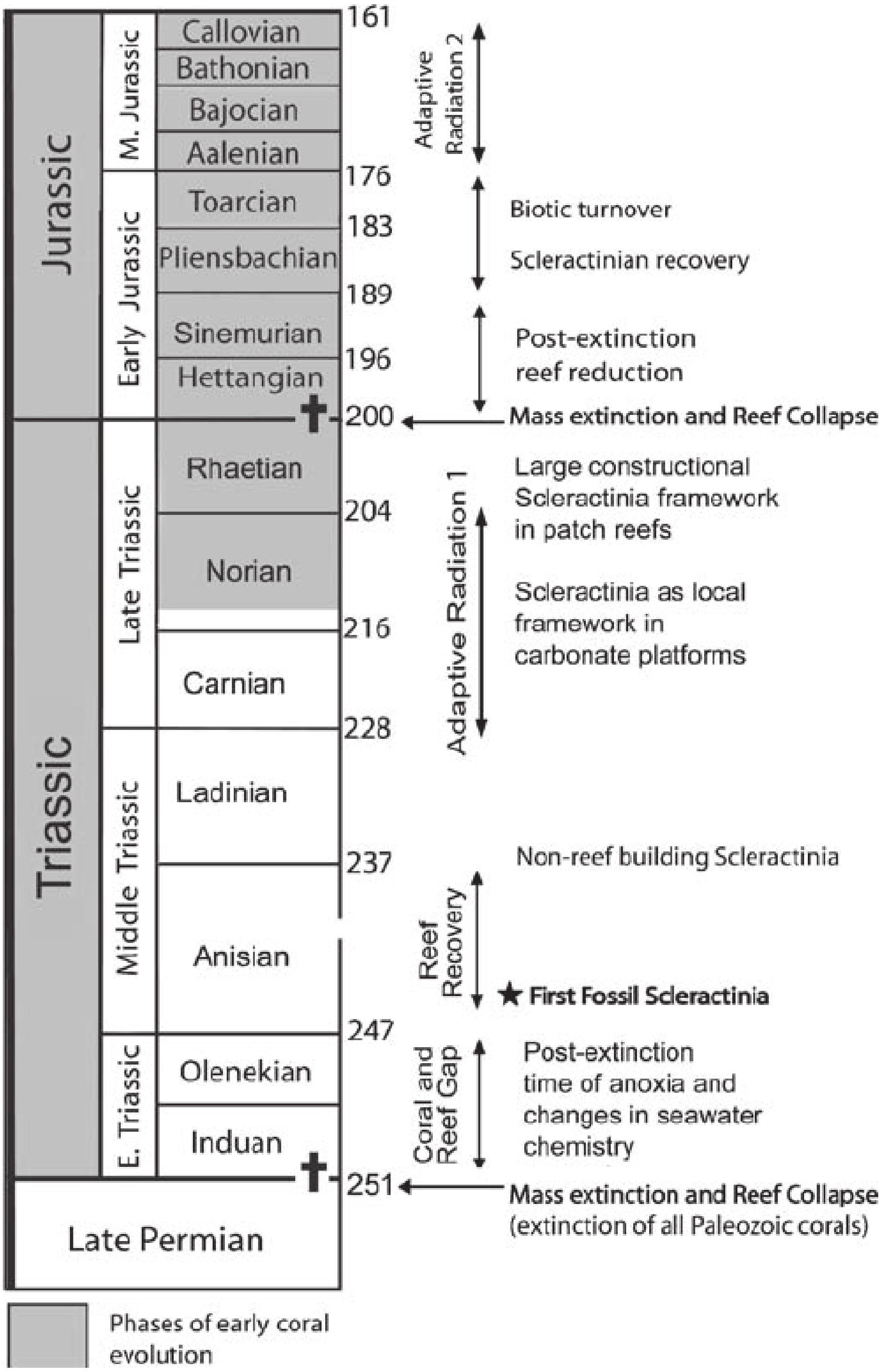

Figure 2: Reef generation history (Source: Stanley, 2007)

The first calcified scleractinians of the Middle Triassic period may have been photosymbiotic, while having various and sophisticated corallum morphologies, but strangely, they did not create reefs. Reef mounds and carbonate buildups are produced by these abruptly appearing organisms, which also include calcareous algae, foraminifera, bryozoans, and non-colonial crustaceans. Sea levels rose, the climate warmed, massive platform complexes emerged, and corals underwent an adaptive radiation throughout the Late Triassic. Scleractinian corals' emergence and potential to create the framework of reefs have been extensively discussed (Flügel 2002; Stanley 2003). Scleractinians weren't the main builders of reefs before the Late Triassic; they were merely reef dwellers. Major alterations in taxonomy and dominance occurred in the early ancestors of contemporary corals following a Late Triassic (Carnian-Norian) turnover and a smaller-scale extinction (Stanley, 1988; Roniewicz, 2011). These occurred within the vast stretches of the shallow-water Tethys Seaway, which are currently represented by deposits in mountain ranges across Central Europe and Eurasia. A later Norian-Rhaetian "reef bloom" saw the importance of huge colonial corals rise and their structure become more sophisticated. According to Rosen *et al.,* (2000), this is correlated with the beginning of the long-term prevalence of platy coral growth and probably represents a photosymbiotic response. Reef complexes in the Tethys are well known coral-dominated reefs from this era (Flügel, 2002). The latitudinal range of reefs increased during this Triassic reef bloom. Kiessling *et al.,* (2009) determined that photo symbiosis was a "key driver" of Triassic coral evolution and reef growth. The Americas were also devastated by the end-Triassic massive mass extinction, in addition to the shallow Tethys corals (Fig. 2). (Hodges and Stanley, 2015). One of the "big five" extinction events of the Phanerozoic, the end-Triassic mass extinction, has variably been attributed to the eruption of flood basalts, the release of aerosols, greenhouse gases, carbon dioxide (CO_2), and a sudden release of methane hydrates (Tanner *et al.,* 2004). This led to severe ocean acidification and significant changes in the marine environment. Despite the fact that a comeback of Early Jurassic corals started soon after, the extinction diversity remained low. Reef-building corals and sponges suffered proportionately greater losses following the extinction than other calcified biotas (corals, 96.1%; sponges, 91.4%), which may be connected to their diminished physiological control of calcification and changes in aragonite saturation in seawater (Hautmann *et al.,* 2008). The first two Early Jurassic stages that followed document a period of widespread reef decline followed by a rebound. They reflect a period of roughly 4-5*106 years during which most Triassic coral species perished and reefs disintegrated, with the exception of a few in isolated areas of the Tethys (Kiessling *et al.,* 2009; Gretz *et al.,* 2013). Despite an anoxic catastrophe at the end of the Early Jurassic (Toarcian) period, the Lower Jurassic stages that followed show evidence of recovery and biotic turnover that resulted in a restoration of coral and reef variety over the Middle to Late Jurassic (Lathuilière and Marchal, 2009). Although coral, sponge, and microbial reefs existed during the Middle and Late Jurassic, it was during this time that corals once again took the lead in the construction of shallow reefs, while siliceous sponges and microbial deposits predominated in deeper water environments (Leinfelder, 2001). Some coral biostromes in deeper waters exhibit signs of an ecology very dissimilar from the nutrient-limited concept of coral reefs (Insalaco, 1996). There was a little biotic extinction at the end of the Jurassic, but reef communities were barely affected. Rudistid bivalves took up residence on tropical shallow-water reefs during a significant portion of the Cretaceous (Johnson, 2002). Rudists were social bivalves that took advantage of odd adaptive morphologies. By the Late Cretaceous, they had achieved ecological success and were extraordinarily diversified, producing reefs or substantial buildups. Rudists adopted the forms, compactness, and interconnecting borders of colonial corals, and numerous taxa exhibit signs of photo symbiosis. During the Early Cretaceous, these particular reef-adapted bivalves coexisted with corals, sponges, and other species for around 30 million years. They inhabited carbonate platforms in the warm, tropical Tethys during the Middle to Late Cretaceous, where they grew more prevalent in the formation of reefs. During a super greenhouse phase of high sea surface temperature, this rudistid dominance occurred at the same time as global warming (Johnson *et al.,*2001). It's interesting to note that corals were extant and even diversified further during the last Cretaceous period of maximal rudistid evolution. Corals continued to thrive and remain diversified, especially in deeper, downslope environments, despite losing their former dominance on the reef and their capacity for reef formation.

According to Lipps and Stanley, (2016a, b), the significantly changed rudists provide strong evidence for photo symbiosis. This period was probably characterized by widespread photo symbiosis, and stable isotope analysis of planktonic foraminifers from the Late Cretaceous revealed the presence of symbionts (Houston and Huber, 1998). Indisputable evidence indicates that the end of the Cretaceous at the Cretaceous/Paleogene boundary (K/Pg mass extinction), which also resulted in the extinction of all rudistids, caused devastating extinctions of marine life. This took place throughout a hot greenhouse supercycle. Rudistids perished during the terrible K/Pg mass extinction, yet corals managed to survive. However, both zooxanthellate and azooxanthellate corals died out, with 33% of all families and 70% of species being lost. In comparison to azooxanthellate taxa, Cretaceous zooxanthellate corals were more severely damaged (Veron, 2008).

Coral extinction had a distinct latitudinal component, with azooxanthellate taxa faring better at cooler, higher latitudes (Kiessling and Baron-Szabo, 2004). Extinction was brought on by huge volcanism that was occurring at the time of the K/Pg boundary in addition to the well-known meteorite strike at that boundary. The complete effect on corals is unknown, although both episodes caused surface ocean acidification (D'Hondt *et al.,* 1994; Hautmann *et al.,* 2008). There have been many hypothesised causes for this extinction, but convincing arguments have been made for the role of ocean acidification in the collapse of the Cretaceous and other reef ecosystems across geologic time (Veron, 2008; Kiessling and Simpson, 2011).

Although the rebound from the K/Pg mass extinction has received extensive study, corals have not been the subject of many of these studies. All of the Danian coral species discovered in the shortly after Paleogene period were azooxanthellate species, and some of them constructed deepwater mounds in the aphotic zone (Bernecker and Weidlich, 1990). Data indicate that at the beginning of the Cenozoic, preferentially more azooxanthellate than zooxanthellate organisms persisted (Kiessling and Baron-Szabo, 2004). After the extinction, scleractinians quickly underwent diversification, but reefs took much longer to regenerate. The late Paleocene to early Eocene period, which followed the K/Pg event, is widely recognized for experiencing significant global warming. A sea disturbance known as the Paleocene Eocene Thermal Maximum (PETM) took place during this time. It has been used as a comparison of what might occur soon to the current marine ecology. A rapid release of carbon caused the extraordinary 100,000-year PETM warming period. It was estimated that the surface seawater temperature increased by 5-6 ℃ throughout that time (Wright and Schaller, 2013). Sea surface temperatures are thought to have reached 38-40 ℃ as deep ocean water heated. The acidification of the oceans was another problem. Coral reefs completely disappeared during the PETM as a result of coral diversity's response to the early warming, which resulted in bleaching and a subsequent migration to colder, northern latitudes (Scheibner and Speijer, 2008). After this incident, corals and reefs gradually recovered.

Beginning in the Middle Eocene with an Oligocene diversity plateau, which was followed by numerous coral extinctions, the remaining Cenozoic record of corals and reefs demonstrates the endurance of coral reef framework (Perrin, 2002). There are examples of reef expansion and collapse from the Neogene. The rise of the Central American Seaway, which currently divides species from the Pacific and Caribbean worlds, and the Pleistocene Ice Age glacial episodes were two ecological shocks that corals withstood at the end of the Neogene.

Clearly, most mass extinctions, if not all of them, are followed by reef gaps. They lasted anywhere from a few to as many as 8 million years. The repeated pattern of reef collapse and recovery across much of geologic history has been attributed to these gaps as the breakdown of photo symbiosis (Talent, 1988). Some predict that we will soon experience a second great mass extinction of comparable size and with a comparable collapse of the reef (Payne *et al.,* 2016).

1.5 TYPES OF CORAL REEFS

Hermatypic corals, which can only thrive in marine environments, warm water, and good lighting, form coral reefs. Reef development is constrained along shallow tropical coastlines by these criteria and Atolls, barrier reefs, and fringing reefs are the three main types of reefs according to their complexity and form.

1. Fringing Reef

According to Charles Darwin, the first corals appeared as fringing reef, which is geographically closer to the seashore than the other two forms and develops along the coast. The angle of the slope of the continental shelf where the reef is located determines the width of such a reef. The width will be shorter and vice versa if the continental shelf is sloping downward into the sea. They are often referred to as shore reefs, and they are the most basic kind of reef. These kinds of reefs are often immature, but when time and geographic conditions alter, they might develop into different kinds of reefs. Typically, this kind of reef only forms a narrow platform and lacks a significant lagoon.

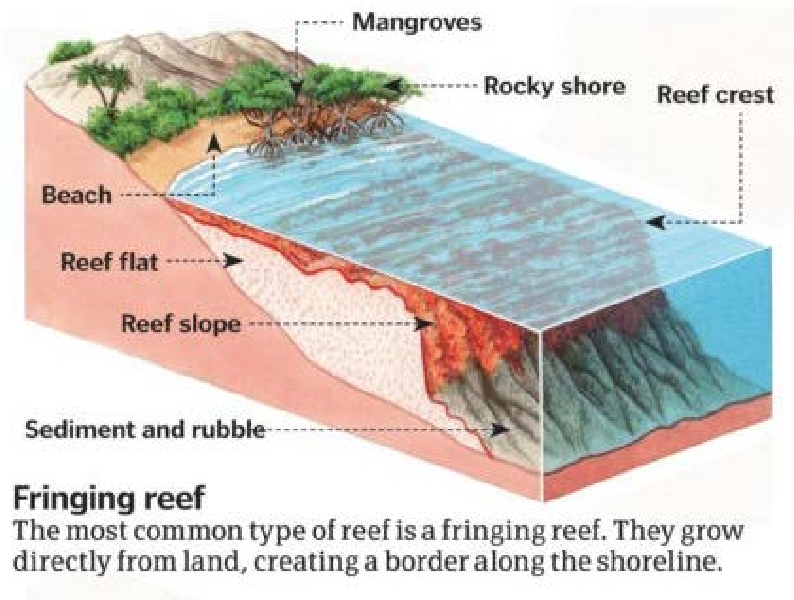

Figure 3: Fringing Reef

(Source:https://www.howitworksdaily.com/coral-reefs-exploring-the-rainforest-of-the-seas/)

The depth, fauna and flora population, and reef structure all greatly affect how the reef differs from one another throughout the entire reef region. Due to the shallow, well-lit water of this reef, where coral development is most rapid and prolific, the calcium carbonate platform can also grow quickly upward in this area. Fringing reefs can be found in the Caribbean, the South Pacific, and the Hawaiian Islands. The Andaman and Nicobar Islands in India have surrounding reefs (Venkataraman *et al.,* 2003).

2. Barrier Reef

A tiny lagoon separates the land from the barrier reef, which is also situated parallel to the seashore but distant from the beach. When compared to the fringing reef, they are thought to be older. When the landmass they are developing on sinks or is inundated by water due to eustatic transgression, barrier reefs can sometimes develop from the bordering reef. The shape and size of the barrier reefs might vary. According to Darwin, the barrier reef can occasionally completely encircle an island, and the distance between the island and reef can vary from one mile to hundreds of miles. Like atolls, the reef typically encloses a small lagoon. Darwin described the barrier reefs as chains or stripes of reef in the middle of the ocean. Fragile corals flourish more on the lagoon side of the barrier than on the open side of the reef because the seaward side of the reef faces more powerful waves. The barrier reefs might significantly impede shipping. The largest barrier reef in the world, the Great Barrier Reef in northern Australia's Indo-Pacific area, stretches for more than 2,000 km (Venkataraman *et al.,* 2003). Because they are merely separated from the mainland by a relatively shallow lagoon or because they are not situated on the edge of the continental shelf, Florida, Cuba, and other places sometimes aren't considered to be actual barrier reefs despite having lengths that resemble many true barrier reefs (Spalding *et al.,* 2001). The barrier reefs are not known to exist off the coast of India.

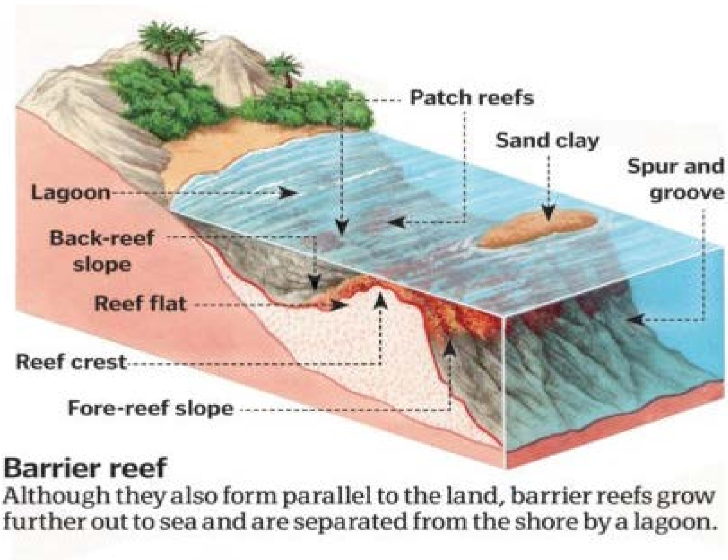

Figure 4: Barrier reef

(Source:https://www.howitworksdaily.com/coral-reefs-exploring-the-rainforest-of-the-seas/)

3. Atolls

Atolls typically form distant from the major land masses in the middle of the ocean. They are unusual reef structures with a broadly circular shape that are around by oceans and have a shallow lagoon inside of them. The lagoon's inner water's physical qualities stand in stark contrast to the water outside. According to Darwin, atolls first consist of an island surrounded by a reef, which subsides to form a lagoon. An annular reef then forms at or near the sea's surface and is known as an atoll. Old underwater volcanoes that have formed rings of coral on their tops may likewise serve as a substratum for such reefs. Some atolls were not formed by islands sinking; rather, they were formed as a result of the sea level rising. In the Indian and South Pacific oceans, atolls are abundant. Lakshadweep Archipelago in India has atoll reefs (Venkataraman *et al.,* 2003).

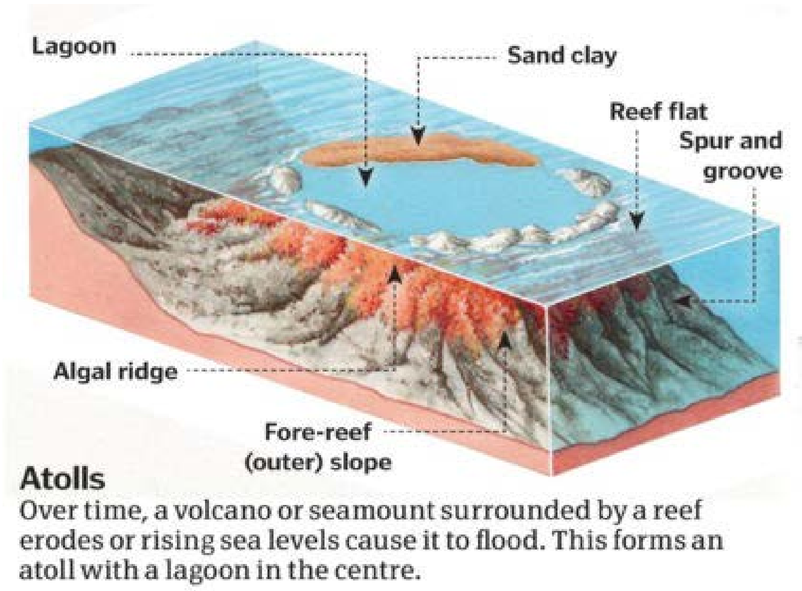

Figure 5: Atolls

(Source:https://www.howitworksdaily.com/coral-reefs-exploring-the-rainforest-of-the-seas/)

1.6 REEF DISTRIBUTION

Throughout the world, 110 countries have coral reefs, with the majority of them located between the tropics of Cancer and Capricorn.

Reef typically grows well on the eastern shores of landmasses, whether they be big continents or islands. This is due to the ways in which the currents circulate in the western region of the sea and ocean, which promote the growth and development of reefs. Rarely, if the proper environmental conditions are present, the western shores of the continents can also sustain reef development. The Ningaloo reef, which is located off the northwestern coast of Australia, is the largest fringing reef in the world. The longest bordering coral reef in Australia is the only one that is situated so close to a landmass.

The evolution of coral reefs and the conditions necessary for their survival, expansion, and reproduction have all contributed to the dispersion of coral reefs as we know it today. This demonstrates how the ecosystem's stem species have spread to diverse oceanic regions. As a result, coral reefs are found now in shallow waters between the tropics of Cancer and Capricorn all over the world, with variations, as a result of numerous known and unknown variables that have been there since ages ago. Only 0.089% of the world's ocean, or around 2, 84,300 km^2, is covered by coral reefs, according to Spalding *et al.,* (2001), making them a unique habitat. Less than 1.2 percent of the global continental shelf is occupied by the coral reef. The major portion of coral reefs are located in the eastern Indian Ocean and western Pacific Ocean, whereas the Atlantic, Caribbean, and eastern Pacific Oceans have very little coral reef area. This is a clear contrast to the global distribution of coral reefs. Additionally, according to the research conducted so far, coral reefs are largely nonexistent or only occasionally seen throughout the Central Atlantic and West African coasts (Spalding *et al.,* 2001). The Indo-Pacific region's horizontal range encompasses the Red Sea and Gulf of Aden, Arabian Gulf and Arabian Sea, Indian Ocean, Southeast Asia, and the Pacific region, which are all home to significant coral reef systems.

The Philippines, Australia, and Indonesia are the countries with the largest coral reef systems in the world, respectively. Other small nations, like Papua New

Guinea, Fiji, the Maldives, the Marshall Islands, the Solomon Islands, the Bahamas, and Cuba, contribute significantly to the reef system despite their limited area.

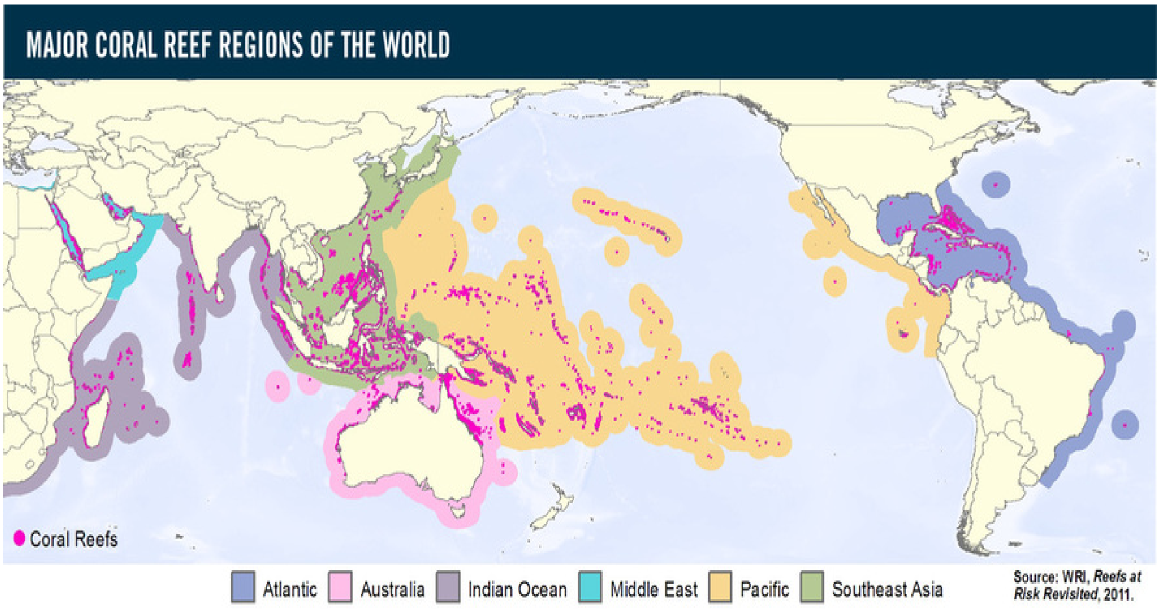

Figure 6: World Reef distribution

(Source: WRI, Reefs at Risk Revised, 2011)

The marine latitudinal diversity gradient, which indicates an increase in species richness with decreasing latitude from the equator to both Polar Regions, is likewise followed by the species richness gradient of corals (Briggs, 1974). The species richness and distribution vary even within a single latitude, with the Indo-Pacific region being about ten times more diverse than the western Atlantic. The Indo-Pacific coral community has between 500 and 600 species, whereas the western Atlantic has between 50 and 60. Southeast Asia is known as the heartland of coral species because scientists have discovered more coral species there than have been discovered throughout the entire Caribbean. The desired seawater temperatures and maximum sun irradiation close to the equator are accredited with the high species richness in the circum-tropical area. Through their photo-symbiotic relationship with algae (zooxanthellae), these two abiotic variables are thought to be in charge of the relatively quick growth of shallow-water corals, which may eventually result in the formation of reefs.

1.6.1 Reef Distribution in India

There are four significant coral reef formations in India. They are the Gulf of Kachchh in the state of Gujarat, the Lakshadweep Islands, the Gulf of Mannar and Palkbay in the state of Tamil Nadu, and the Andaman and Nicobar group of Islands.

The Gulf of Kachchh is one of the indentations on the northern side of Gujarat situated at 22°15'-23°40' N and 68°20'-70°40' E. The reefs of GoK are spread across an area of 352.5 square kilometers (Jayaprakas and Radhakrishnan, 2014). Out of 52 islands, around 40 in GoK have patchy reef structures. Patches of coral can be seen on the substrate of sandstone. When compared to other regions of India, the coral species in the Gulf of Kachchh is much less diverse (Pillai, 1996).

The Gulf of Mannar reefs, in contrast, are developed around a chain of 21 islands that are located along the 140 kilometers coast between Tuticorin and Rameswaram (Krishnamurthy, 1987). On the southeast coast of India, these islands are situated between 8°47' - 9°15' N to 78°12' - 79°14' E. An average distance of 8 km separates the 21 islands that run parallel to the shoreline. In the Gulf of Mannar, many reef morphologies, including shore platforms, patches, coral pinnacles, and atoll types, can also be seen. Patch reefs and fringing coral reefs surround the islands. The majority of the time, narrow fringing reefs are found between 50 and 100 meters from the islands. Patch reefs, on the other hand, start at depths of 2 to 9 m and can reach up to 1 to 2 km with a maximum width of 50 m (DOD and SAC, 1997). These reefs have an extensive distribution of reef flora and the reef and its related features occupy a total of 94.3 sq. km. area.

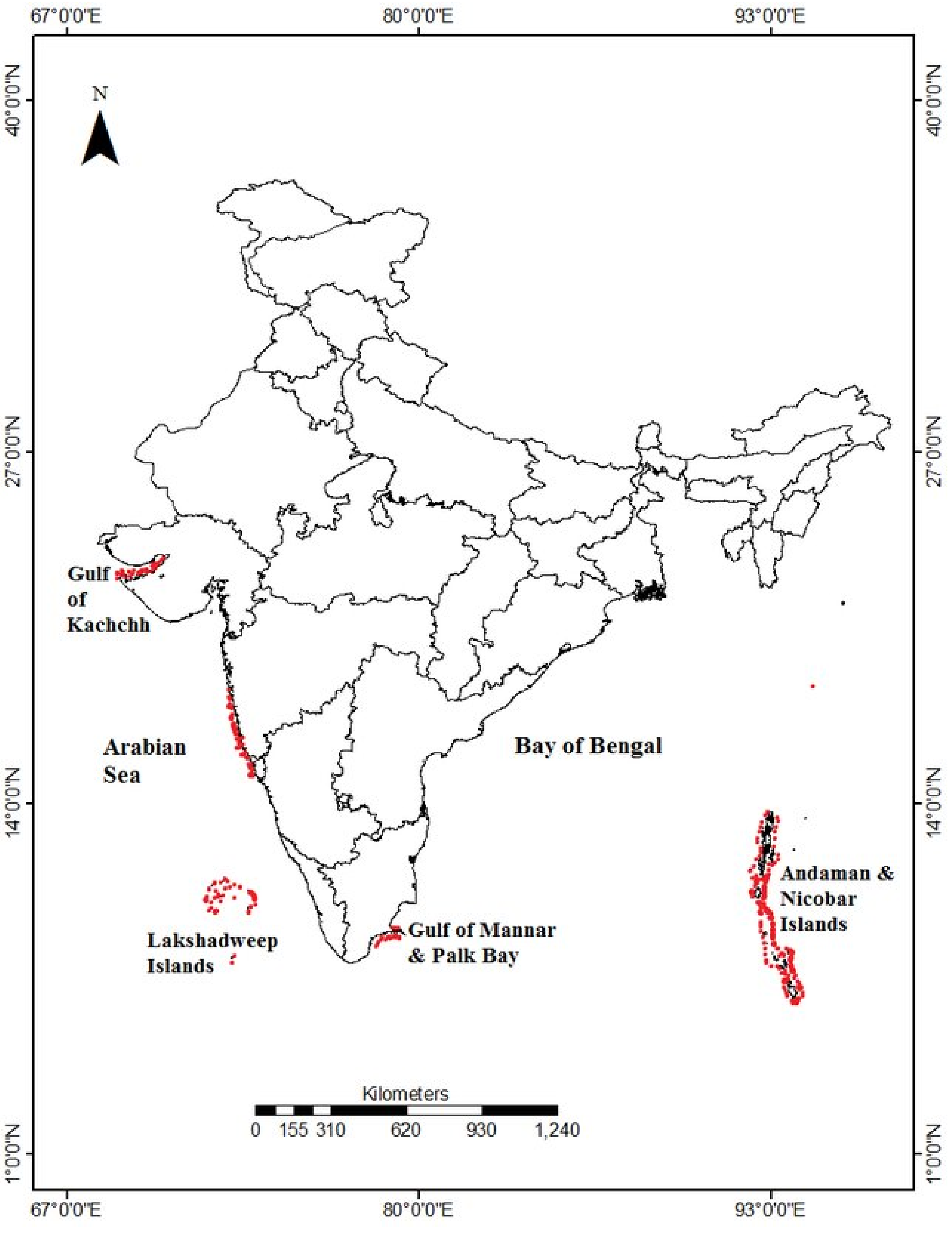

Figure 7: Coral reef distribution in India

(Source: Manikandan & Ravindran, 2015)

In Palk Bay, close to Rameswaram, and in the Gulf of Mannar, coral reefs can be seen along the coast of Tamil Nadu. Rameswaram Island and the Mandapam peninsula divide the Gulf of Mannar from Palk Bay. The Palk Bay, which stretches from the Pamban channel at the Pamban end of the bridge to Rameshwaram Island, has only one fringing reef. It is located along the mainland in an east-west orientation. This reef has a length of 25 to 30 km and a typical width of less than 200 m. Common seagrasses make up the majority of the diversity in the Palk Bay reef. It also has many different species of coral, many of which are of the Acroporidae family (Pillai, 1996). There are turtles and dugongs in the region.

The Andaman and Nicobar group of Islands are situated between 6°- 14° N to 91° - 94° E in the south-east of the Bay of Bengal. There are about 350 islands and all of these islands in the Andaman and Nicobar group have fringing reefs that are narrow, linear, and extensively well-developed (Hoon, 1997). Reef covers a total size of 1021.46 square kilometers (SAC, 2010) with home to almost 59 genera of corals.

The Lakshadweep islands are spread over the Arabian Sea, 225 to 450 kilometers off the coast of Kerala. The Laccadive-Chagos undersea ridge, which rises sharply from a depth of around 1500 m to 4000 m off the west coast of India, is the base upon which the reefs of Lakshadweep have been formed. The island's coral reefs, with the exception of one platform reef at Androth, are mostly atolls. Reef occupies a total of 933.7 square kilometers, including 510 square kilometers of the lagoon (SAC, 2010).

India is blessed with these five major coral reef formations. In addition to these reefs, there is evidence of coral reefs in the areas of Ratnagiri and Malvan on the coast of Maharashtra, Redi on the coast of Goa, and Vishakhapatnam on the coast of Andhra Pradesh. Recent reports have documented the presence of live corals in the Colaba region of Mumbai.

The formation of coral reefs in the Indian Ocean is dependent on a number of environmental conditions, such as seasonal monsoons, equatorial calm, tropical cyclones, and trade winds. These are the key factors that regulate reef distribution in the various regions of the Indian Ocean. Because reefs generally grow up to a specific tide level, the effects of tidal ranges are most vividly visible in regions where there are reefs, such as the Gulf of Kachchh. The growth of corals, algae, and other related species in the reef zones is regulated by exposure to the atmosphere and desiccation (Bakus *et al.,* 1994). The reefs of Andaman and Nicobar Islands are responsible for 41% of the Indian reefs. This is followed by the reefs of Lakshadweep with the contribution contribute 35%, the reefs of the Gulf of Kachchh, which contribute 20%, and the reefs of the Gulf of Mannar, which contribute 4%.

1.7 REEF SIGNIFICATIONS

Significant underwater habitats for marine organisms are provided by coral reefs. By reducing the strength of waves that reach the coast, it serves to safeguard coastal areas from threats like tsunamis, preventing loss of life and property damage. It also offers the coastal inhabitants an extremely valuable source of income through tourism, food, nutrition, medicines, etc. Additional biological, geological, and economic benefits are also provided by coral reefs.

1. Biological Importance

Coral reefs are home to a wide variety of aquatic life and are rich in biodiversity. They promote fish diversity and aid in the reproduction of fish with significant economic value as well as the development of other ecosystems. Corals' conservation enables the development of related seagrass and mangrove ecosystems, which helps the integration of food chains and a marine ecosystem's food web (Moberg and Folke, 1999). Many aquatic species use coral reefs and mangroves as important nesting grounds for their larvae and young (Bhattaji, 2011). By producing biochemical molecules, it also has a significant impact on future medical research as a lot of the organisms found in reefs are beneficial in treating conditions like cancer, ulcers, cardiovascular problems, etc.

2. Economic Importance

Even while coral reefs are significant from a biological and geological standpoint, it is crucial to take into account how they directly affect human existence. A large population depends on coral reefs for food, employment, and other products and services. According to estimates made by Pomerance (1999); Dixit *et al.,* (2010), 8% of the world's population, or roughly 0.5 billion people, reside within 100 kilometres of the coral reef ecosystem. These individuals may depend partially or entirely on the coral reef for their daily needs. Around 30 million of the world's poorest people live in coastal villages where their only source of income and sustenance is the reef (Gomez *et al.,* 1994; Dixit *et al.,* 2010). Coral reefs support local economies by generating revenue from tourists, building materials, fishing, bio-chemical compounds, and other sources (Carte, 1996; Moberg & Folke, 1999; Spalding *et al.,* 2001).

1.8 POTENTIAL THREATS AND THEIR IMPACTS ON THE REEF ECOSYSTEM

Numerous dangers and concerns exist for coral reefs. More reef resources are being aggressively exploited as human populations and coastal pressures rise, and many coral habitats are still under decline. According to recent estimates, 10% of all coral reefs are irreparably damaged. In 30 percent of cases, the death rate is between 10 and 20 years and they are in critical condition. By 2050, experts anticipate that 60% of the world's coral reefs may be completely extinct if current pressures are not mitigated (CRTF, 2000). Reefs degrade in response to both anthropogenic and natural stressors. Both local and global threats to coral reefs exist. Local threats to coral reefs include overfishing, destructive fishing methods, nutrient runoff, sedimentation, and coral disease. Global threats to coral reefs include mass coral bleaching brought on by rising sea surface temperatures (which is made worse by climate change), as well as ocean acidification. These pose some of the biggest dangers to coral reefs collectively.

Threats to coral reefs frequently don't happen separately; rather, they combine to weaken the reefs' capacity for resilience. Reefs can be destroyed or weakened in the wake of disastrous natural occurrences like hurricanes, cyclones, or disease outbreaks, but healthy ones are often resilient and eventually recover. However, in many instances, anthropogenic factors like pollution, sedimentation, and overfishing, which can weaken coral systems further and jeopardize their capacity to recover from disturbances, exacerbate natural disturbances. In contrast, a reef that has been negatively or positively impacted by artificial stressors may not be strong enough to endure a natural occurrence. Furthermore, a lot of scientists think that human activities amplify natural disturbances, making coral reefs more vulnerable to greater, more frequent storms, disease outbreaks, and other natural occurrences.

1. Natural Threats and their Impacts

Reefs have always been susceptible to catastrophic natural occurrences. Weather-related damage actually happens rather frequently.

Large, strong waves that come with hurricanes and cyclones can shatter or flatten massive coral heads, scattering pieces (Barnes & Hughes, 1999; Jones & Endean, 1976). Branching corals are more susceptible to storm damage than huge forms like brain coral or the stouter branching forms because they are typically more delicate and become more unstable as they grow. Slow-growing corals may become covered by algae before they can recover from a storm, but this is a rare occurrence that might be made worse by increased nutrient output from runoff and sedimentation (UVI, 2001).

Reefs depend on particular environmental factors. For optimum growth, the majority require a certain water temperature range (23 to 29 °C). Some coral species can withstand higher temperatures, but only temporarily. Corals can "bleach," or lose their symbiotic zooxanthellae and start to starve, when temperatures drop outside of this optimum range. Mass coral mortality occurs when temperatures are excessively high or remain unchecked for an extended period of time. Additionally, for corals to grow properly with certain salinity levels (between 32 and 42 ppt), water clarity, and light levels often need to stay constant throughout the year. The delicate equilibrium of the ocean's chemistry is being upset by effects of global climate change, such as higher quantities of carbon dioxide and other greenhouse gases, a dangerous phenomenon known as "ocean acidification." Rising ocean temperatures and levels are another effect of global warming that makes conditions unsuitable for coral survival (NMFS, 2001).

Disease outbreaks can also affect coral reefs. Disease typically starts as a reaction to biotic and/or abiotic stressors. The presence of bacteria, fungi, protozoa, and possibly viruses are examples of biotic stressors. Increased seasurface temperatures, ultraviolet radiation, nutritional intake, or other contaminants are examples of abiotic stress factors, which are physical and chemical changes (NMFS, 2001).

Many coral experts claim that disease outbreak rates are rising and that more reef species are being affected (NMFS, 2001). According to scientists, the presence of specific stressors can foster an environment that is beneficial for disease-causing bacteria while weakening and making corals more susceptible to colonization. White-band disease, black-band disease, white plague, and yellow-blotch disease are currently the most prevalent diseases damaging coral in the Caribbean (NMFS, 2001), whereas white syndrome may be the most prevalent and deadly disease in the Pacific.

Tidal emersions, which occur during low tide and expose coral heads, are a natural occurrence that can harm shallow-water reefs, particularly those that lie along the reef flat and on the reef crest. The amount of damage sustained is influenced by the time of day and the weather when low tide occurs. Chronic emersions that take place during the day, when the sun and heat are at their peak, are typically more harmful to coral systems than other emersions. Corals are most exposed to ultraviolet radiation during the day, which can cause the coral to overheat and become dry. Coral bleaching is a phenomenon that occurs when corals get so stressed that they start to expel their symbiotic zooxanthellae (Barnes & Hughes, 1999).

Corals can be harmed by prolonged exposure to cold and rainy conditions (Barnes & Hughes, 1999). Sometimes corals exposed to such conditions develop a greyish fuzz covering that is mostly made of coral tissue that is decaying (Jones & Endean, 1976). For as long as coral reefs have existed, they have been subject to natural calamities like storms, low tides, and El Nino events. Coral reefs are capable of recovering from natural disasters; otherwise, there wouldn't be any. They do not actually warrant much attention by itself. However, it is important to note that reefs are likely becoming less "resilient," or able to recover from such catastrophes, as a result of human influences.

Natural occurrences like the El Nino weather pattern can also have long-lasting, and even disastrous, effects on coral reefs. Easterly trade winds decrease during an El Nino season, which slows down regular marine upwelling processes and has an impact on the climate. Along the eastern Pacific, rainfall increases, although drought conditions are present in Indonesia and Australia. Due to significant rainfall, El Nino can result in higher sea surface temperatures, lower sea levels, and changed salinity (Forrester, 1997). Coral reefs experienced extensive and severe bleaching during the 1997–1998 El Nino season, particularly in the Indo–Pacific, and Caribbean. On numerous Indo-Pacific reefs, between 70 and 80 percent of all shallow-water corals perished (NMFS, 2001). Coral reefs in the Florida Keys underwent mild to severe bleaching incidents that same year (NMS, 2001). Recent El Nino episodes have led to higher sea surface temperatures, on top of gradually rising temperatures brought on by global warming. The combination results in temperatures that are high enough to induce widespread coral bleaching. Not just El Nino alone, but also global warming is a major cause for concern.

Furthermore, corals are susceptible to predators. Many animals, such as parrotfish, polychaetes, barnacles, crabs, and gastropods, feed on coral polyps, degrading the substrate and inhibiting the settling of more corals in the process (Jones & Endean, 1976). *Acanthaster planci*, a predator that recently went on the rampage, wreaked havoc on reef systems in Guam, along Australia's Great Barrier Reef, and elsewhere. The multilayered starfish *A. planci* has long, slender, somewhat poisonous spines covering it. A fully grown specimen has a diameter of between 0.25 and 0.5 m, and it feeds by adhering to the coral head, inverting its stomach, and breaking down the coral tissue underneath. When it separates, a sizable white dead skeletal patch is left behind, which filamentous algae quickly colonize. Soon after, colonies of calcareous algae and soft corals appear (Barnes & Hughes, 1999). Coral colonies can recover rather quickly when *A. planci* infestations happen at low densities. But severe infestations- as many as 15 adults per square meter can completely destroy a coral colony (Barnes, 1987).

For instance, in American Samoa's Fagatele Bay, a severe *A. planci* outbreak in those years caused up to 90% of the coral reefs to be destroyed (NMS, 2001). Although scientists are unsure of the exact causes of severe outbreaks, evidence suggests that starfish populations have exploded because their natural predators have been eradicated in many areas, particularly due to overfishing of giant tritons and other predator fish (Barnes & Hughes, 1999; Jones & Endean, 1976). According to additional data, plankton blooms may occur during larval phases of high-population outbreaks (Barnes, 1987).

2. Anthropogenic Threats and their Impacts

Coral reefs are seriously threatened by human activity in addition to natural dangers. Pollution, a word that refers to a variety of human-caused marine discharges, is one of the biggest risks to reefs. Dredging and shoreline changes, coastal development activities, agricultural and deforestation activities, and sewage treatment plant operations can all lead to excessive runoff, sedimentation, and pollution discharges. Additionally, hot-water discharges from big power plants and water treatment facilities can drastically change the chemistry of the water in coastal locations (UVI, 2001). Nitrate and phosphates concentrations in the water can rise when contaminants are released. This may result in an environment that is overly nutrient-rich (eutrophic), which promotes the growth of other creatures that may suffocate corals or outcompete them for space and algal blooms (Jones & Endean, 1976). Direct sedimentation can also suffocate a coastline reef or worsen the turbidity of the water, which reduces the amount of light that corals can absorb. A coral that is light-dependent and depends on its symbiotic algae (zooxanthellae) to produce food photosynthetically may eventually starve (UVI, 2001; Bryant *et al.,* 1998).

Coral reef habitats are overfished and overexploited for economic and recreational interests (UVI, 2001). Corals and colourful reef fish are gathered for the expanding aquarium and jewelry industries. Additionally, reef fishes are harvested for food. Divers who are careless or uneducated frequently damage delicate corals. Additionally, their fishing methods have the potential to harm both the coral ecosystem and fish. For instance, blast fishing uses large explosives like dynamite to shock fish so they may be caught quickly. This kind of fishing breaks apart coral heads and causes neighboring coral colonies to become so stressed that they expel their symbiotic algae. Large portions of reefs may be destroyed as a result.

In addition to killing coral polyps, cyanide fishing, which includes spraying or pouring cyanide onto reefs in order to shock and catch live fish, harms the reef ecosystem. Additionally, between one-third and fifty percent of all fish harvested in this fashion, perishes shortly after being removed, either during the trade process or, ultimately, in captivity (NMFS, 2001). According to some estimates, blast fishing involves more than 40 countries, while more than 15 countries have reported engaging in cyanide fishing (ICRI, 1995).

Other destructive fishing methods include muro-aminetting, which involves pounding corals with weighted bags to frighten fish out of crevices, and deep-water trawling, which involves dragging a fishing net along the ocean floor (Bryant *et al.,* 1998). Fishing nets are frequently discarded as trash. Live corals become caught in nets and are torn from their bases in wave-affected locations (Coles, 1996). Additionally, anchors dropped from fishing vessels onto reefs have the potential to break and wipe off coral colonies (Bryant *et al.,* 1998).

Finally, marine pollution has a direct effect on coral reefs. Leaking fuels, anti-fouling paints and coatings, as well as other chemicals, can have a negative impact on corals and other species by leaking into the sea (UVI, 2001). Oil spills are another issue. It is unclear how much oil spills directly impact corals because the oil typically remains near the water's surface and a large portion of it evaporates into the atmosphere within days. However, when a spill occurs is very important. The eggs and sperm, which are discharged into the water at very specific timings, float at shallow water depths for various periods of time before they settle, which can harm corals that are spawning during an oil spill. Furthermore, since dispersants cause more oil to be suspended in the water column rather than the surface, it is yet unclear how they may impact corals.

Coral reefs are in danger as coastal populations rise and marine resources are still being depleted. To address and resolve the risks that imperil the sustainability of coral reef ecosystems, an international initiative has been formed.

1.9 CORAL BLEACHING AND CLIMATE CHANGE

Corals are a key marine invertebrate that contribute to the oceans' enormous biological variety, which has been severely impacted by climate change. These delicate invertebrates are subject to inescapable challenges under the scenario of climate change. Coral reef ecosystems are subject to interacting chronic and acute pressures brought on by global climate change at scales ranging from the global to the local.

The process of coral bleaching, which causes the coral colony to appear white or pale, involves the expulsion of dinoflagellate algae called zooxanthellae from the coral tissue. In reality, corals without algae have translucent living tissue, which allows the white calcium carbonate skeleton to show through and give the appearance of being bleached. But, due to the presence of pigments in corals, the tissue can seem pinkish or bluish in some species, such as the starlet coral Siderastrea sidereal. Some species are more vulnerable to bleaching than others under the same conditions, and bleaching typically is not uniform among individual coral colonies within coral communities or across reef zones (Glynn, 1996). In certain cases, the colony's top or bottom surfaces are the only ones harmed. Others have bleached tissue that looks as a circular area, a ring, or a wedge.

Bleaching is a common stress reaction that can be brought on by extremes in temperature, light intensity, salinity, or other physico-chemical stresses. Ecologists have also described coral bleaching as a biological response to environmental changes that are present above corals' capability for acclimation (Glynn, 1993). Extreme temperature (heat shock and cold shock), high irradiance, protracted darkness, heavy metals (particularly copper and cadmium), and pathogenic microorganisms are among the environmental variables that have been found to cause the dissociation of host and symbiont (Hoegh-Guldberg, 1999; Brown, 2000). However, it is well acknowledged that the increased sea surface temperature is a significant factor in the numerous coral bleaching occurrences (Stone *et al.,* 1999). High temperature and/or light are linked to three different bleaching mechanisms: "algal-stress bleaching," "physiological bleaching," and "animal stress bleaching" (Fitt *et al.,* 2001). The algal-stress bleaching, which is an acute response to impairment of photosynthesis by high temperature coupled with high light levels, and physiological bleaching, which reflects depleted reserves, reduced tissue biomass, and less capacity to house algae as a result of the added energy demands of sustained above-normal temperature.

Depending on the kind and size of the causing variables, coral bleaching may be seen as a localized or widespread phenomenon over huge geographic areas. At least since the beginning of the 20th century, localized bleaching has been noticed. However, since the 1980s, regional and global bleaching on reefs all around the world has affected many species. Localized bleaching events are frequently brought on by direct anthropogenic stressors such as pollution, high turbidity and sedimentation, which lower light levels, salinity extremes and other abiotic variables (Glynn, 1996). Additionally, bleaching has been linked to bacterial infections in several species (Kushmaro *et al.,* 1996). However, the seven significant bleaching episodes that have occurred since 1979 have been predominantly linked to rising sea temperatures brought on by El Nino/la Nina events and global climate change, with a probable synergistic effect of increasing UV and visible light (Hoegh-Guldberg, 1999).

Reduced skeletal growth and reproductive activity, as well as a decreased ability to shed sediments and fend off the invasion of competing species and illnesses, are all crippling effects of bleaching (Glynn, 1996). Long-term bleaching may result in partial or complete colony demise. Affected colonies can restore their symbiotic algae within a few weeks to months if the bleaching is not too severe and the stressful conditions subside quickly (Glynn, 1996). which can be lessened by improved management techniques and reducing the stress source (Salm *et al.,* 2001).

1.10 REMOTE SENSING AND CORAL REEFS

Coral reef remote sensing is a naturally interdisciplinary field of study. Characterizing some aspect of reef structure or function is the overarching scientific goal, which calls for knowledge of reef ecology, geology, and/or biogeochemistry. However, because observations must be done at a distance, it is necessary to draw inferences about the reef. For instance, linking optical signals from remote measurements with coral structure necessitates an understanding of how light interacts with reef elements as well as how light travels across aquatic and aeolian mediums. Advanced sensor systems that include fore-optics (lenses), optical detectors, navigation units, data storage devices, motion-control units, and control electronics are needed for the actual light measurements. The sensor's launch, orbital characteristics, targeting, and data downlink become important considerations if it is mounted on a satellite platform, in addition to heat dissipation, power issues, and other things. Fortunately, no one person is in charge of all of these factors, but it's crucial to understand that engineering, environmental optics, and reef science all interact in coral reef remote sensing. Remote sensing of coral reefs has taken many directions in terms of advancement and use. Remote sensing technologies and approaches for processing and evaluating images of shallow water systems, in general, are being improved via basic research. The creation of a remote sensing instrument to explore certain coral reef processes is the subject of more focused research. When it comes to applications, reef scientists and managers now frequently combine images and other products produced from remote sensing into their ongoing efforts.

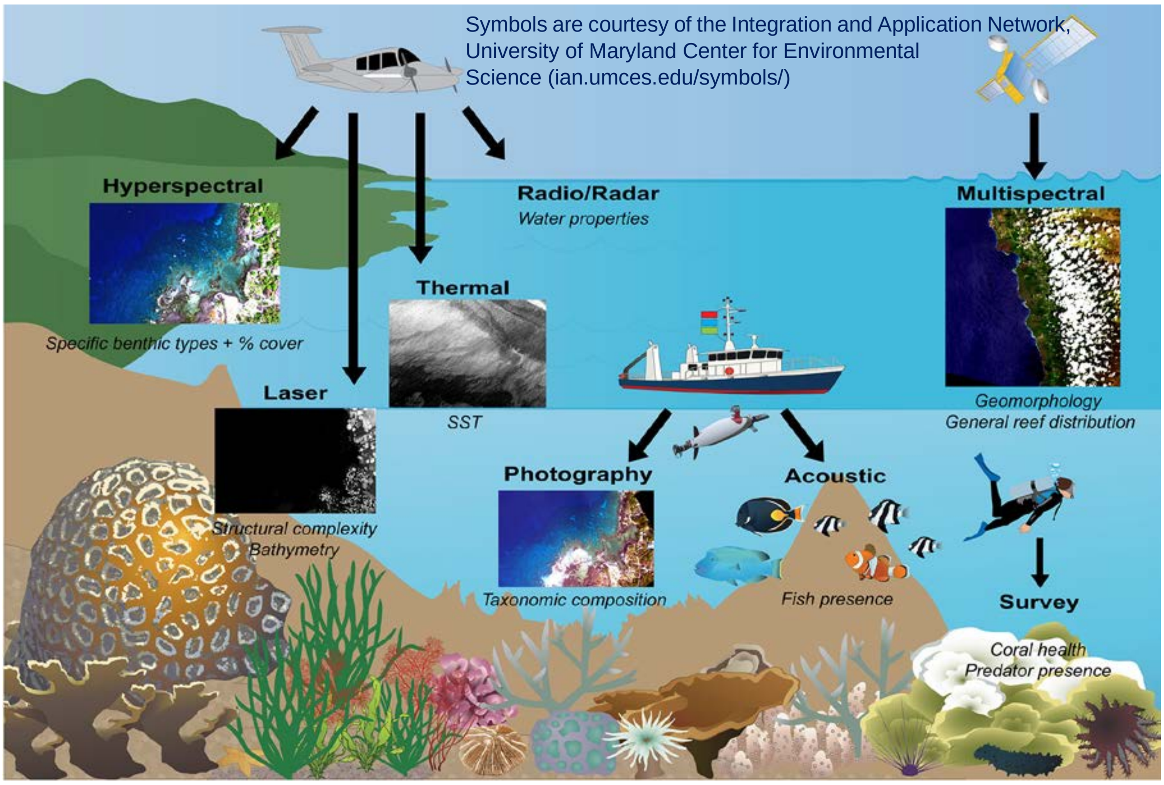

Figure 8: Remote sensing and Coral reef (Source: Foo and Asner, 2019)

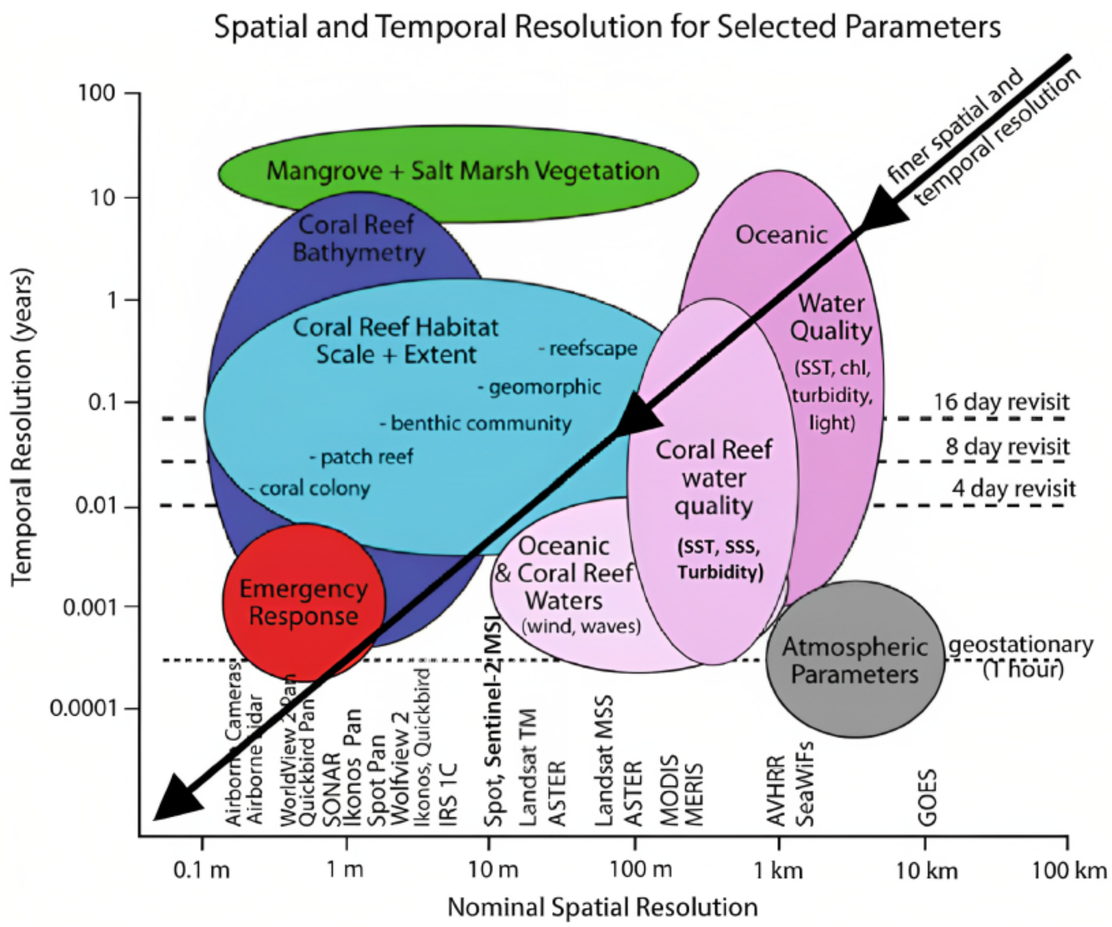

Figure 9: Spatial- Temporal Resolutions for different satellites

(Source: Hedley *et al.,* 2016)

With the launch of Landsat 1, digital remote sensing of coral reefs started in the early 1970s (Smith *et al.,* 1975). Images from sensors onboard the Landsat and SPOT (Satellite Pour l'Observation de la Terre) satellites provided the basis for the early investigations conducted in the 1970s and 1980s. This imagery had a modest spatial resolution, was multispectral (two or three visible wavebands), and was broadband (each waveband was 60-100 nm wide and pixel size, 20-80 m). Most studies were only able to identify reefs and define their geomorphology because of the few, broad wavebands and moderate spatial resolution (e.g. Loubersac *et al.,* 1988). Some studies were able to identify the fundamental reef biotopes by taking advantage of correlations between reef geomorphological and biological zones (e.g., Bour *et al.,* 1986; Vercelli *et al.,* 1988; Ahmad and Neil, 1994).

The increased public accessibility of IKONOS during the 2000s was a crucial development. These data had a spatial resolution that was substantially better (2.4-4 m for colour imaging, 0.6-1 m for panchromatic imagery), but their spectrum resolution was nearly similar to that of Landsat (i.e., broadband multispectral). Researchers using remote sensing have found varying degrees of utility for these data in mapping reef communities (Maeder *et al.,* 2002; Mumby and Edwards, 2002; Andréfout *et al.,* 2003). Depending on the study, commercial satellite imagery could generally discern between five and nine benthic classes with an accuracy of 50-80%. Benthic classes were typically arbitrarily determined on a case-by-case basis, and they frequently did not correspond with core community types that reef scientists were more familiar with. However, for the first time, precise but reasonably priced images of coral reefs were made possible by satellite observations, which were previously only possible through expensive aircraft surveys. This sparked interest within the larger reef research and management community, who started to produce their own remote sensing-derived products and use these images as contextual foundation maps for field studies.