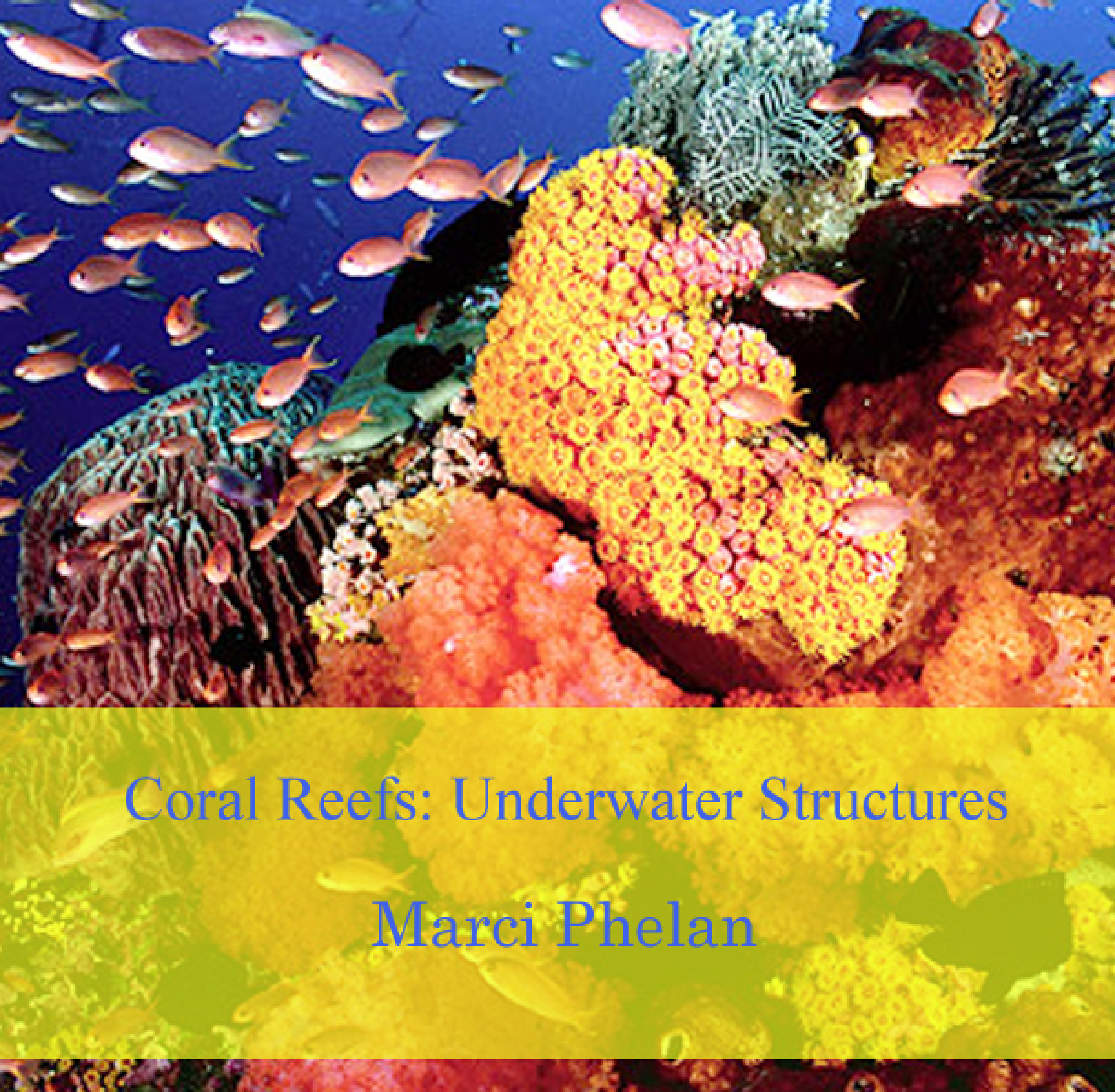

Coral Reefs: Underwater Structures

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Coral Reef

Coral reefs are underwater structures made from calcium carbonate secreted by corals. Corals are colonies of tiny living animals found in marine waters containing few nutrients. Most coral reefs are built from stony corals, and are formed by polyps that live together in groups. The polyps secrete a hard carbonate exoskeleton which provides support and protection for the body of each polyp. Reefs grow best in warm, shallow, clear, sunny, and agitated waters.

Often called “rainforests of the sea”, coral reefs form some of the most diverse ecosystems on Earth. They occupy less than one tenth of one percent of the world ocean surface, about half the area of France, yet they provide a home for twenty-five percent of all marine species, including fish, molluscs, worms, crustaceans, echinoderms, sponges, tunicates and other cnidarians. Paradoxically, coral reefs flourish even though they are surrounded by ocean waters that provide few nutrients. They are most commonly found at shallow depths in tropical waters, but deep water and cold water corals also exist on smaller scales in other areas.

Coral reefs deliver ecosystem services to tourism, fisheries and shoreline protection. The annual global economic value of coral reefs has been estimated at $US375 billion. However, coral reefs are fragile ecosystems, partly because they are very sensitive to water temperature. They are under threat from climate change, ocean acidification, blast fishing, cyanide fishing for aquarium fish, overuse of reef resources, and harmful land-use practices, including urban and agricultural runoff and water pollution, which can harm reefs by encouraging excess algae growth.

Reef structure

Types

The three principal reef types are:

- **Fringing reef** – a reef that is directly attached to a shore or borders it with an intervening shallow channel or lagoon
- **Barrier reef** – a reef separated from a mainland or island shore by a deep channel or lagoon
- **Atoll reef** – a more or less circular or continuous barrier reef extending all the way around a lagoon without a central island

A small atoll in the Maldives.

Inhabited cay in the Maldives

Other reef types or variants are:

- **Patch reef** – an isolated, comparatively small reef outcrop, usually within a lagoon or embayment, often circular and surrounded by sand or seagrass. Patch reefs are common
- **Apron reef** – a short reef resembling a fringing reef, but more sloped; extending out and downward from a point or peninsular shore
- **Bank reef** – a linear or semi-circular shaped-outline, larger than a patch reef.
- **Ribbon reef** – a long, narrow, possibly winding reef, usually associated with an atoll lagoon
- **Table reef** – an isolated reef, approaching an atoll type, but without a lagoon.
- **Habili** - reef in the Red Sea that does not reach the surface near enough to cause visible surf, although it may a hazard to ships (from the Arabic for "unborn")
- **Microatolls** – certain species of corals form communities called microatolls. The vertical growth of microatolls is limited by average tidal height. By analysing growth morphologies, microatolls offer a low resolution record of patterns of sea level change. Fossilized microatolls can also be dated using radioactive carbon dating. Such methods have been used to reconstruct Holocene sea levels.

- **Cays** – small, low-elevation, sandy islands formed on the surface of a coral reef. Material eroded from the reef piles up on parts of the reef or lagoon, forming an area above sea level. Plants can stabilize cays enough to become habitable by humans. Cays occur in tropical environments throughout the Pacific, Atlantic and Indian Oceans (including the Caribbean and on the Great Barrier Reef and Belize Barrier Reef), where they provide habitable and agricultural land for hundreds of thousands of people.

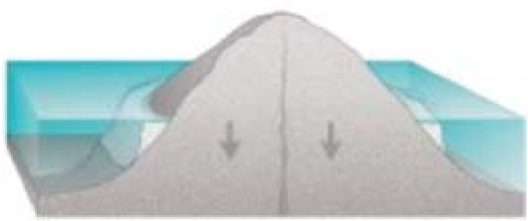
- When a coral reef cannot keep up with the sinking of a volcanic island, a **seamount** or **guyot** is formed. The tops of seamounts and guyots are below the surface. Seamounts are rounded at the top and guyots are flat. The flat top of the guyot, also called a *tablemount*, is due to erosion by waves, winds, and atmospheric processes.

Formation

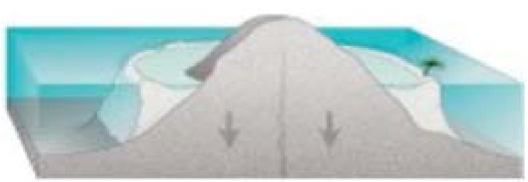
Most coral reefs were formed after the last glacial period when melting ice caused the sea level to rise and flood the continental shelves. This means that most coral reefs are less than 10,000 years old. As coral reef communities were established on the shelves, they built reefs that grew upwards, keeping pace with the rise in sea level. Reefs that didn't keep pace could become *drowned reefs*, covered by so much water that there was insufficient light for further survival. Coral reefs are also found in the deep sea away from the continental shelves, around oceanic islands and as atolls. The vast majority of these ocean coral islands are volcanic in origin. The few exceptions have tectonic origins where plate movements have lifted the deep ocean floor on the surface.

In 1842 in his first monograph, *The Structure and Distribution of Coral Reefs* Charles Darwin set out his theory of the formation of atoll reefs, an idea he conceived during the voyage of the *Beagle*. His theory was that atolls were formed by the uplift and subsidence of the Earth's crust under the oceans. Darwin's theory sets out a sequence of three stages in atoll formation. It starts with a fringing reef forming around an extinct volcanic island as the island and ocean floor subsides. As the subsidence continues, the fringing reef becomes a barrier reef, and ultimately an atoll reef.

Darwin's theory starts with a volcanic island which becomes extinct



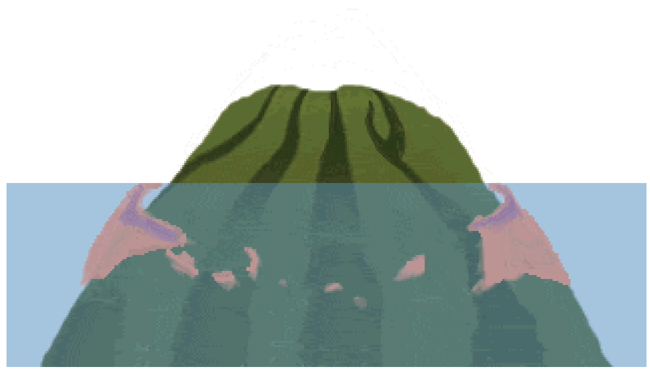
As the island and ocean floor subside, coral growth builds a fringing reef, often including a shallow lagoon between the land and the main reef



As the subsidence continues the fringing reef becomes a larger barrier reef further from the shore with a bigger and deeper lagoon inside

Ultimately the island sinks below the sea, and the barrier reef becomes an atoll enclosing an open lagoon

Darwin predicted that underneath each lagoon would be a bed rock base, the remains of the original volcano. Subsequent drilling proved this correct. Darwin's theory followed from his understanding that coral polyps thrive in the clean seas of the tropics where the water is agitated, but can only live within a limited depth of water, starting just below low tide. Where the level of the underlying land stays the same, the corals grow around the coast to form what he called fringing reefs, and can eventually grow out from the shore to become a barrier reef.



A fringing reef can take ten thousand years to form, and an atoll can take up to 30 million years

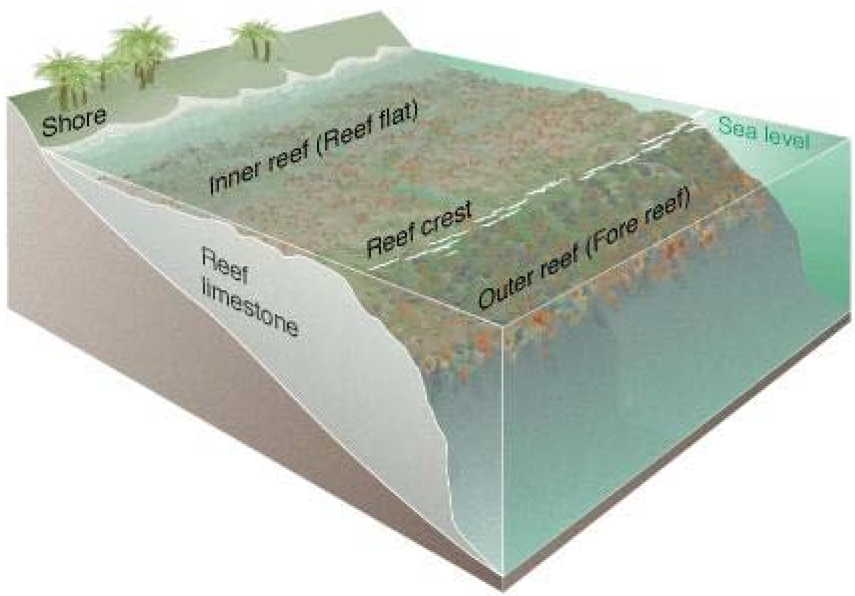
Where the land is rising, fringing reefs can grow around the coast, but coral raised above sea level dies and becomes white limestone. If the land subsides slowly, the fringing reefs keep pace by growing upwards on a base of dead coral, forming a barrier reef enclosing a lagoon between the reef and the land. A barrier reef can encircle an island, and once the island sinks below sea level a roughly circular atoll of growing coral continues to keep up with the sea level, forming a central lagoon. Barrier reefs and atolls don't usually form complete circles, but are broken in places by storms. Should the land subside too quickly or sea level rise too fast, the coral dies as it is below its habitable depth.

In general, the two main variables determining the geomorphology, or shape, of coral reefs are the nature of the underlying substrate on which they rest, and the history of the change in sea level relative to that substrate.

As an example of how coral reefs have formed on continental shelves, the current living reef structure of the Great Barrier Reef began growing about 20,000 years ago. Sea level was then 120 metres (390 ft) lower than it is today. As sea level rose, the water and the corals encroached on what had been hills of the Australian coastal plain. By 13,000 years ago sea level had risen to 60 metres (200 ft) lower than at present, and the hills of the coastal plains were, by then, continental islands. As the sea level rise continued, water topped most of the continental islands. The corals could then overgrow the hills, forming the present cays and reefs. Sea level on the Great Barrier Reef has not changed significantly in the last 6,000 years, and the age of the present living reef structure is estimated to be between 6,000 and 8,000 years. Although the Great Barrier Reef formed along a continental shelf, and not around a volcanic island, Darwin's principles apply. The Great Barrier Reef development stopped at the barrier reef stage, since Australia is not about to submerge. It formed the world's largest barrier reef, 300–1,000 metres (980–3,300 ft) from shore, stretching for 2,000 kilometres (1,200 mi).

Healthy coral reefs grow horizontally from 1 to 3 centimetres (0.39 to 1.2 in) per year, and grow vertically anywhere from 1 to 25 centimetres (0.39 to 9.8 in) per year; however, they grow only at depths shallower than 150 metres (490 ft) due to their need for sunlight, and cannot grow above sea level.

Zones



The three major zones of a coral reef: the fore reef, reef crest, and the back reef

Coral reef ecosystems contain distinct zones that represent different kinds of habitats. Usually three major zones are recognized: the fore reef, reef crest, and the back reef (frequently referred to as the reef lagoon).

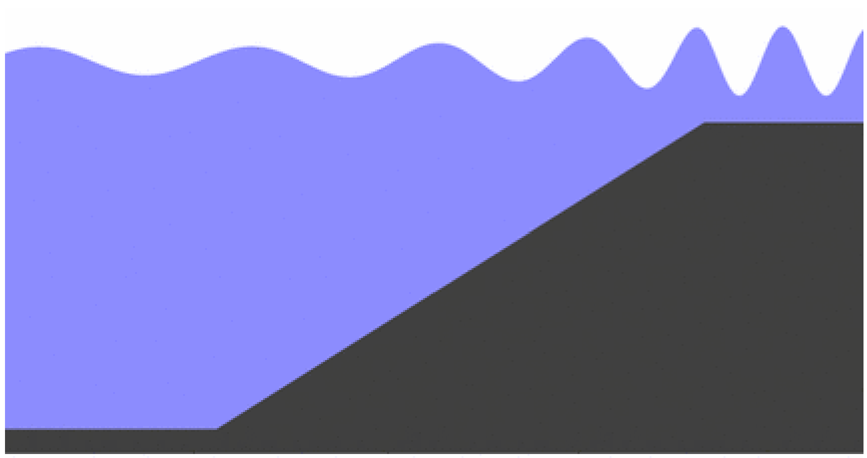
All three zones are physically and ecologically interconnected. Reef life and oceanic processes create opportunities for exchange of seawater, sediments, nutrients, and marine life among one another.

Thus, they are integrated components of the coral reef ecosystem, each playing a role in the support of the reefs' abundant and diverse fish assemblages.

Most coral reefs exist in shallow waters less than fifty metres deep. Some inhabit tropical continental shelves where cool, nutrient rich upwelling does not occur, such as Great

Barrier Reef. Others are found in the deep ocean surrounding islands or as atolls, such as in the Maldives. The reefs surrounding islands form when islands subside into the ocean, and atolls form when an island subsides below the surface of the sea.

Alternatively, Moyle and Cech distinguish six zones, though most reefs possess only some of the zones.



Water in the reef surface zone is often agitated. This diagram represents a reef on a continental shelf. The water waves at the left travel over the *off-reef floor* until they encounter the *reef slope* or *fore reef*. Then the waves pass over the shallow *reef crest*. When a wave enters shallow water it shoals, that is, it slows down and the wave height increases.

- **The reef surface** is the shallowest part of the reef. It is subject to the surge and the rise and fall of tides. When waves pass over shallow areas, they shoal, as shown in the diagram at the right. This means that the water is often agitated. These are the precise condition under which coral flourish. Shallowness means there is plenty of light for photosynthesis by the symbiotic zooxanthellae, and agitated water promotes the ability of coral to feed on plankton. However other organisms must be able to withstand the robust conditions to flourish in this zone.

- **The off-reef floor** is the shallow sea floor surrounding a reef. This zone occurs by reefs on continental shelves. Reefs around tropical islands and atolls drop abruptly to great depths, and don't have a floor. Usually sandy, the floor often supports seagrass meadows which are important foraging areas for reef fish.

- **The reef drop-off** is, for its first 50 metres, habitat for many reef fish who find shelter on the cliff face and plankton in the water nearby. The drop-off zone applies mainly to the reefs surrounding oceanic islands and atolls.

- **The reef face** is the zone above the reef floor or the reef drop-off. "It is usually the richest habitat. Its complex growths of coral and calcareous algae provide cracks and crevices for protection, and the abundant invertebrates and epiphytic algae provide an ample source of food."

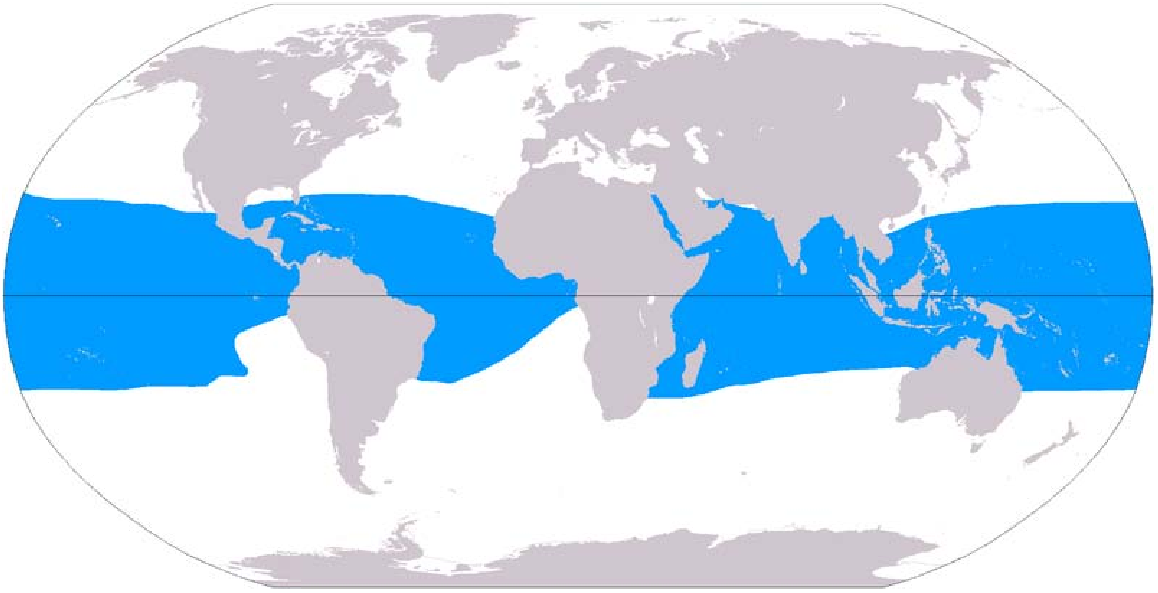
- **The reef flat** – sandy bottomed flat can be behind the main reef, containing chunks of coral. "The reef flat may be a protective area bordering a lagoon, or it may be a flat, rocky area between the reef and the shore. In the former case, the number of fish species living in the area often is the highest of any reef zone."

- **The reef lagoon** – "many coral reefs completely enclose an area, thereby creating a quiet-water lagoon that usually contains small patches of reef."

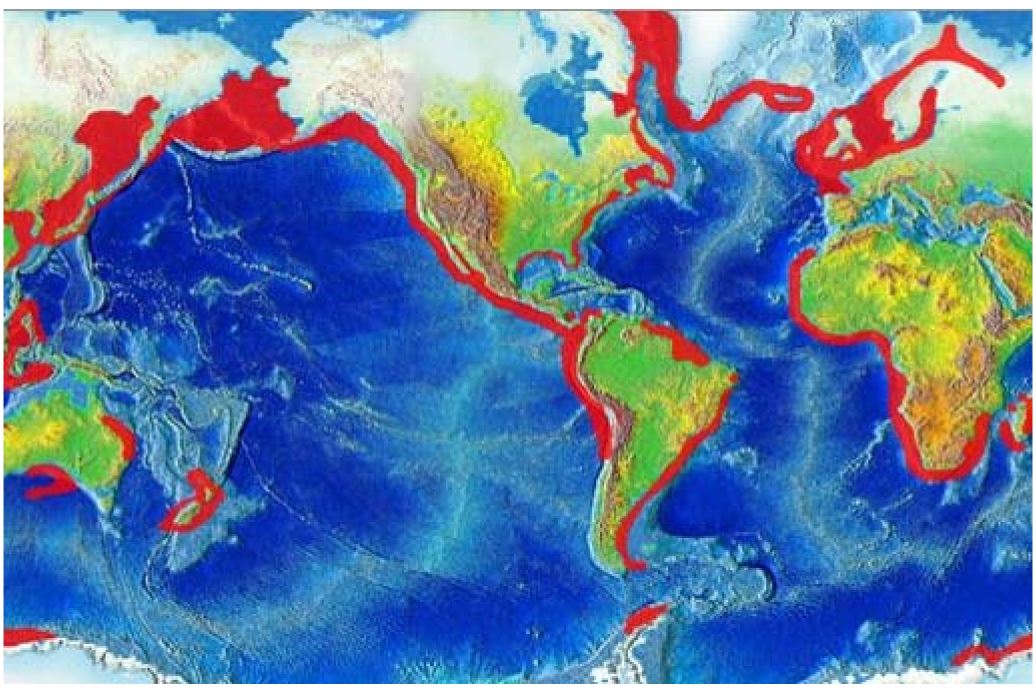
However, the "topography of coral reefs is constantly changing. Each reef is made up of irregular patches of algae, sessile invertebrates, and bare rock and sand. The size, shape and relative abundance of these patches changes from year to year in response to the various factors that favour one type of patch over another. Growing coral, for example, produces constant change in the fine structure of reefs. On a larger scale, tropical storms may knock out large sections of reef and cause boulders on sandy areas to move."

Distribution

Locations of coral reefs.



Boundary for 20 °C isotherms. Most corals live within this boundary. Note the cooler waters caused by upwelling on the south west coast of Africa and off the coast of Peru.



This map shows areas of upwelling in red. Coral reefs are not found in coastal areas where colder and nutrient-rich upwellings occur

Coral reefs are estimated to cover 284,300 square kilometers (109,800 sq mi), which is just under one tenth of one percent of the oceans' surface area. The Indo-Pacific region (including the Red Sea, Indian Ocean, Southeast Asia and the Pacific) account for 91.9%

of this total. Southeast Asia accounts for 32.3% of that figure, while the Pacific including Australia accounts for 40.8%. Atlantic and Caribbean coral reefs account for 7.6%.

Although corals exist both in temperate and tropical waters, shallow-water reefs form only in a zone extending from 30° N to 30° S of the equator. Tropical corals do not grow at depths of over 50 meters (160 ft). The optimum temperature for most coral reefs is 26–27 °C (79–81 °F), and few reefs exist in waters below 18 °C (64 °F). However reefs in the Persian Gulf have adapted to temperatures of 13 °C (55 °F) in winter and 38 °C (100 °F) in summer.

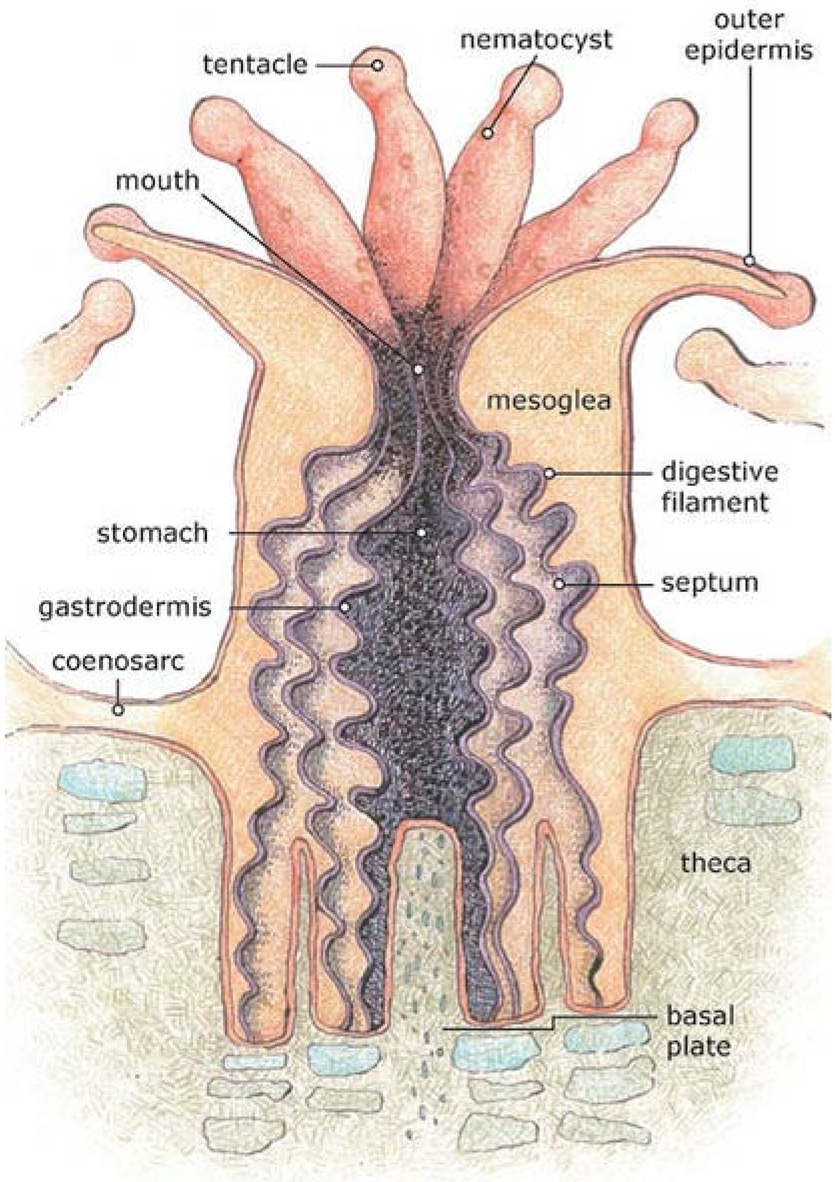
Deep water coral can exist at greater depths and colder temperatures. Although deep water corals can form reefs, very little is known about them.

Coral reefs are rare along the American west coast, as well as along the African west coast. This is due primarily to upwelling and strong cold coastal currents that reduce water temperatures in these areas (respectively the Peru, Benguela and Canary streams). Corals are seldom found along the coastline of South Asia from the eastern tip of India (Madras) to the border of Bangladesh and Myanmar. They are also rare along the coast around north-eastern South America and Bangladesh due to the freshwater release from the Amazon and Ganges Rivers respectively.

Principal coral reefs and reef areas

- The Great Barrier Reef - largest, comprising over 2,900 individual reefs and 900 islands stretching for over 2,600 kilometers (1,616 mi) off Queensland, Australia
- The Mesoamerican Barrier Reef System - second largest, stretching 1,000 kilometers (621 mi) from Isla Contoy at the tip of the Yucatán Peninsula down to the Bay Islands of Honduras
- The New Caledonia Barrier Reef - second longest double barrier reef, covering 1,500 kilometers (930 mi)
- The Andros, Bahamas Barrier Reef - third largest, following the east coast of Andros Island, Bahamas, between Andros and Nassau
- The Red Sea Coral Reef - located off the coast of Israel, Egypt, Sudan, Eritrea, Djibouti, Somalia, Jordan, Saudi Arabia, and Yemen
- Pulley Ridge - deepest photosynthetic coral reef, Florida
- Numerous reefs scattered over the Maldives
- Ghe Raja Ampat Islands in Indonesia's West Papua province offer the highest known marine diversity.

Coral biology



Anatomy of a coral polyp.

Live coral are small animals embedded in calcium carbonate shells. It is a mistake to think of coral as plants or rocks. Coral heads consist of accumulations of individual animals called polyps, arranged in diverse shapes. Polyps are usually tiny, but they can range in size from a pinhead to a foot across. Reef-building or hermatypic corals live only in the photic zone (above 50 m depth), the depth to which sufficient sunlight penetrates the water for photosynthesis to occur. Coral polyps do not themselves photosynthesize, but have a symbiotic relationship with single-celled organisms called zooxanthellae; these organisms live within the tissues of polyps and provide organic nutrients that nourish the polyp. Because of this relationship, coral reefs grow much faster in clear water, which admits more sunlight. Indeed, the relationship is responsible for coral reefs in the sense that without their symbionts, coral growth would be too slow for the corals to form significant reef structures. Corals get up to 90% of their nutrients from their zooxanthellae symbionts.

Reefs grow as polyps and other organisms deposit calcium carbonate, the basis of coral, as a skeletal structure beneath and around themselves, pushing the coral head's top upwards and outwards. Waves, grazing fish (such as parrotfish), sea urchins, sponges, and other forces and organisms act as bioeroders, breaking down coral skeletons into fragments that settle into spaces in the reef structure or form sandy bottoms in associated reef lagoons. Many other organisms living in the reef community contribute skeletal calcium carbonate in the same manner. Coralline algae are important contributors to reef structure in those parts of the reef subjected to the greatest forces by waves (such as the reef front facing the open ocean). These algae deposit limestone in sheets over the reef surface, thereby strengthening it.

The colonies of the one thousand coral species assume a characteristic shape such as wrinkled brains, cabbages, table tops, antlers, wire strands and pillars.

Table coral

Close up of polyps arrayed on a coral, waving their tentacles. There can be thousands of polyps on a single coral branch.

Reproduction

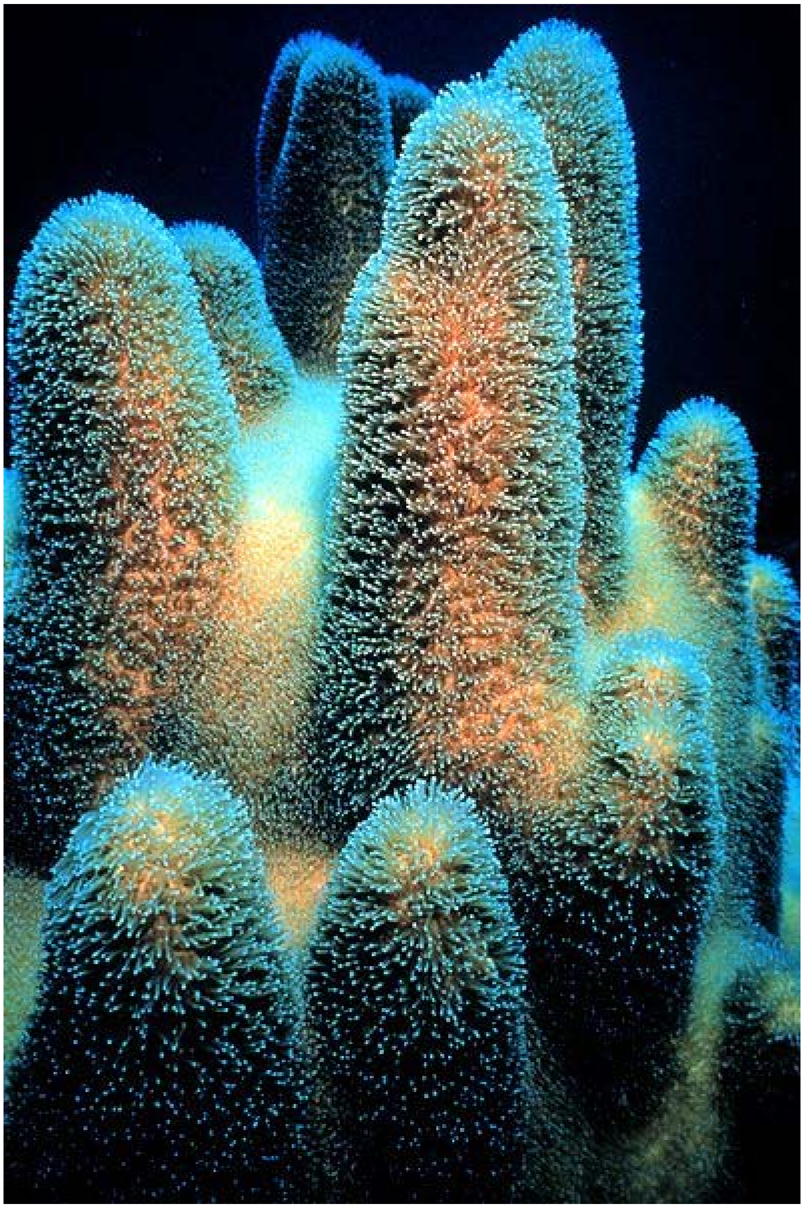
Corals reproduce both sexually and asexually. Individual polyp uses both reproductive modes within its lifetime. Corals reproduce sexually by either internal or external fertilization. The reproductive cells are found on the mesentery membranes that radiate inward from the layer of tissue that lines the stomach cavity. Some mature adult corals are hermaphroditic; others are exclusively male or female. A few species change sex as they grow.

Internally fertilized eggs develop in the polyp for a period ranging from days to weeks. Subsequent development produces a tiny larva, known as a planula. Externally fertilized eggs develop during synchronized spawning. Polyps release eggs and sperm into the water en masse, simultaneously. Eggs disperse over a large area. The timing of spawning depends on time of year, water temperature, and tidal and lunar cycles. Spawning is most successful when there is little variation between high and low tides. The less water movement, the better the chance for fertilization. Ideal timing occurs in the spring. Release of eggs or planula usually occurs at night and is sometimes in phase with the lunar cycle (3–6 days after a full moon). The period from release to settlement lasts only a few days, but some planulae can survive afloat for several weeks. They are vulnerable to predation and environmental conditions. The lucky few who attach to substrate next confront competition for food and space.

Brain coral

Staghorn coral

Spiral wire coral



Pillar coral

Ecology

Darwin's paradox

Darwin's paradox

Coral... seems to proliferate when ocean waters are warm, poor, clear and agitated, a fact which Darwin had already noted when he passed through Tahiti in 1842.

This constitutes a fundamental paradox, shown quantitatively by the apparent impossibility of balancing input and output of the nutritive elements which control the coral polyp metabolism.

Recent oceanographic research has brought to light the reality of this paradox by confirming that the oligotrophy of the ocean euphotic zone persists right up to the swell-battered reef crest. When you approach the reef edges and atolls from the quasi-desert of the open sea, the near absence of living matter suddenly becomes a plethora of life, without transition. So why is there something rather than nothing, and more precisely, where do the necessary nutrients for the functioning of this extraordinary coral reef machine come from ? — Francis Rougerie

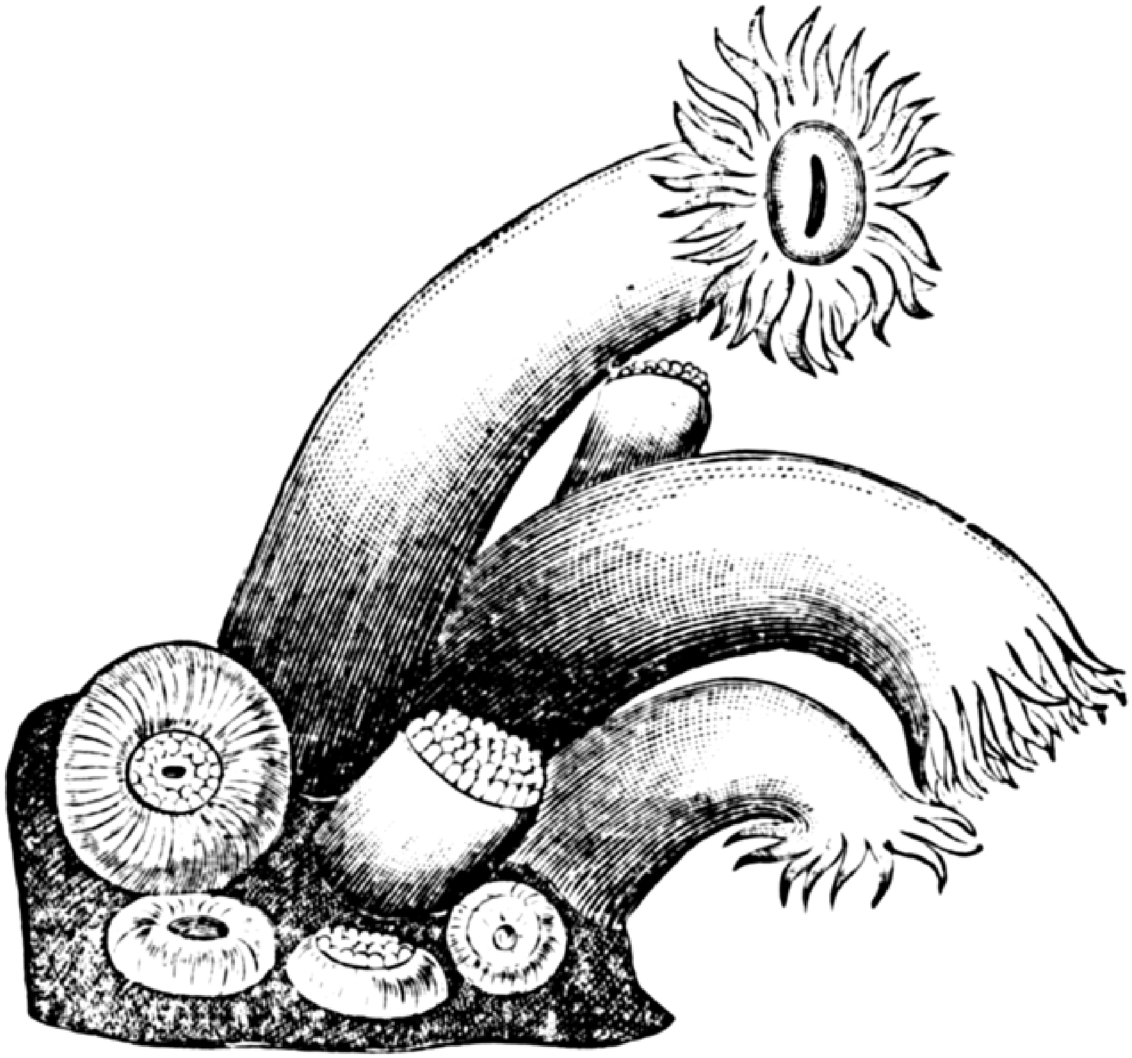
The nutrient paradox

During his voyage on the *Beagle*, Darwin described tropical coral reefs as oases in the desert of the ocean. He reflected on the paradox that tropical coral reefs, which are among the richest and most diverse ecosystems on earth, flourish surrounded by tropical ocean waters that provide hardly any nutrients.

Coral reefs cover less than one tenth of one percent of the surface of the world's ocean, yet they support over one-quarter of all marine species. This huge number of species results in complex food webs, with large predator fish eating smaller forage fish that eat yet smaller zooplankton and so on. However, all food webs eventually depend on plants, which are the primary producers. Coral reefs' primary productivity is very high, typically producting 5-10g C m^{-2} day^{-1} biomass.

One reason for the startling clarity of tropical waters is that they are deficient in nutrients and drifting plankton. Further, the sun shines year round in the tropics, warming the surface layer, making it less dense than subsurface layers. The warmer water is separated from the cooler water by a stable thermocline, where the temperature makes a rapid change. This keeps the warm surface waters floating above the cooler deeper waters. In most parts of the ocean there is little exchange between these layers. Organisms that die in aquatic environments generally sink to the bottom where they decompose. This decomposition releases nutrients in the form of nitrogen (N), phosphorus (P) and potassium (K). These nutrients are necessary for plant growth, but in the tropics they are not directly recycled back to the surface.

Plants form the base of the food chain, and need sunlight and nutrients to grow. In the ocean these plants are mainly microscopic phytoplankton which drift in the water column. They need sunlight for photosynthesis, which powers carbon fixation, so they are found only relatively near the surface. But they also need nutrients. Phytoplankton rapidly use nutrients in the surface waters, and in the tropics these nutrients are not usually replaced because of the thermocline.



Coral polyps

Solution: retention and recycling

Around coral reefs, lagoons fill in with material eroded from the reef and the island. They become havens for marine life, providing protection from waves and storms.

Most importantly, reefs recycle nutrients, which happens much less in the open ocean. In coral reefs and lagoons, producers include phytoplankton as well as seaweed and coralline algae, especially small types called turf algae, which pass nutrients to corals. The phytoplankton are eaten by fish and crustaceans, who also pass nutrients along the food web. Recycling ensures that fewer nutrients are needed overall to support the community.

Coral reefs support many symbiotic relationships. In particular, zooxanthellae provides energy to coral in the form of glucose, glycerol, and amino acids. Zooxanthellae can provide up to 90% of a coral's energy requirements. In return, as an example of mutualism, the coral shelter the zooxanthellae, averaging one million for every cubic centimetre of coral, with and provide a constant supply of the carbon dioxide it needs for photosynthesis.

The colour of corals depends on the type of zooxanthella they host

Corals also absorb nutrients, including inorganic nitrogen and phosphorus, directly from the water. Many corals extend their tentacles at night to catch zooplankton that brush them when the water is agitated. Zooplankton provide the polyp with nitrogen, and the polyp shares some of the nitrogen with the zooxanthellae, which also require this element. The varying pigments in different species of zooxanthellae give corals their different colours. Coral which loses its zooxanthellae becomes white and is said to be bleached, a condition which unless corrected can kill the coral.

Sponges are another key to explaining Darwin's paradox. They live in crevices in the coral reefs. They are efficient filter feeders, and in the Red Sea they consume about sixty percent of the phytoplankton that drifts by. The sponges eventually excrete nutrients in a form the corals can use.

Most coral polyps are nocturnal feeders. Here, in the dark, polyps have extended their tentacles to feed on zooplankton

The roughness of coral surfaces is the key to coral survival in agitated waters. Normally a boundary layer of still water surrounds a submerged object, which acts as a barrier. Waves breaking on the extremely rough edges of corals disrupt the boundary layer, allowing the corals access to nutrients. Turbulent water thereby promotes rapid reef growth and lots of branching. Without the nutritional gains brought by rough coral surfaces, even the most effective recycling would leave corals wanting in nutrients.

Cyanobacteria provide soluble nitrates for the reef via nitrogen fixation.

Coral reefs also often depend on surrounding habitats, such as seagrass meadows and mangrove forests, for nutrients. Seagrass and mangroves supply dead plants and animals which are rich in nitrogen and also serve to feed fish and animals from the reef by supplying wood and vegetation. Reefs in turn protect mangroves and seagrass from waves and produce sediment for the mangroves and seagrass to root in.

Biodiversity

Tube sponges attracting cardinal fishes, glassfishes and wrasses

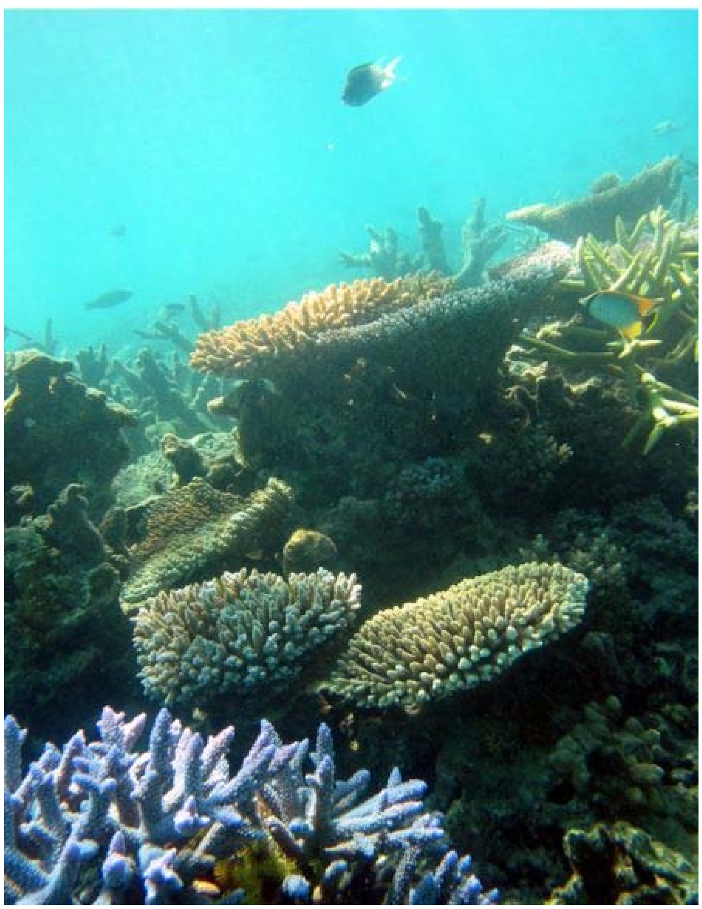
Reefs are home to a large variety of organisms, including fish, seabirds, sponges, Cnidarians (which includes some types of corals and jellyfish), worms, crustaceans (including shrimp, cleaner shrimp, spiny lobsters and crabs), molluscs (including cephalopods), echinoderms (including starfish, sea urchins and sea cucumbers), sea squirts, sea turtles and sea snakes. Aside from humans, mammals are rare on coral reefs, with visiting cetaceans such as dolphins being the main exception. A few of these varied species feed directly on corals, while others graze on algae on the reef.

Fish

Coral reefs are home to a wide variety of tropical or reef fish, among them are the following:

- Fish that influence the coral (such as *Labridae* and parrotfish) These types of fish feed either on small animals living near the coral, seaweed, or on the coral itself. Fish that feed on small animals include cleaner fish (these fish feed on organisms that inhabit larger fish), bullet fish and Balistidae (these eat sea urchins) while seaweed eating fish include the Pomacentridae (damselfishes). Serranidae cultivate the seaweed by removing creatures feeding on it (such as sea urchins), and they remove inedible seaweeds. Fish that eat coral itself include parrotfish and butterflyfish.

- Fish that cruise the boundaries of the reef or nearby seagrass meadows. These include predatory fish such as pompanos, groupers, Horse mackerels, certain types of shark, *Epinephelus marginatus*, barracudas and snappers). Herbivorous and plankton-eating fish also populate reefs. Seagrass-eating fish include Horse mackerel, snapper, Pagellus and Conodon. Plankton-eating fish include Caesio, manta ray, chromis, Holocentridae and pterapogon kauderni.



Organisms can cover every square inch of a coral reef.

Fish that swim in coral reefs can be as colorful as the reef. Examples are the parrotfish, angelfish, damselfish, *Pomacanthus paru*, *Clinidae* and butterflyfish. At night, some change to a less vivid color. Besides colorful fish matching their environment, other fish (e.g., predatory and herbivorous fish such as *Lampanyctodes hectoris*, *Holocentridae* and *Pterapogon kauderni*) as well as aquatic animals (Comatulida, Crinoidea and Ophiuroidea) emerge and become active while others rest.

Other fish groups found on coral reefs include groupers, grunts and wrasses. Over 4,000 species of fish inhabit coral reefs. It has been suggested that the fish species that inhabit coral reefs are able to coexist in such high numbers because the reef is "full" in that any free living space is inhabited by the first planktonic fish larvae that find it in what has been termed "a lottery for living space".

Invertebrates

Sea urchins, Dotidae and sea slugs eat seaweed. Some species of sea urchins, such as *Diadema antillarum*, can play a pivotal part in preventing algae overrunning reefs. Nudibranchia and sea anemones eat sponges.

A number of invertebrates, collectively called **cryptofauna**, inhabit the coral skeletal substrate itself, either boring into the skeletons (through the process of bioerosion) or living in pre-existing voids and crevices. Those animals boring into the rock include sponges, bivalve mollusks, and sipunculans. Those settling on the reef include many other species, particularly crustaceans and *polychaete* worms.

Algae

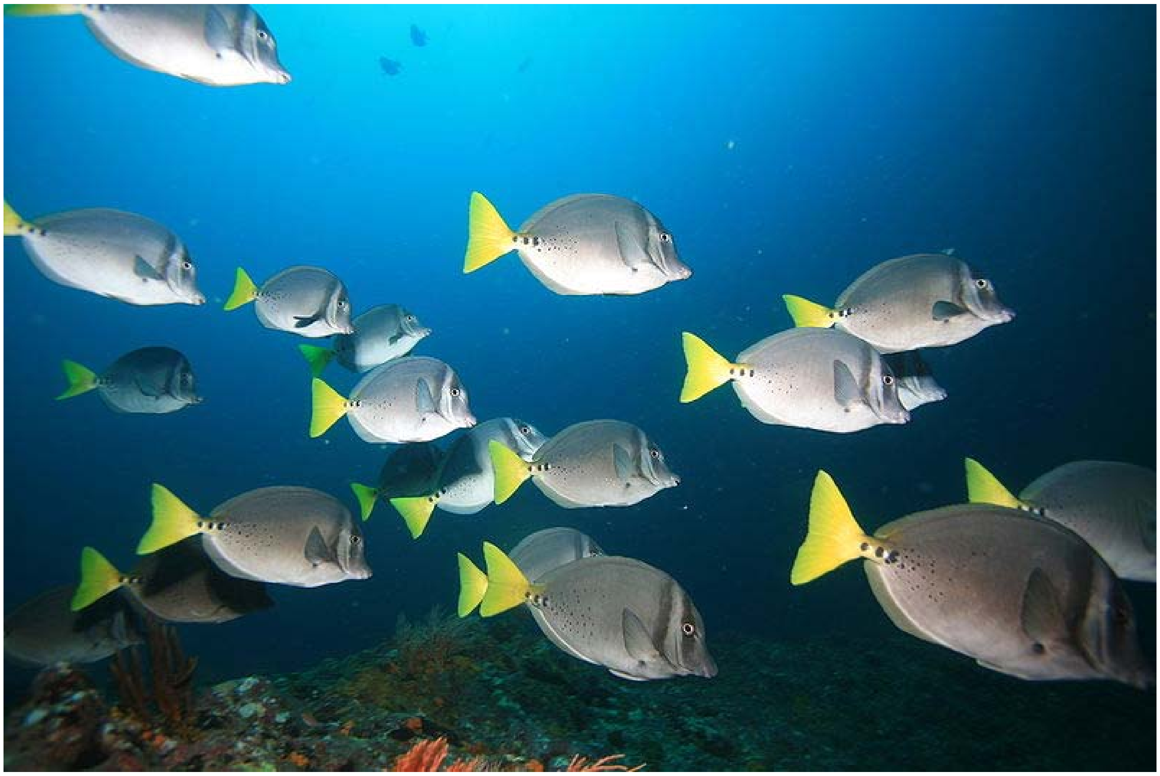
Researchers have found evidence of algae dominance in locations of healthy coral reefs. In surveys done around largely uninhabited US Pacific islands, algae inhabit a large percentage of surveyed coral locations. The algae population consists of turf algae, coralline algae, and macroalgae.

Seabirds

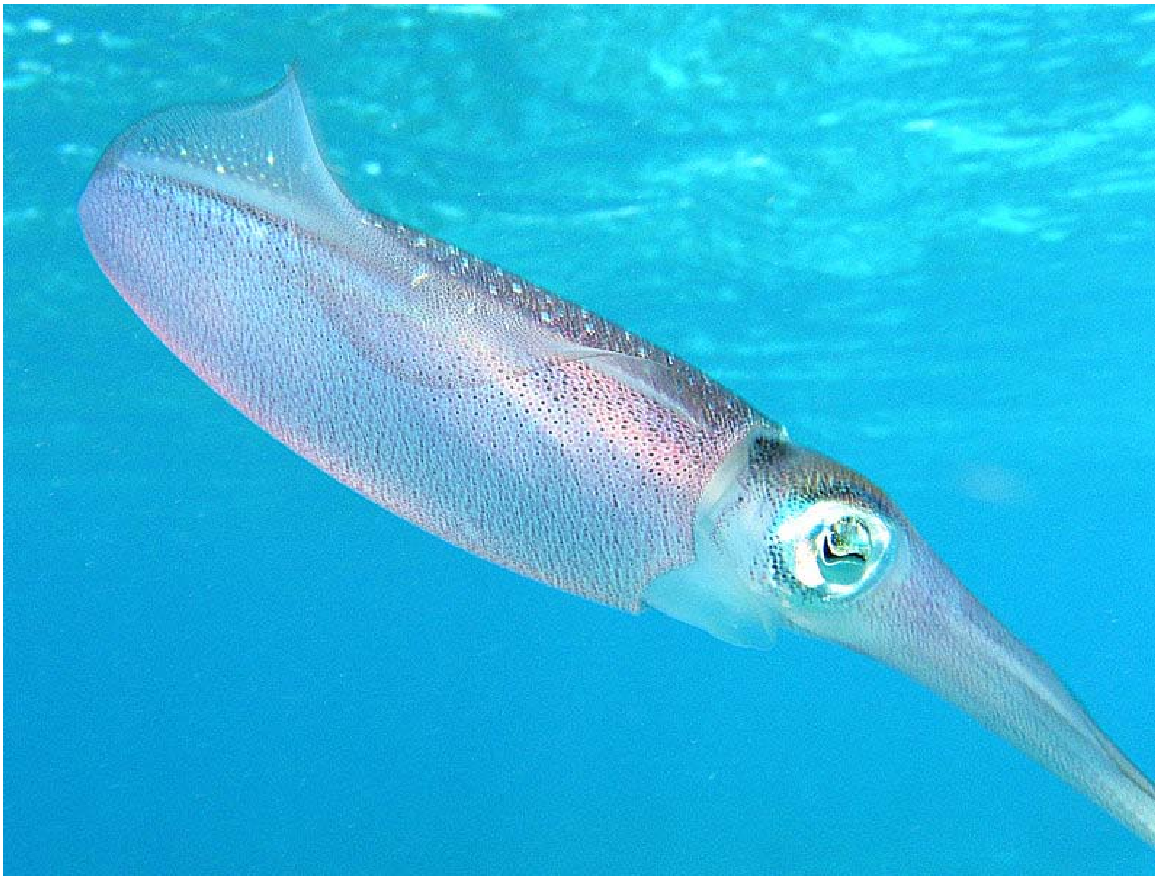
Coral reef systems provide important habitats for seabird species, some endangered. For example, Midway Atoll in Hawaii supports nearly three million seabirds, including two-thirds (1.5 million) of the global population of Laysan Albatross, and one-third of the global population of black-footed albatross. Each seabird species has specific sites on the atoll where they nest. Altogether, 17 species of seabirds live on Midway. The short-tailed albatross is the rarest, with fewer than 2,200 surviving after excessive feather hunting in the late nineteenth century.

Other

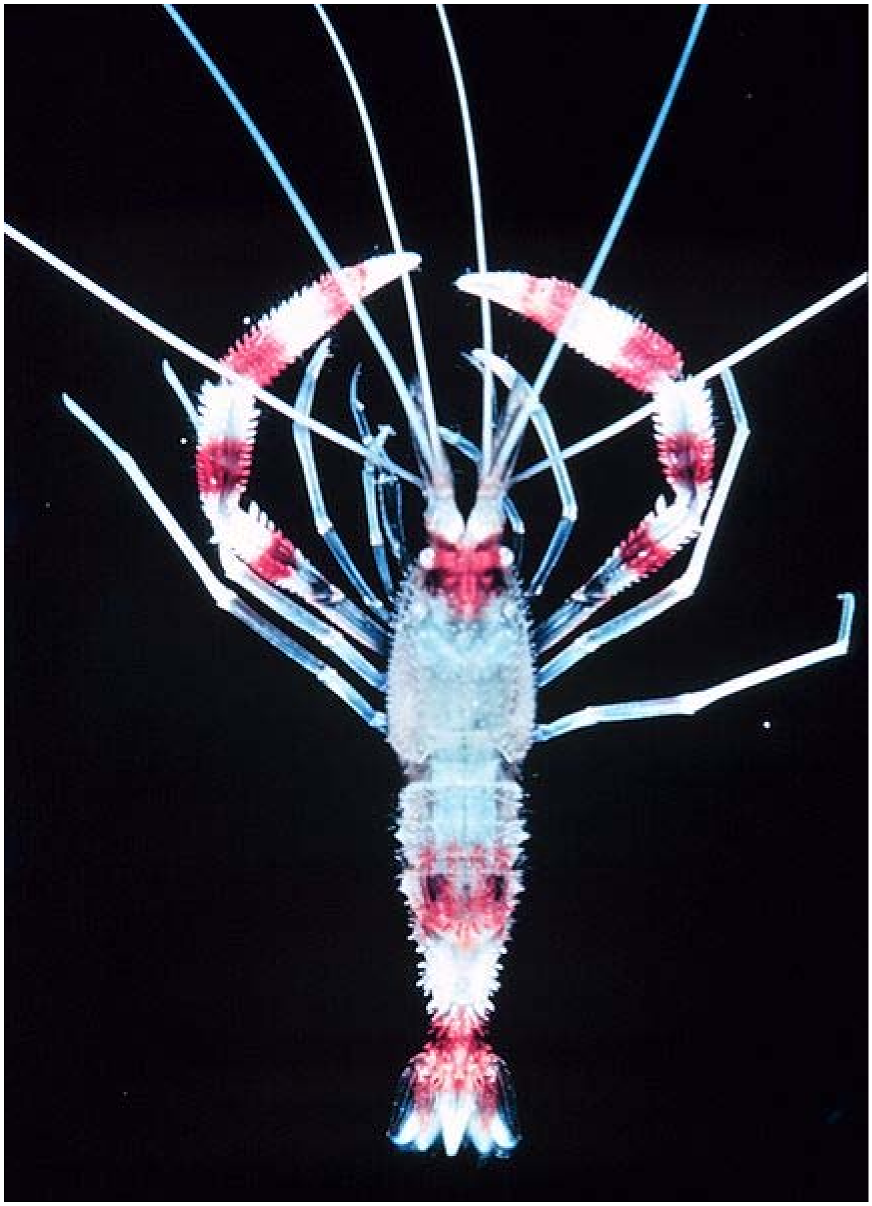
Sea snakes feed exclusively on fish and their eggs. Tropical birds such as herons, gannets, pelicans and boobies feed on reef fish. Some land based reptiles intermittently associate with reefs, such as monitor lizards, the marine crocodile and semi-aquatic snakes like *Laticauda colubrina*. Sea turtles eat sponges.



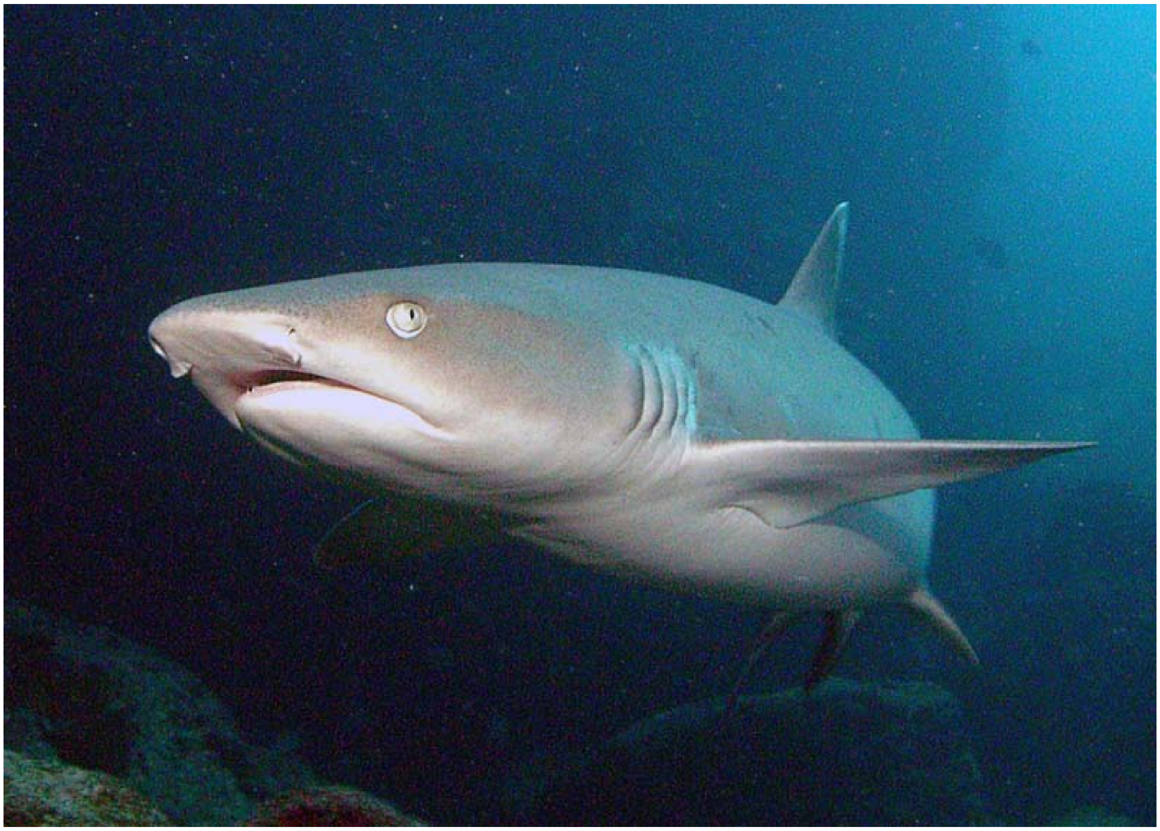
Schooling reef fish



Caribbean reef squid



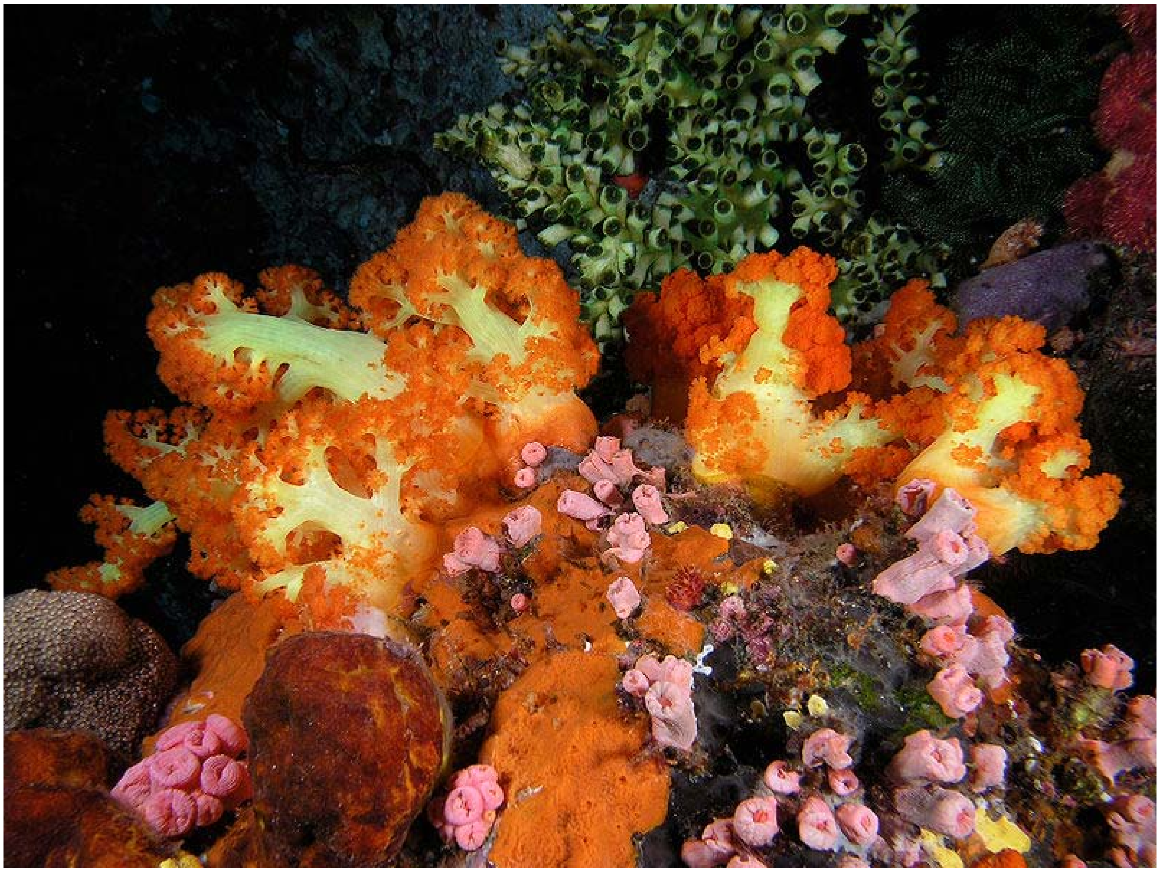
Banded coral shrimp



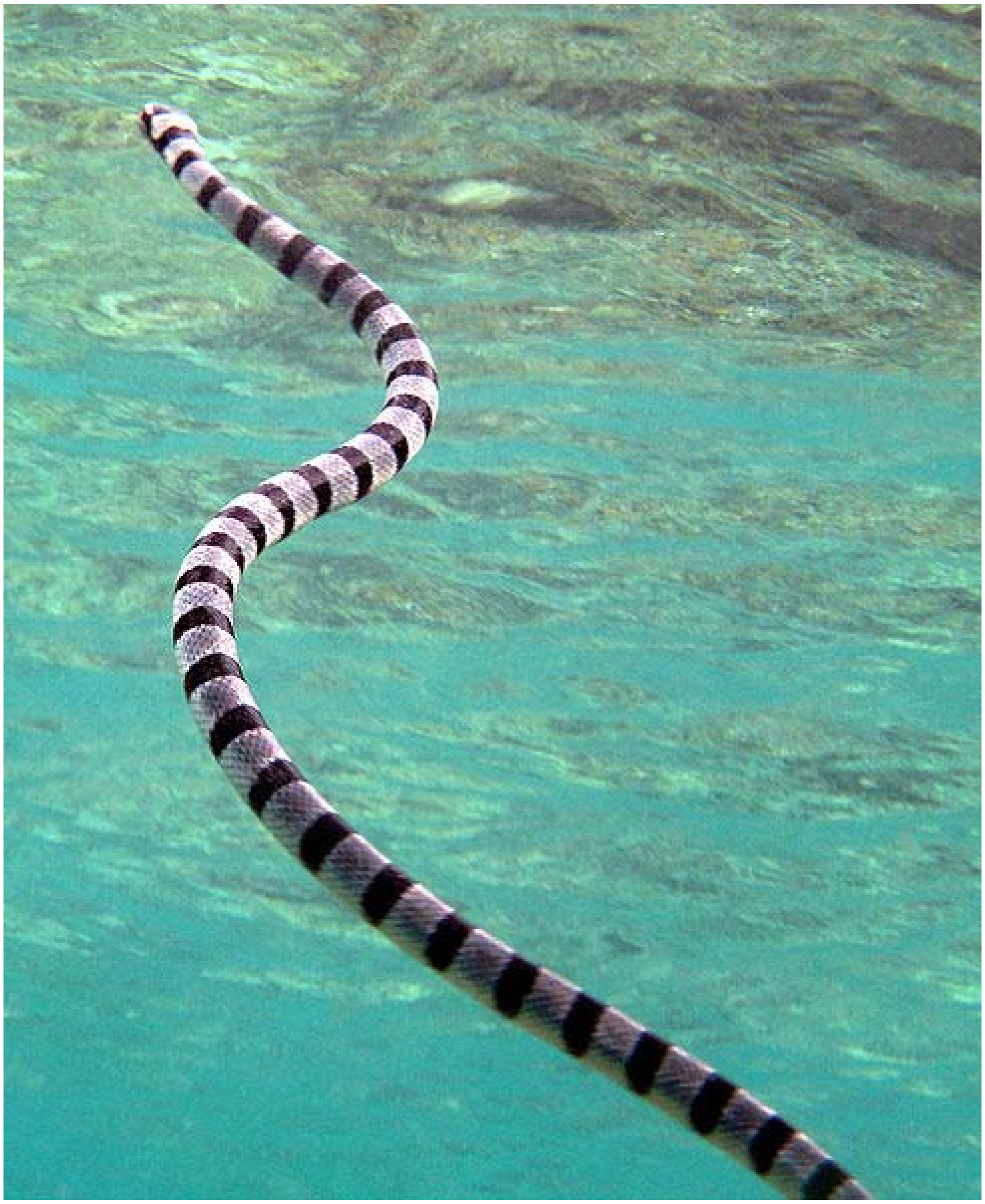
The whitetip reef shark almost exclusively inhabits coral reefs

Green turtle

Giant clam



Soft coral, cup coral, sponges and ascidians



Banded sea krait

Economic value

Coral reefs deliver ecosystem services to tourism, fisheries and coastline protection. The global economic value of coral reefs has been estimated at as much as $US375 billion per year. Coral reefs protect shorelines by absorbing wave energy, and many small islands would not exist without their reef to protect them. According to the WWF, the economic cost over a 25 year period of destroying one kilometre of coral reef is somewhere between $137,000 and $1,200,000. About 6 million tons of fish are taken each year from coral reefs. Well managed coral reefs have an annual yield of 15 tons seafood on average per square kilometre. Southeast Asia's coral reef fisheries alone yield about $ 2.4 billion annually from seafood.

To improve the management of coastal coral reefs the WRI (World Resource Institute) has been trying to retrieve reliable information on the actual value of services possible due to the existence of coral reefs. Currently they are working partners in five Caribbean countries and have come up with a detailed estimate of the value of coral reef related tourism, shoreline protection and fisheries. The WRI is also making sure that the study results actually support the improved coastal policies and management planning recently set up them. They have completed economic valuation in St. Lucia, Tobago, Belize, and the Dominican Republic and are now conducting an economic valuation in Jamaica. They have also created a excel-based program called the “Economic Valuation Tool” that helps guide users through step by step instructions of getting data, checking assumptions and coming up with appropriate results.

Threats

Island with fringing reef off Yap, Micronesia. Coral reefs are dying around the world.

Coral reefs are dying around the world. In particular, coral mining, agricultural and urban runoff, pollution (organic and non-organic), overfishing, blast fishing, disease, and the digging of canals and access into islands and bays are serious threats to these ecosystems. Broader threats are sea temperature rise, sea level rise and pH changes from ocean acidification, all associated with greenhouse gas emissions. In El Nino-year 2010, preliminary reports show global coral bleaching reached its worst level since another El Nino year, 1998, when 16 percent of the world's reefs died as a result of excessive water temperature. In Indonesia's Aceh province, surveys showed some 80 percent of bleached corals died. In July, Malaysia closed several dive sites after virtually all the corals In some areas were damaged by bleaching.

In order to find answers for these problems, researchers study the various factors that impact reefs. The list of factors is long, including the ocean's role as a carbon dioxide sink, atmospheric changes, ultraviolet light, ocean acidification, biological virus, impacts of dust storms carrying agents to far flung reefs, pollutants, algal blooms and others. Reefs are threatened well beyond coastal areas.

General estimates show approximately 10% world's coral reefs are already dead. About 60% of the world's reefs are at risk due to destructive, human-related activities. The threat to the health of reefs is particularly strong in Southeast Asia, where 80% of reefs are endangered.

Protection

A diversity of corals

Marine Protected Areas (MPAs) have become increasingly prominent for reef management. MPAs in Southeast Asia and elsewhere around the world attempt to promote responsible fishery management and habitat protection. Much like national parks and wildlife refuges, MPAs prohibit potentially damaging extraction activities. The objectives of MPAs are both social and biological, including reef restoration, aesthetics, increased and protected biodiversity, and economic benefits. Conflicts surrounding MPAs involve lack of participation, clashing views and perceptions of effectiveness, and funding.

Biosphere reserves are other protected areas that may protect reefs. Also, Marine parks, as well as world heritage sites can protect reefs. World heritage designation can also play a vital role. For example Belize's Barrier reef, Chagos archipelago, Sian Ka'an, the Galapagos islands, Great Barrier Reef, Henderson Island, Palau and Papahānaumokuākea Marine National Monument have been designated as world heritage sites.

In Australia, the Great Barrier Reef is protected by the Great Barrier Reef Marine Park Authority, and is the subject of much legislation, including a Biodiversity Action Plan.

Inhabitants of Ahus Island, Manus Province, Papua New Guinea, have followed a generations-old practice of restricting fishing in six areas of their reef lagoon. Their cultural traditions allow line fishing but not net and spear fishing. The result is that both the biomass and individual fish sizes are significantly larger in these areas than in places where fishing is unrestricted.

Organizations

Organizations which currently undertake coral reef/atoll restoration projects using simple methods of plant propagation:

- Coral Cay
- Counterpart
- U.S. Coral Reef Task Force (CRTF)
- National Coral Reef Institute (NCRI)
- US Department of Commerce's National Oceanic and Atmospheric Administration (NOAA): Coral Reef Conservation Program
- National Center for Coral Reef Research (NCORE)
- Reef Ball
- Southeast Florida Coral Reef Initiative (SEFCRI)
- Foundation of the peoples of the South Pacific
- WorldFishCenter: promotes sustainable mariculture techniques to grow reef organismsas tridacnidae
- Coral Restoration Foundation (CRF) : Adopt a Coral

Organizations which promote interest, provide knowledge bases about coral reef survival, and promote activities to protect and restore coral reefs:

- Australian Coral Reef Society
- Biosphere Foundation
- Chagos Conservation Trust
- Conservation Society of Pohnpei
- Coral Cay Conservation
- Coral Reef Care
- Coral Reef Alliance (CORAL)
- Coral Reef Targeted Research and Capacity Building for Management
- Coral Triangle Initiative

- Cousteau Society
- Crusoe Reef Society
- CEDAM International
- Earthwatch
- Environmental Defense Fund
- Environmental Solutions International
- Friends of Saba Marine Park
- Global Coral Reef Alliance (GCRA)
- Global Coral Reef Monitoring Network
- Great Barrier Reef Marine Park Authority
- Green Fins
- ICRAN Mesoamerican Reef Alliance
- International Coral Reef Initiative (ICRI)
- International Marinelife Alliance
- International Society for Reef Studies
- Intercoast Network
- Kosrae Conservation and Safety Organization
- Marine Conservation Group
- Marine Conservation Society
- Mesoamerican Reef Tourism Initiative (MARTI)
- NSF Moorea Coral Reef Long-term Ecological Research site
- Nature Conservancy
- Ocean Voice International
- PADI
- Planetary Coral Reef Foundation
- Practical Action
- Project Reefkeeper
- ReefBase
- Reef Check
- Reef Relief
- Reefwatch
- Save Our Seas Foundation
- Seacology
- SECORE
- Singapore Underwater Federation
- Society for Andaman and Nicobar Ecology
- Tubbataha Foundation
- Wildlife Conservation International
- WWF

Artificial reefs

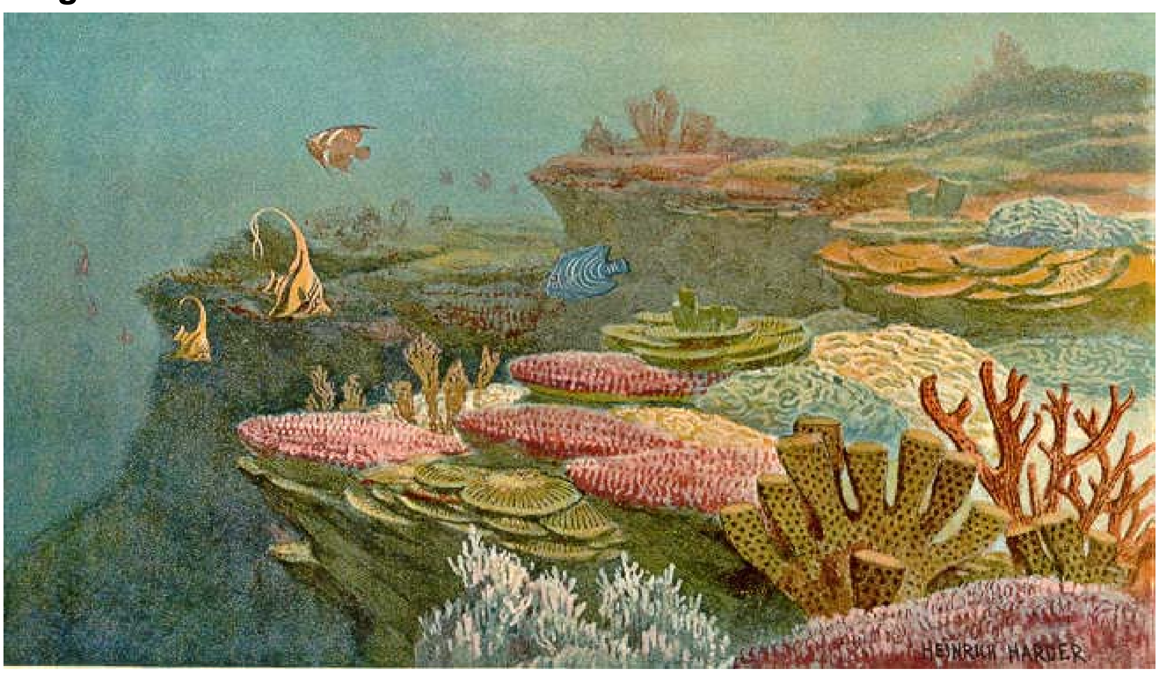
Efforts to expand the size and number of coral reefs generally involve supplying substrate to allow more corals to find a home. Substrate materials include discarded vehicle tires, scuttled ships, subway cars, and formed concrete such as reef balls. Reefs also grow unaided on marine structures such as oil rigs.

In large restoration projects, propagated hermatypic coral on substrate can be secured with metal pins, superglue or milliput. Needle and thread can also attach A-hermatype coral to substrate.

Low voltage electrical currents applied through seawater crystallize dissolved minerals onto steel structures. The resultant white carbonate (aragonite) is the same mineral that makes up natural coral reefs. Corals rapidly colonize and grow at accelerated rates on these coated structures. The electrical currents also accelerate formation and growth of both chemical limestone rock and the skeletons of corals and other shell-bearing organisms. The vicinity of the anode and cathode provides a high pH environment which inhibits the growth of competitive filamentous and fleshy algae. The increased growth rates fully depend on the accretion activity.

During accretion, the settled corals display an increased growth rate, and size, and density, but after the process is complete, growth rate and density return to levels that are comparable to naturally growing corallites, and are about the same size or slightly smaller.

Origins



Ancient coral reefs

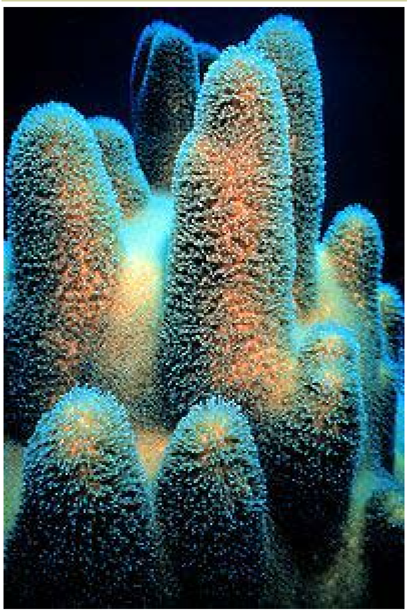
Beginning a few thousand years after hard skeletons were developed by marine organisms, coral reefs emerged. The times of maximum development were in the Middle Cambrian (513–501 Ma), Devonian (416–359 Ma) and Carboniferous (359–299 Ma), due to Order Rugosa extinct corals, and Late Cretaceous (100–65 Ma) and all Neogene (23 Ma–present), due to Order Scleractinia corals.

Not all reefs in the past were formed by corals: Early Cambrian (542–513 Ma) reefs resulted from calcareous algae and archaeocyathids (small animals with conical shape, probably related to sponges) and rudists, a type of bivalve, built Late Cretaceous (100–65 Ma) reefs.

Chapter- 2

Coral

Coral	



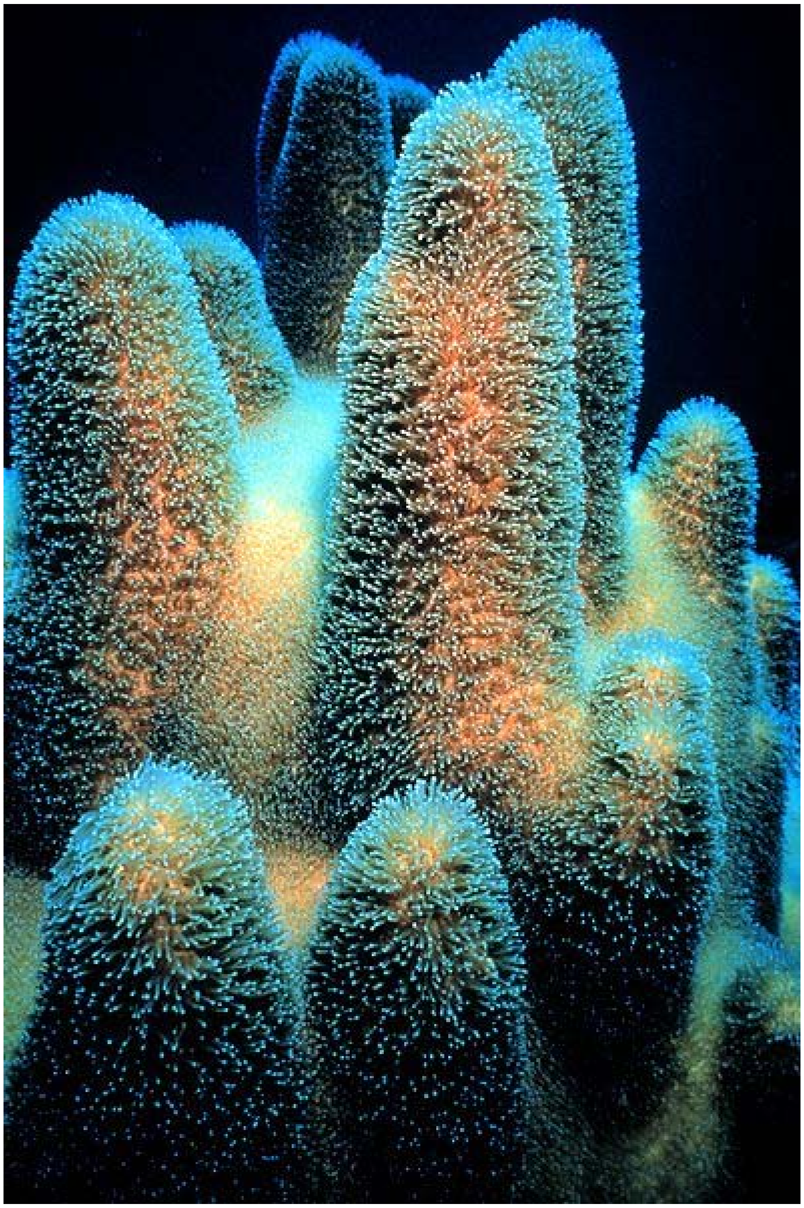
Pillar coral, *Dendrogyra cylindricus*

Scientific classification	
Kingdom:	Animalia
Phylum:	Cnidaria
Class:	Anthozoa Ehrenberg, 1831

Extant Subclasses and Orders

Alcyonaria
  Alcyonacea
  Helioporacea
Zoantharia

Antipatharia
Corallimorpharia
Scleractinia
Zoanthidea



Corals are marine organisms in class Anthozoa of phylum Cnidaria typically living in compact colonies of many identical individual "polyps." The group includes the important reef builders that inhabit tropical oceans, which secrete calcium carbonate to form a hard skeleton.

A coral "head," which appears to be a single organism, is a colony of myriad genetically identical polyps. Each polyp is typically only a few millimeters in diameter. Over many generations the colony secretes a skeleton that is characteristic of the species. Individual heads grow by asexual reproduction of individual polyps. Corals also breed sexually by spawning. Polyps of the same species release gametes simultaneously over a period of one to several nights around a full moon.

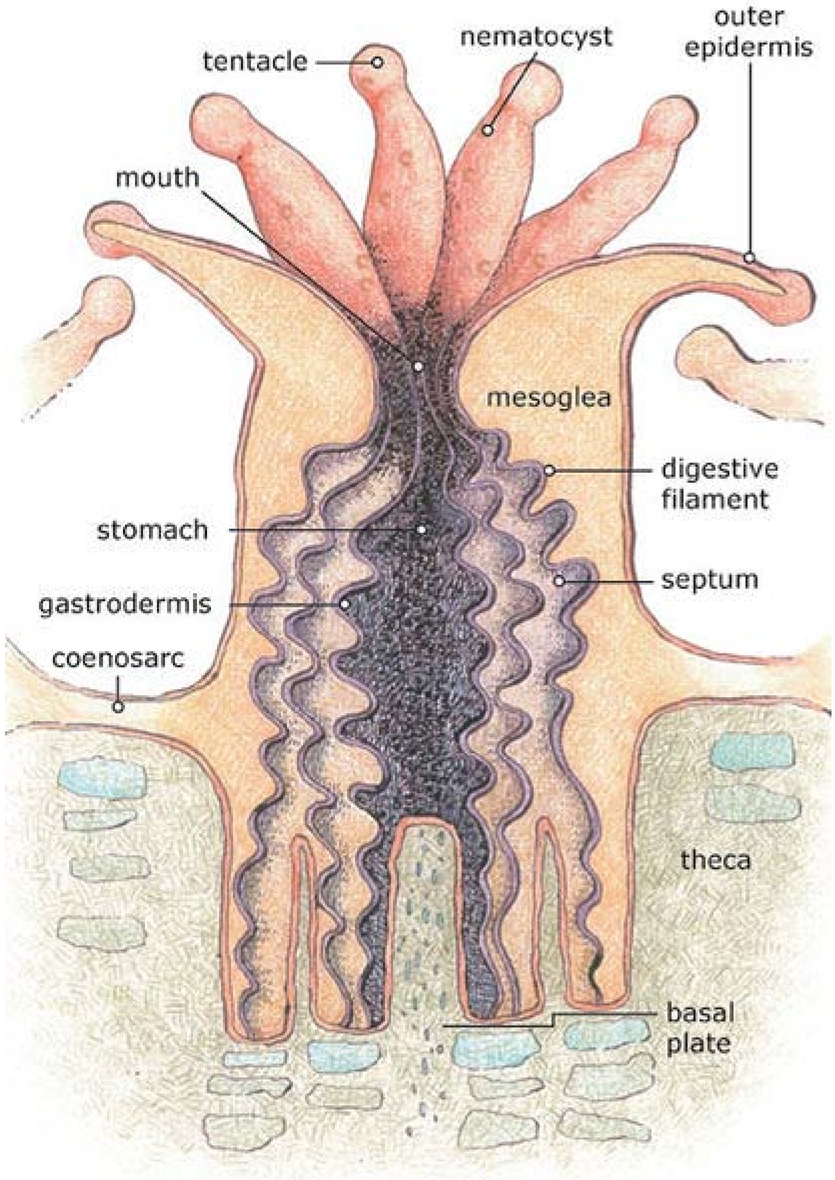
Although corals can catch small fish and animals such as plankton using stinging cells on their tentacles, most corals obtain the majority of their energy and nutrients from photosynthetic unicellular algae called zooxanthellae. Such corals require sunlight and grow in clear, shallow water, typically at depths shallower than 60 metres (200 ft). Corals can be major contributors to the physical structure of the coral reefs that develop in tropical and subtropical waters, such as the enormous Great Barrier Reef off the coast of Queensland, Australia. Other corals do not have associated algae and can live in much deeper water, with the cold-water genus *Lophelia* surviving as deep as 3,000 metres (9,800 ft). Examples live on the Darwin Mounds located north-west of Cape Wrath, Scotland. Corals have also been found off the coast of the U.S. in Washington state and the Aleutian Islands in Alaska.

Taxonomy

A Short Tentacle Plate coral in Papua New Guinea

Corals divide into two subclasses, depending on the number of tentacles or lines of symmetry, and a series of orders corresponding to their exoskeleton, nematocyst type and mitochondrial genetic analysis. Those with eight tentacles are called octocorallia or Alcyonaria and comprise soft corals, sea fans and sea pens. Those with more than eight in a multiple of six are called hexacorallia or Zoantharia. This group includes reef-building corals (Scleractinians), sea anemones and zoanthids.

Anatomy



Anatomy of a coral polyp

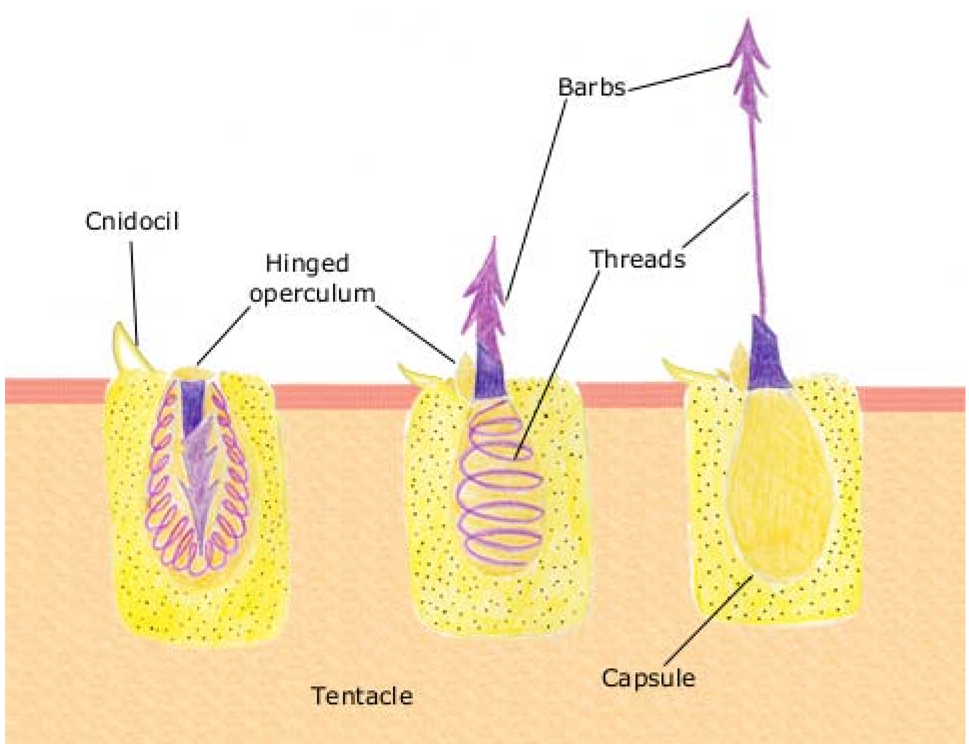
Initially believed to be a plant, William Herschel used a microscope to establish in the 18th Century that Coral had the characteristic thin cell membranes of an animal.

While a coral head appears to be a single organism, it is actually a group of many individual, yet genetically identical, polyps. The polyps are multicellular organisms. Polyps are usually a few millimeters in diameter, and are formed by a layer of outer epithelium and inner jellylike tissue known as the mesoglea. They are radially symmetrical with tentacles surrounding a central mouth, the only opening to the stomach or coelenteron, through which food is ingested and waste expelled.

The stomach closes at the base of the polyp, where the epithelium produces an exoskeleton called the basal plate or calicle (L. small cup). The calicle is formed by a thickened calcareous ring (annular thickening) with six supporting radial ridges (as shown below). These structures grow vertically and project into the base of the polyp. When a polyp is physically stressed, its tentacles contract into the calyx so that virtually no part is exposed above the skeletal platform. This protects the organism from predators and the elements.

The polyp grows by extension of vertical calices which occasionally septate to form a new, higher, basal plate. Over many generations this extension forms the large calcareous structures of corals and ultimately coral reefs.

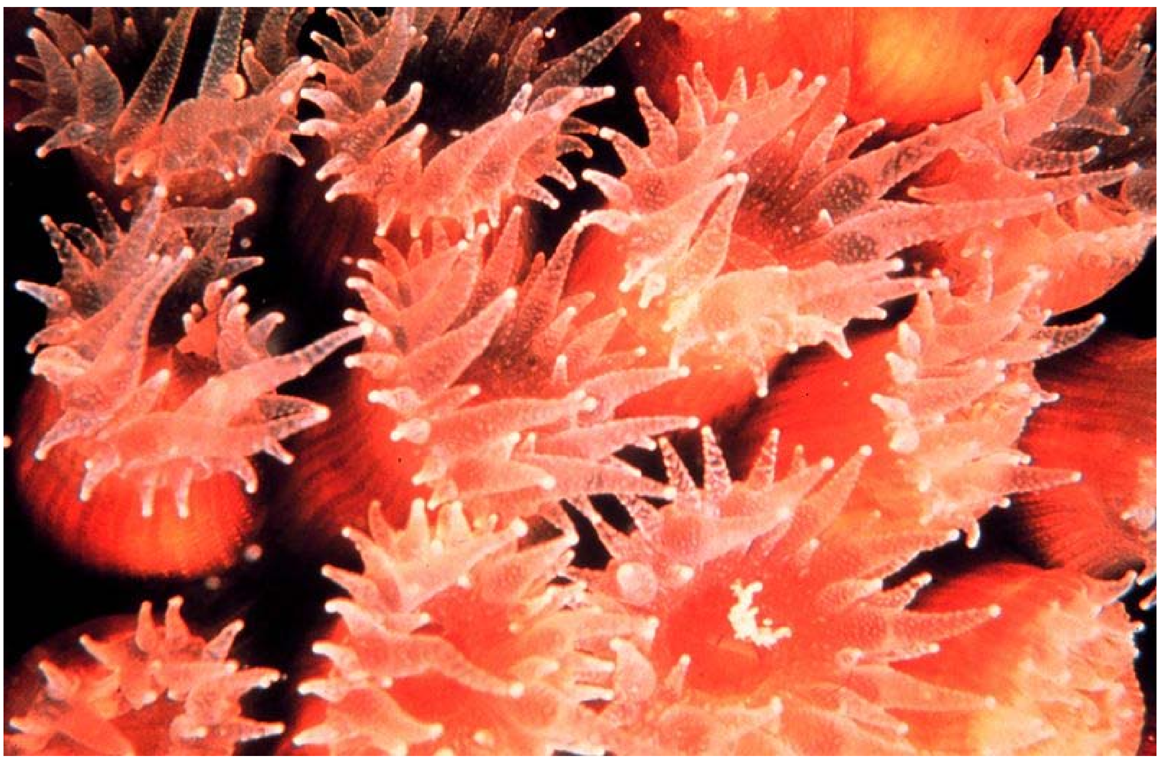
Formation of the calcareous exoskeleton involves deposition of the mineral aragonite by the polyps from calcium and carbonate ions they acquire from seawater. The rate of deposition, while varying greatly across species and environmental conditions, can be as much as 10 g / m² of polyp / day (0.3 ounce / sq yd / day). This is light dependent, with night-time production 90% lower than that during the middle of the day.



Nematocyst discharge: A dormant nematocyst discharges response to nearby prey touching the cnidocil, the operculum flap opens and its stinging apparatus fires the barb into the prey leaving a hollow filament through which poisons are injected to immobilise the prey, then the tentacles manoeuvre the prey to the mouth.

Nematocysts are stinging cells at the tips of the calices that carry poison which they rapidly release in response to contact with another organism. The tentacles also bear a contractile band of epithelium called the pharynx. Jellyfish and sea anemones also carry nematocysts.

The polyps interconnect by a complex and well developed system of gastrovascular canals allowing significant sharing of nutrients and symbiotes. In soft corals these range in size from 50–500 micrometres (0.0020–0.020 in) in diameter and allow transport of both metabolites and cellular components.



Close-up of *Montastrea cavernosa* polyps. Tentacles are clearly visible.

Many corals as well as other cnidarian groups such as sea anemones (e.g. Aiptasia), form a symbiotic relationship with a class of algae, zooxanthellae, of the genus *Symbiodinium*. Aiptasia, while considered a pest among coral reef aquarium hobbyists, serves as a valuable model organism in the study of cnidarian-algal symbiosis. Typically a polyp harbors one species of algae. Via photosynthesis, these provide energy for the coral, and aid in calcification. The algae benefit from a safe environment, and consume the carbon dioxide and nitrogenous waste produced by the polyp. Due to the strain the algae can put on the polyp, stress on the coral often drives the coral to eject the algae. Mass ejections are known as coral bleaching, because the algae contribute to coral's brown coloration; other colors, however, are due to host coral pigments, such as GFPs (green fluorescent protein). Ejection increases the polyp's chances of surviving short-term stress—they can regain algae at a later time. If the stressful conditions persist, the polyp eventually dies.

Feeding

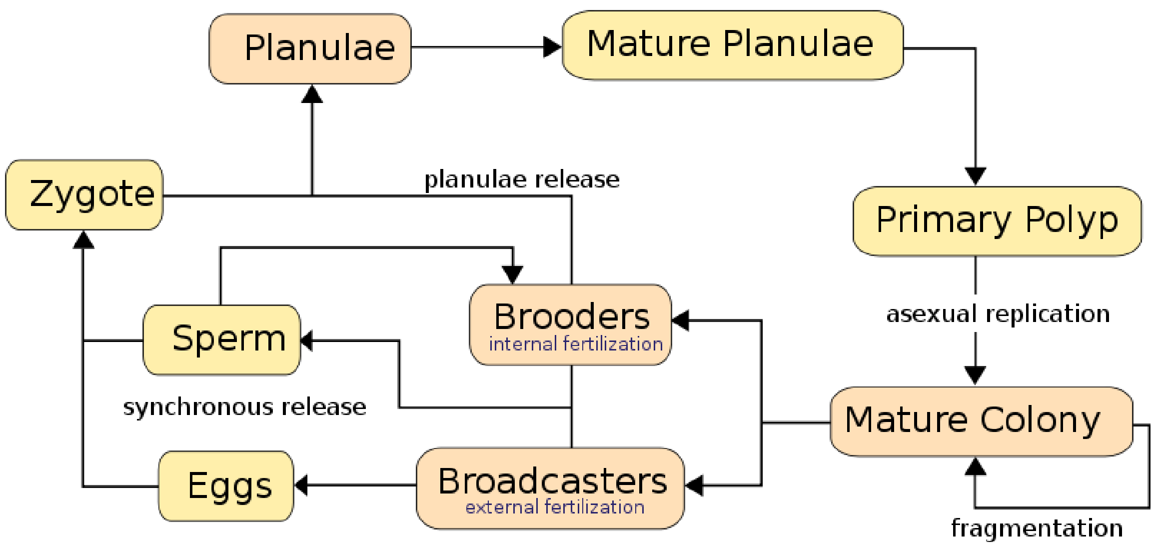
Polyps feed on a variety of small organisms, from microscopic plankton to small fish. The polyp's tentacles immobilize or kill prey using their nematocysts. The tentacles then contract to bring the prey into the stomach. Once digested, the stomach reopens, allowing the elimination of waste products and the beginning of the next hunting cycle.

These poisons are usually too weak to harm humans. An exception is fire coral.

Reproduction

Corals can be both gonochoristic (unisexual) and hermaphroditic, each of which can reproduce sexually and asexually. Reproduction also allows coral to settle new areas.

Sexual



Life cycles of broadcasters and brooders.

Corals predominantly reproduce sexually. 25% of hermatypic corals (stony corals) form single sex (gonochoristic) colonies, while the rest are hermaphroditic. About 75% of all hermatypic corals "broadcast spawn" by releasing gametes—eggs and sperm—into the water to spread offspring. The gametes fuse during fertilization to form a microscopic larva called a planula, typically pink and elliptical in shape. A typical coral colony form several thousand larvae per year to overcome the odds against formation of a new colony.

Planulae exhibits positive *phototaxis*, swimming towards light to reach surface waters where they drift and grow before descending to seek a hard surface to which it can attach and establish a new colony. They also exhibit positive *sonotaxis*, moving towards sounds that emanate from the reef and away from open water. High failure rates afflict many stages of this process, and even though millions of gametes are released by each colony very few new colonies form. The time from spawning to settling is usually 2–3 days, but can be up to 2 months. The larva grows into a polyp and eventually becomes a coral head by asexual budding and growth.

A male star coral, *Montastraea cavernosa*, releases sperm into the water.

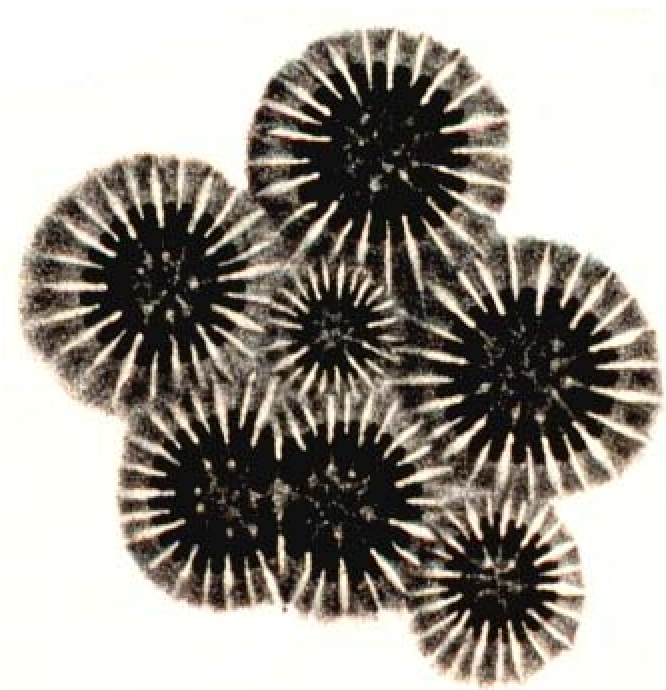
Synchronous spawning is very typical on the coral reef and often, even when multiple species are present, all corals spawn on the same night. This synchrony is essential so that male and female gametes can meet. Corals must rely on environmental cues, varying from species to species, to determine the proper time to release gametes into the water. The cues involve lunar changes, sunset time, and possibly chemical signalling. Synchronous spawning may form hybrids and is perhaps involved in coral speciation. In some places the spawn can be visually dramatic, clouding the usually clear water with gametes, typically at night.

Corals use two methods for sexual reproduction, which differ in whether the female gametes are released:

- **Broadcasters**, the majority of which mass spawn, rely heavily on environmental cues, because they release both sperm and eggs into the water. The corals use long-term cues such as day length, water temperature, and/or rate of temperature change. The short-term cue is most often the lunar cycle, with sunset cuing the release. About 75% of coral species are broadcasters, the majority of which are hermatypic, or reef-building corals. The positively buoyant gametes float towards the surface where fertilization produces planula larvae. The larvae swim towards the surface light to enter into currents, where they remain usually for two days, but can be up to three weeks, and in one known case two months, after which they settle and metamorphose into polyps and form colonies.

- **Brooders** are most often ahermatypic (non-reef building) in areas of high current or wave action. Brooders release only sperm, which is negatively buoyant, and can harbor unfertilized eggs for weeks, lowering the need for mass synchronous spawning events, which do sometimes occur. After fertilization the corals release planula larvae which are ready to settle.

Asexual



Calices (basal plates) of *Orbicella annularis* showing multiplication by gemmation (small central calice) and division (large double calice).

The tabulate coral *Aulopora* (Devonian) showing initial budding from protocorallite.

Within a coral head the genetically identical polyps reproduce asexually, either via gemmation (budding) or division, both shown in the photo of *Orbicella annularis*. Budding involves a new polyp growing from an adult, whereas division forms two polyps each as large as the original.

- **Budding** expands colony size. It occurs when a new corallite grows out from an adult polyp. As the new polyp grows it produces its body parts. The distance between the new and adult polyps grows, and with it the coenosarc. Budding can be:
    - **Intra-tentacular**—from its oral discs, producing same-sized polyps within the ring of tentacles.
    - **Extra-tentacular**—from its base, producing a smaller polyp.

- **Longitudinal division** begins when a polyp broadens and then divides its coelenteron. The mouth also divides and new tentacles form. The two "new" polyps then generate their missing body parts and exoskeleton.
- **Transversal division** occurs when polyps and the exoskeleton divide transversally into two parts. This means that one has the basal disc (bottom) and the other has the oral disc (top). The two new polyps must again generate the missing pieces.

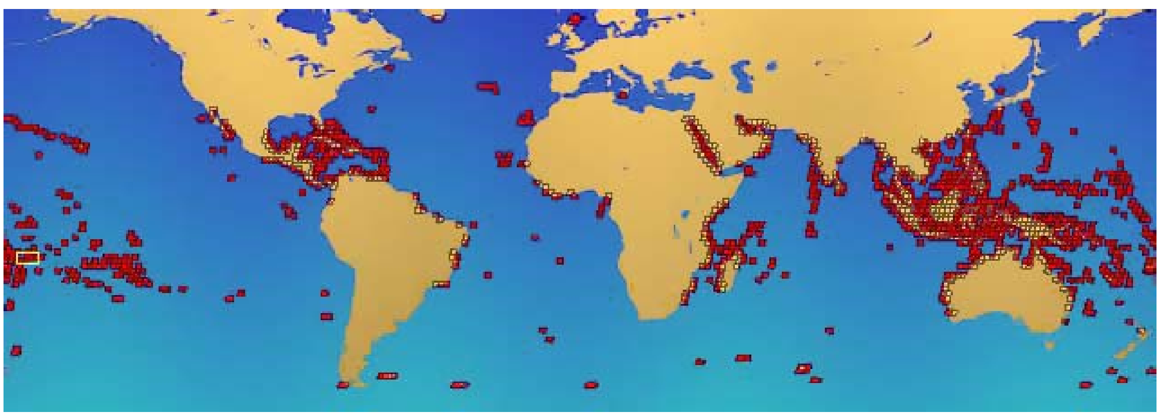
Colony division

- **Fission** occurs in some corals, especially among the family Fungiidae, where the colony splits into two or more colonies during early developmental stages.

Whole colonies can reproduce asexually through fragmentation or bailout, forming another individual colony with the same genotype.

- **Bailout** occurs when a single polyp abandons the colony and settles on a different substrate to create a new colony.
- **Fragmentation**, involves individuals broken from the colony during storms or other situations. The separated individuals can start new colonies.

Reefs



Locations of coral reefs

The hermatypic, stony corals are often found in coral reefs, large calcium carbonate structures generally found in shallow, tropical water. Reefs are built up from coral skeletons and held together by layers of calcium carbonate produced by coralline algae. Reefs are extremely diverse marine ecosystems hosting over 4,000 species of fish, massive numbers of cnidarians, mollusks, crustaceans, and many other animals.

Types

Perforate corals

Corals can be perforate or imperforate. Perforate corals have porous skeletons, which allows their polyps to connect with each other through the skeleton. Imperforate corals have hard solid skeletons.

Hermatypic corals

Hermatypic or stony corals build reefs. With the help of zooxanthellae, they convert surplus food to calcium carbonate forming a hard skeleton. Hermatypic species include Scleractinia, Millepora, Tubipora and Heliopora.

In the Caribbean alone 50 species of uniquely structured hard coral exist. Well known types include:

- Brain coral grow to 1.8 meters (6 ft) in width.
- Acropora and Staghorn coral grow fast and large and are important reef-builders. Staghorn coral displays large antler-like branches and grows in areas with strong surf.
- Galaxea fascicularis or star coral is another important reef-builder.
- Pillar coral forms pillars which can grow to 3 meters (10 ft) in height.
- Leptopsommia or rock coral, appears almost everywhere in the Caribbean.

Ahermatypic corals

Ahermatypic corals have no zooxanthellae and do not build reefs. They include Alcyonaceas, as well as some Anthipatharia-species (Black coral, Cirripathes, Antipathes). Ahermatypic corals such as sea whips, sea feathers, and sea pens are also known as soft corals. Unlike stony corals, they are flexible, undulating back and forth in the current, and often are perforated, with a lacy appearance. Their skeletons are proteinaceous, rather than calcareous. Soft corals are somewhat less plentiful (in the Caribbean, twenty species appear) than stony corals.

Evolutionary history

Solitary rugose coral (*Grewingkia*) in three views; Ordovician, southeastern Indiana.

Although corals first appeared in the Cambrian period, some 542 million years ago, fossils are extremely rare until the Ordovician period, 100 million years later, when Rugose and Tabulate corals became widespread.

Tabulate corals occur in the limestones and calcareous shales of the Ordovician and Silurian periods, and often form low cushions or branching masses alongside Rugose corals. Their numbers began to decline during the middle of the Silurian period and they finally became extinct at the end of the Permian period, 250 million years ago. The skeletons of Tabulate corals are composed of a form of calcium carbonate known as calcite.

Rugose corals became dominant by the middle of the Silurian period, and became extinct early in the Triassic period. The Rugose corals existed in solitary and colonial forms, and are also composed of calcite.

The Scleractinian corals filled the niche vacated by the extinct Rugose and Tabulate species. Their fossils may be found in small numbers in rocks from the Triassic period, and become common in the Jurassic and later periods. Scleractinian skeletons are composed of a form of calcium carbonate known as aragonite. Although they are geologically younger than the Tabulate and Rugose corals, their aragonitic skeleton is less readily preserved, and their fossil record is less complete.

At certain times in the geological past corals were very abundant. Like modern corals, these ancestors built reefs, some of which now lie as great structures in sedimentary rocks.

Fossils of fellow reef-dwellers algae, sponges, and the remains of many echinoids, brachiopods, bivalves, gastropods, and trilobites appear along with coral fossils. This makes some corals useful index fossils, enabling geologists to date the age the rocks in which they are found.

Coral fossils are not restricted to reef remnants, and many solitary corals may be found elsewhere, such as *Cyclocyathus*, which occurs in England's Gault clay formation.

A Petoskey stone is a rock and a fossil, often pebble-shaped, that is composed of a fossilized coral, Hexagonaria percarinata. They are found predominantly in Michigan's Upper Peninsula, and the northwestern portion of Michigan's lower peninsula.

Threats

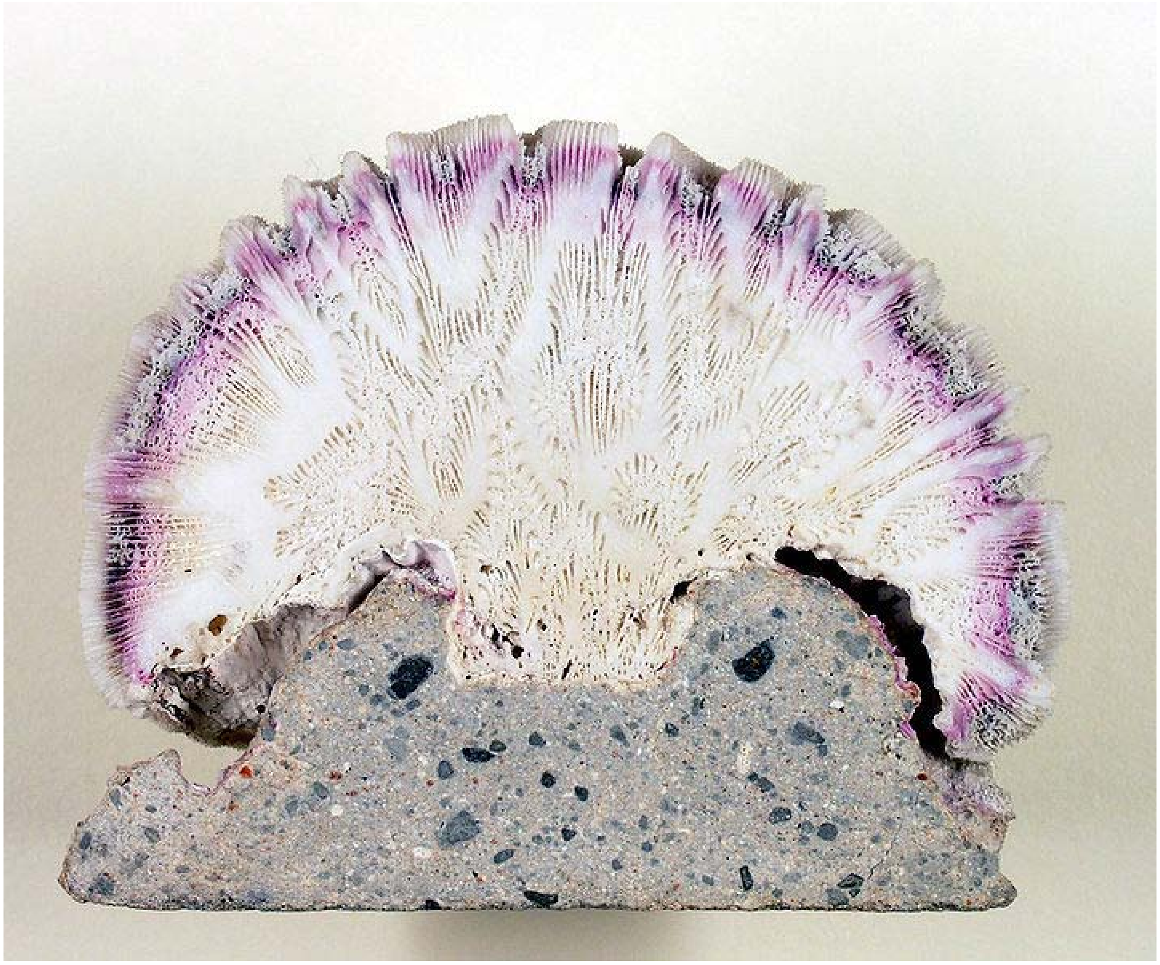
A healthy coral reef has a striking level of biodiversity in many forms of marine life.

Corals are highly sensitive to environmental changes. Scientists have predicted that over 50% of the world's coral reefs may be destroyed by 2030; as a result most nations protect them through environmental laws.

Seaweed/Algae can destroy a coral reef. In the Caribbean and tropical Pacific, direct contact between ~40 to 70% of common seaweeds and coral cause bleaching and death to the coral via transfer of lipid–soluble metabolites. Seaweed and algae proliferate given adequate nutrients and limited grazing by herbivores. Coral die if surrounding water temperature changes by more than a degree or two beyond their normal range or if water salinity drops. In an early symptom of environmental stress, corals expel their zooxanthellae; without their symbiotic algae, coral tissues become colorless as they reveal the white of their calcium carbonate skeletons, an event known as coral bleaching.

Many governments now prohibit removal of coral from reefs and use education to inform their populations about reef protection and ecology. However, many other human activities damage reefs, including runoff, mooring, fishing, diving, mining and construction.

Coral's narrow niche and the stony corals' reliance on calcium carbonate deposition makes them susceptible to changes in water pH. The increase in atmospheric carbon dioxide has caused enough dissolution of carbon dioxide to lower the ocean's pH, in a process known as ocean acidification. Lowered pH reduces corals' ability to produce calcium carbonate, and at the extreme, can dissolve their skeletons. Without deep and immediate cuts in anthropogenic CO_2, many scientists fear that acidification will severely degrade or destroy coral ecosystems.



A section through a coral, dyed to determine growth rate

Importance to humans

Local economies near major coral reefs benefit from an abundance of fish and other marine creatures as a food source. Reefs also provide recreational scuba diving and snorkeling tourism. Unfortunately these activities can have deleterious effects, such as accidental destruction of coral. Coral is also useful as a protection against hurricanes and other extreme weather.

Coral reefs provide medical benefits for humans. Chemical compounds taken from corals are used in medicine for cancer, AIDS, pain, and other uses. Corals are also commonly used for bone grafting in humans.

Live coral is highly sought after for aquaria. Given the proper ecosystem, live coral makes a stunning addition to any salt water aquarium. Soft corals are easier to maintain in captivity than hard corals.

Isididae may be usable as living bone implants and in aquatic cultivation, because of their potential to mimic valuable biological properties.

In jewelry

Coral's many colors give it appeal for necklaces and other jewelry. Intensely red coral is prized as a gemstone. It is sometimes called fire coral, but is not the same as fire coral. Red coral is very rare because of overharvesting due to the great demand for perfect specimens.

In construction

Tabulate coral (a syringoporid); Boone Limestone (Lower Carboniferous) near Hiwasse, Arkansas. Scale bar is 2.0 cm.

Ancient coral reefs on land provide lime or use as building blocks ("coral rag"). Coral rag is an important local building material in places such as the East African coast.

In climate research

The annual growth bands in bamboo corals and others allow geologists to construct year-by-year chronologies, a form of incremental dating, which underlie high-resolution records of past climatic and environmental changes using geochemical techniques.

Certain species form communities called microatolls, which are colonies whose top is dead and mostly above the water line, but whose perimeter is mostly submerged and alive. Average tide level limits their height. By analyzing the various growth morphologies, microatolls offer a low resolution record of sea level change. Fossilized microatolls can also be dated using radioactive carbon dating. Such methods can help to reconstruct Holocene sea levels.

Deep sea bamboo corals (*Isididae*) may be among the first organisms to display the effects of ocean acidification. They produce growth rings similar to those of tree and can provide a view of changes in the condition in the deep sea over time.

Chapter- 3

Fringing Reef

Fringing reef off the coast of Eilat, Israel.

A **Fringing reef** is one of the three main types of coral reefs recognized by most coral reef scientists. It is distinguished from the other two main types (barrier reefs and atolls) in that has either an entirely shallow backreef zone (lagoon) or none at all. If a fringing reef grows directly from the shoreline the reef flat extends right to the beach and there is no backreef. In other cases (e.g., most of The Bahamas), fringing reefs may grow hundreds of yards from shore and contain extensive backreef areas with numerous seagrass meadows and patch reefs.

This type of coral reef is the most common type of reef found in the Caribbean and Red Sea. It is Darwin's belief that fringing reefs are the first kind of reefs to form around a landmass in a long-term reef growth process.

Barrier reef

Sometimes it is hard to tell the difference between fringing reefs and another type of reef called a **barrier reef**. One of the ways that these two types of reefs are separated is based on the depth of the lagoon in the back reef which is the area near to shore. Barrier reefs have at least some deep portions; fringing reefs do not. Another major difference is that barrier reefs tend to be much farther away from shore than fringing reefs.

Structure

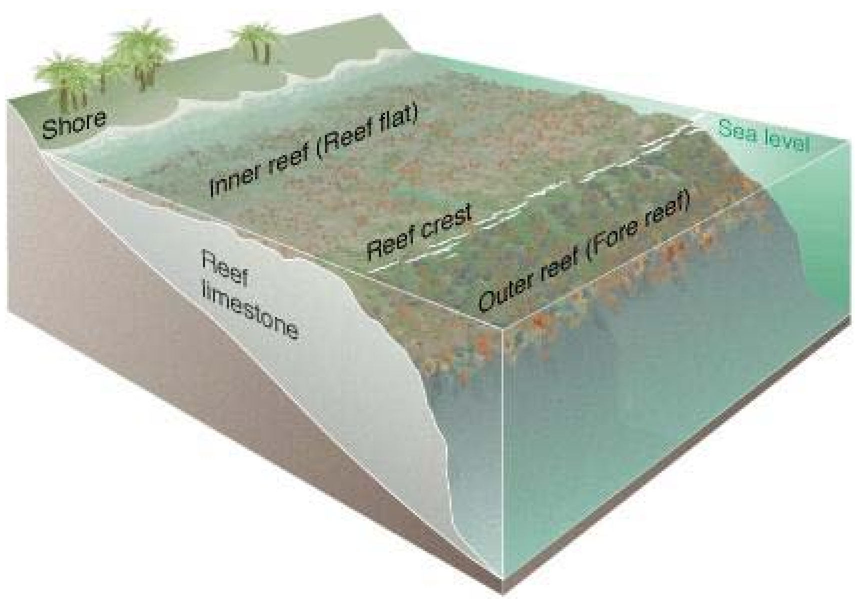


Diagram of a fringing coral reef.

There are two main components that make up a fringing reef, the reef flat and the reef slope.

Reef flat

The reef flat is the shoreward, flat, broadest area of the reef. The reef flat is found in fairly shallow water, and can be uncovered during low tide. This area of the reef is only slightly sloped towards the open ocean.

Since the reef flat is adjacent or nearly adjacent to land, it sustains the most damage from runoff and sediments. Typically, few of the flat's corals are alive. Seagrasses, seaweeds, and soft corals are often found there.

Reef slope (Fore reef)

The reef slope is found at the outer edge of the fringing reef, closest to the open ocean. This area of the reef is often quite steep and descends either to a relatively shallow sand bottom or to depths too great to allow coral growth.

Coral grows much more abundantly on this slope, both in numbers and in species diversity. This is mostly because runoff and sediments are less concentrated here. Greater wave action disperses pollutants and carries nutrients to this area.

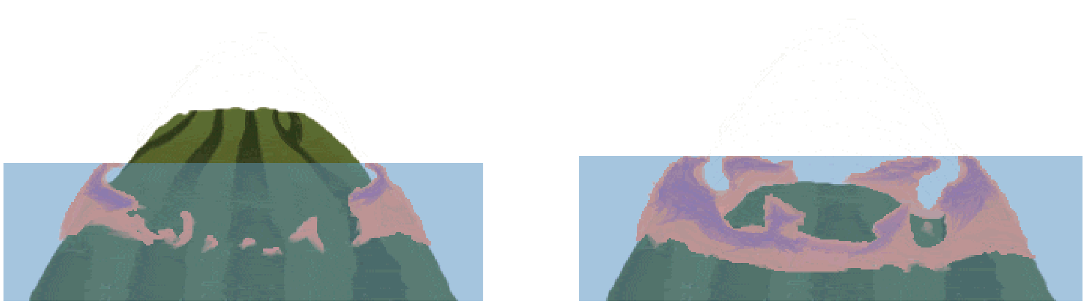
The upper portion of this slope is called the reef crest. The crest has the best balance between sunlight and waves, so coral grows fastest here. The base of the slope receives the least sunlight and has the least growth out of the whole slope!

Location of fringing reefs

Fringing reefs are located near shore in the tropics in many areas and are the most common reef type. Coral reefs are found in the tropics in which the water is between 18°C and 30°C.

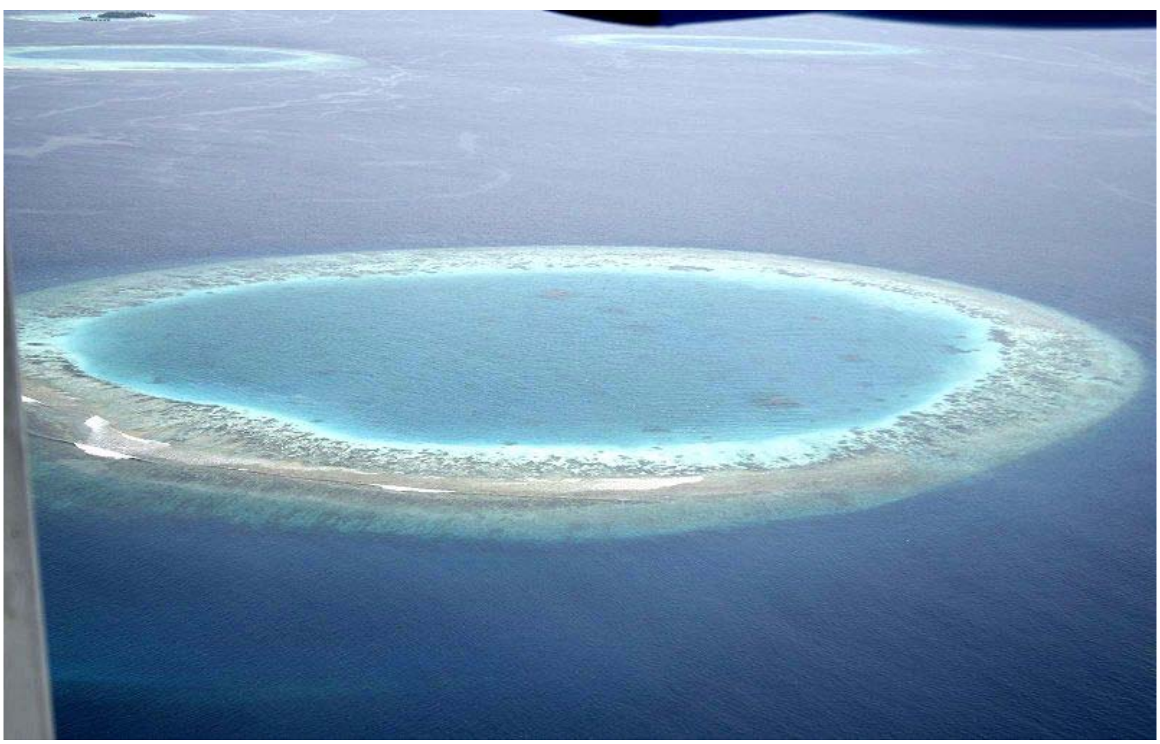
Many of the Great Barrier Reef's components are actually fringing reefs. Of the close to 3400 individual reefs, 760 are actually fringing reefs.

Reefs growth



This shows the dynamic process of coral atoll formation. Corals (represented in tan and purple) settle and grow around an oceanic island, forming a fringing reef. In favorable conditions, the reef expands, and the interior island subsides. Eventually the island completely subsides beneath the water, leaving a ring of growing coral with an open lagoon in its center. The process of atoll formation may take as long as 30,000,000.

Island with fringing reef in the Maldives



Reefs in the Maldives

Keep-up: These reefs grow at the same rate that sea level rises.

Catch-up: These reefs initially grow more slowly than sea level rises, but eventually catch up when the rise in sea level slows or stops.

Give-up: These reefs are not able to grow fast enough and are "drowned out".

Reef development

The most important determinant of reef growth is available space as determined by sea level changes. Sea level changes are mostly due to glaciation or plate tectonics. There are six different major ways in which fringing reefs grow and develop.

- Reefs can develop vertically as far as the space below the surface allows. The reef generally grows upward from a starting point towards the surface. Once the reef crest reaches sea level the reef may begin growing seaward. Growth begins after flooding, mostly from parts of the reef that have died. Because the reef grows upward, the oldest sediments are found lower in the reef. The reef flat's age indicates when the reef reached sea level. Catch-up reefs have younger surfaces than keep-up reefs of this type.
- Reefs can expand seaward from the shore. This requires a fairly constant sea level. If the sea level drops, the reef flat in more seaward areas slopes downward.
- Reefs can grow atop muddy sediments which can predate the reef or accrete along with the reef's growth. These reefs also grow seaward from the shore. Older sediments are closest to shore and are not buried. Coral, seagrass and algae filter sediment before it is placed on the reef crest.
- Reefs can form in a gradual, sporadic manner, with alternate vertical and horizontal growth episodes. In this type of fringing reef formation there are multiple separate reefs that are found parallel to the shore and the original fringing reef. These reefs become a single, large reef when reef sediments fill in the spaces between the different reefs.
- Reefs can develop when an offshore reef grows to sea level forming a barrier. When the crest grows faster than the flat, a lagoon forms. The lagoon then fills with inshore sediments.
- Offshore reefs can form their barrier using storms to move coral and other debris inwards. The recurring storms continually reshape the seaward side of such reefs.

Effect of tectonic activity

Tectonic activity can have very detrimental effects. An earthquake on Ranongga Island in the Solomon Islands moved 80% of its fringing reef permanently above sea level. Northern reefs became elevated 1m above the high tide water height, whereas on the south side reefs moved 2 to 3m above the water height.

Species diversity

The backreef area has the least species diversity, which increases seaward towards the reef crest. Some of this difference is due to eutrophication from increased nutrients, sediments and toxicity due to domestic and industrial wastes.

More macrophytes live on the bottom due to the increases in nutrients. They also feel that this increase in nutrients has caused an increase in the number of phytoplankton that are present above the coral reef. The increase in phytoplankton has led to reduced light reaching the coral species and has also led to a greater number of larger invertebrates to be found.

The sediments that are present within the environment cause increased turbidity and may smother some organisms. The corals present on the fringing reefs use four processes to get rid of sediments which include polyp distension, tentacular movement, ciliary action and mucus production. The corals that are present then are thus likely those that can get rid of the sediments the best.

Brooding corals have higher growth and reproduction rates than others.

In the area of the reef closest to the shore there is generally a lot of fleshy algae which forms on sand and coral rubble. These types of algae include 'Lyngbia' sp. and 'Oscilatoria' sp.

Over recent years the dominant species in the reef flat have been affected by environmental changes. On fringing reefs in Barbados, species such as 'Diploria strigosa', 'Palythoa mamillosa', and 'Diadema antillarum' are found.

The reef crest's most common species is 'Porites porites', although there are also significant areas covered in fleshy algae too.

Chapter- 4

Atoll

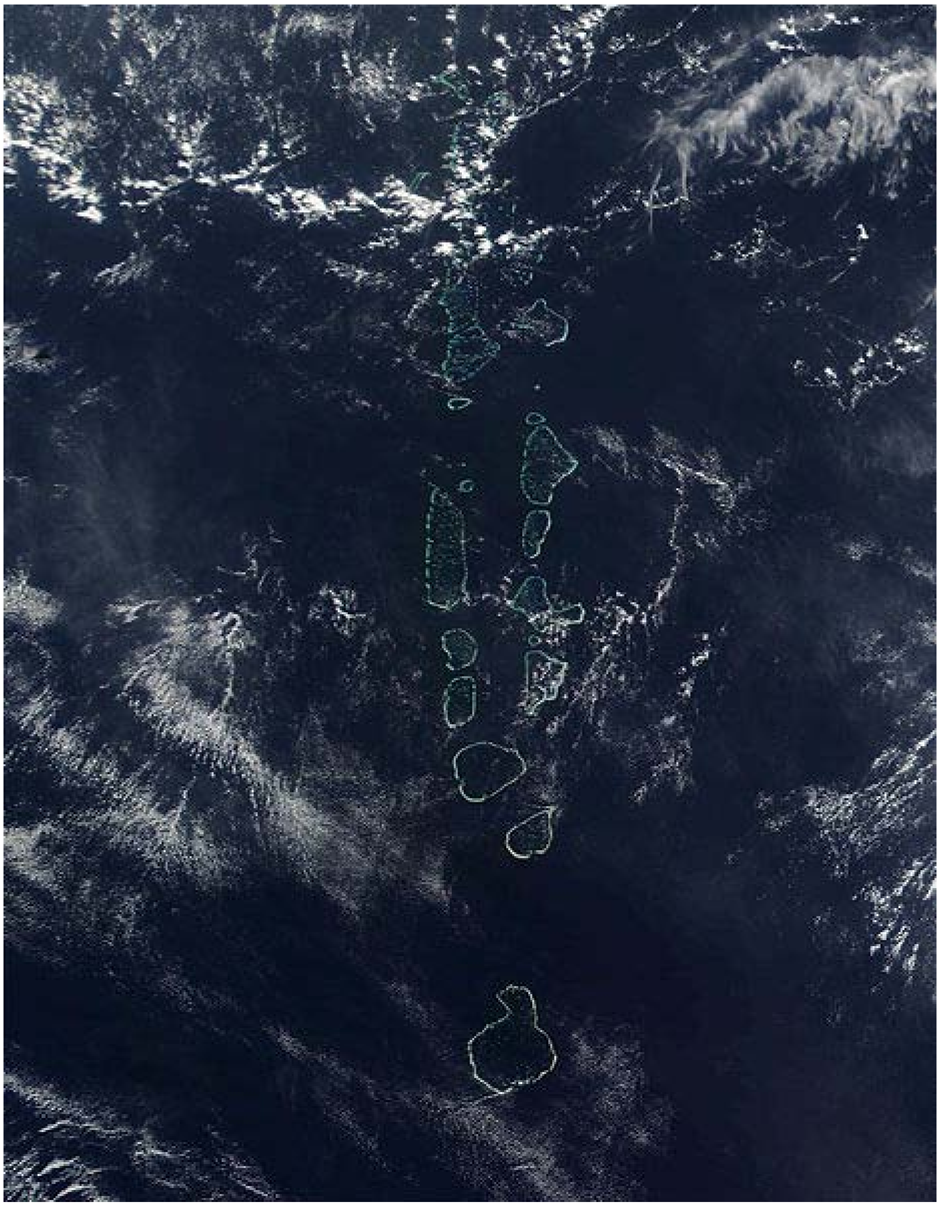
Satellite picture of the Atafu atoll in Tokelau in the Pacific Ocean.

An **atoll** is an island (or islands) of coral that encircles a lagoon partially or completely.

Usage

The word *atoll* comes from the Dhivehi (an Indo-Aryan language spoken on the Maldive Islands) word *atholhu*. Its first recorded use in English was in 1625 as *atollon* - Charles Darwin recognized its indigenous origin and coined, in his *The Structure and*

Distribution of Coral Reefs, the definition of atolls as "..circular groups of coral islets [...] and [the word] is synonymous with 'lagoon-island'." (1842, p. 2). More modern definitions of *atoll* are those of McNeil (1954, p. 396) as "..an annular reef enclosing a lagoon in which there are no promontories other than reefs and islets composed of reef detritus" and Fairbridge (1950, p. 341) "...in an exclusively morphological sense, [as] ...a ring-shaped ribbon reef enclosing a lagoon."



Satellite Image of some of the atolls of the Maldives by NASA. A total of 1322 islands arranged into 26 atolls make up the country.

Distribution and size

The distribution of atolls around the globe is instructive: most of the world's atolls are in the Pacific Ocean (with concentrations in the Tuamotu Islands, Caroline Islands, Marshall Islands, Coral Sea Islands, and the island groups of Kiribati, Tuvalu and Tokelau) and Indian Ocean (the Atolls of the Maldives, the Laccadive Islands, the Chagos Archipelago and the Outer Islands of the Seychelles). The Atlantic Ocean has no large groups of atolls, other than eight atolls east of Nicaragua that belong to the Colombian department of San Andres and Providencia in the Caribbean Sea.

Reef-building corals will thrive only in warm tropical and subtropical waters of oceans and seas, and therefore atolls are only found in the tropics and subtropics. The northernmost atoll of the world is Kure Atoll at 28°24' N, along with other atolls of the Northwestern Hawaiian Islands. The southernmost atolls of the world are Elizabeth Reef at 29°58' S, and nearby Middleton Reef at 29°29' S, in the Tasman Sea, both of which are part of the Coral Sea Islands Territory. The next southerly atoll is Ducie Island in the Pitcairn Islands Group, at 24°40' S. Bermuda is sometimes claimed as the "northernmost atoll" at a latitude of 32°24' N. At this latitude coral reefs would not develop without the warming waters of the Gulf Stream. However, Bermuda is what is termed a *pseudo-atoll* because its general form, while resembling that of an atoll, has a very different mode of formation. While there is no atoll directly on the Equator, the closest atoll to the Equator is Aranuka of Kiribati, with its southern tip just 12 km North of the Equator.

Nukuoro from space. Courtesy NASA.

The largest atolls by total area (lagoon plus reef and dry land) are listed below:

- Saya de Malha Bank, Western Indian Ocean (35000 km^2) (without separate North Bank), submerged, least depth 7 m,
- Lansdowne Bank, west of New Caledonia (21000 km^2), submerged, least depth 3.7 m
- Great Chagos Bank (12642 km^2, land area only 4.5 km^2)
- Reed Bank, Spratly Islands (8866 km^2), submerged, least depth 9 m
- Macclesfield Bank, South China Sea (6448 km^2), submerged, least depth 9.2 m
- North Bank (Ritchie Bank, north of Saya de Malha Bank) (5800 km^2), submerged, least depth <10 m
- Cay Sal Bank, Bahamas (5226.73 km^2, small land area of 14.87 km^2)
- Rosalind Bank, Caribbean Sea (4500 km^2), submerged, least depth 7.3 m
- Boduthiladhunmathi (Thiladhunmathi-Miladhunmadulu) Atoll, Maldives, (two names, but a single atoll structure) (3850 km^2, land area 51 km^2)
- Chesterfield Islands, New Caledonia (3500 km^2, land area <10 km^2)
- Huvadhu Atoll, Maldives (3152 km^2, land area 38.5 km^2)
- Truk Lagoon, Chuuk (3130 km^2)
- Sabalana Islands, Indonesia (2694 km^2)
- Nukuoro atoll, Federated States of Micronesia, lagoon, is 40 km^2, land area of 1.7 km^2, divided among more than 40 islets that lie on the northern, eastern and southern sides of the lagoon
- Lihou Reef, Coral Sea (2529 km^2, land area 1 km^2)
- Bassas de Pedro (2474.33 km^2), submerged, least depth 16.4 m
- Ardasier Bank, Spratly Islands (2347 km^2), cay on the south side?
- Kwajalein, Marshall Islands (2304 km^2, land area 16.4 km^2)
- Diamond Islets Bank, Coral Sea (2282 km^2, land area <1 km^2)
- Namonuito Atoll, Chuuk (2267 km^2, land area 4.4 km^2)
- Ari Atoll, Maldives (2252 km^2, land area 69 km^2)
- Maro Reef, Northwestern Hawaiian Islands, 1934 km^2
- Rangiroa, Tuamotu Islands (1762 km^2, land area 79 km^2)
- Kolhumadulhu Atoll, Maldives (1617 km^2, land area 79 km^2)
- North Malé Atoll, Maldives (1565 km^2, land area 69 km^2)
- Ontong Java, Solomon Islands (1500 km^2, land area 12 km^2)

In most cases, the land area of an atoll is very small in comparison to the total area. According to , Lifou (land area 1146 km^2) is the largest raised coral atoll of the world, followed by Rennell Island (660 km^2). More sources however list as the largest atoll in the world in terms of land area Kiritimati, which is also a raised coral atoll (321.37 km^2 land area; according to other sources even 575 km^2), 160 km^2 main lagoon, 168 km^2 other lagoons (according to other sources 319 km^2 total lagoon size). The remains of an ancient atoll as a hill in a limestone area is called a reef knoll. The second largest atoll by dry land area is Aldabra with 155 km^2. The largest atoll in terms of island numbers is Huvadhu Atoll in the south of the Maldives with 255 islands.

Formation

Darwin explained the creation of coral atolls in the South Pacific (1842) based upon observations made during a five-year voyage aboard the HMS *Beagle* (1831–1836). His explanation, which is accepted as basically correct, involved considering that several tropical island types—from high volcanic island, through barrier reef island, to atoll—represented a sequence of gradual subsidence of what started as an oceanic volcano. He reasoned that a fringing coral reef surrounding a volcanic island in the tropical sea will grow upwards as the island subsides (sinks), becoming an "almost atoll" (barrier reef island) (as typified by an island such as Aitutaki in the Cook Islands, Bora Bora and others in the Society Islands). The fringing reef becomes a barrier reef for the reason that the outer part of the reef maintains itself near sea level through biotic growth, while the inner part of the reef falls behind, becoming a lagoon because conditions are less favorable for the corals and calcareous algae responsible for most reef growth. In time, subsidence carries the old volcano below the ocean surface, but the barrier reef remains. At this point, the island has become an atoll.

Atolls are the product of the growth of tropical marine organisms, so these islands are only found in warm tropical waters. Volcanic islands located beyond the warm water temperature requirements of reef building (hermatypic) organisms become seamounts as they subside and are eroded away at the surface. An island that is located where the ocean water temperatures are just sufficiently warm for upward reef growth to keep pace with the rate of subsidence is said to be at the **Darwin Point**. Islands more polar evolve towards seamounts or guyots; islands more equatorial evolve towards atolls.

Reginald Aldworth Daly offered a somewhat different explanation for atoll formation: islands worn away by erosion (ocean waves and streams) during the last glacial stand of the sea of some 900 feet (270 m) below present sea level developed as coral islands (atolls) (or barrier reefs on a platform surrounding a volcanic island not completely worn away) as sea level gradually rose from melting of the glaciers. Discovery of the great depth of the volcanic remnant beneath many atolls, favors the Darwin explanation, although there can be little doubt that fluctuating sea level has had considerable influence on atoll and other reefs.

Coral atolls are also an important place where dolomitization of calcite occurs. At certain depths water is undersaturated in calcium carbonate but saturated in dolomite. Convection created by tides and sea currents enhance this change. Hydrothermal currents created by volcanoes under the atoll may also play an important role.

United States national monuments

Aerial overview of the Wake Island atoll. Part of the Pacific Remote Islands Marine National Monument.

As of January 6, 2009 U.S. President Bush announced that several remote Pacific islands under U.S. jurisdiction are now national monuments, protecting coral reefs.

Chapter- 5

Cay

Heron Island, Australia

A **cay** is a small, low-elevation, sandy island formed on the surface of coral reefs. Cays occur in tropical environments throughout the Pacific, Atlantic and Indian Oceans (including in the Caribbean and on the Great Barrier Reef and Belize Barrier Reef), where they provide habitable and agricultural land for hundreds of thousands of people.

Their surrounding reef ecosystems also provide food and building materials for island inhabitants.

Formation and composition

Cay sand under a microscope

A cay is formed when ocean currents transport lose sediment across the surface of a reef to a depositional node, where the current slows or converges with another current, releasing its sediment load. Gradually, layers of deposited sediment build up on the reef surface (Hopley 1981, Gorlay 1998). Such nodes occur in windward or leeward areas of reef surfaces and sometimes occur around an emergent outcrop of old reef or beach rock.

The island resulting from sediment accumulation is made up almost entirely of biogenic sediment – the skeletal remains of plants and animals – from the surrounding reef ecosystems (Hopley 1982). If the accumulated sediments are predominantly sand, then the island is called a cay; if they are predominantly gravel, the island is called a motu.

Cay sediments are largely composed of calcium carbonate ($CaCO_3$), primarily of aragonite, calcite, and high magnesium calcite. They are produced by myriad plants (e.g., coralline algae, species of the green algae Halimeda) and animals (e.g., coral, molluscs, foraminifera). Small amounts of silicate sediment are also contributed by sponges and other creatures (Chave 1964, Folk and Robles 1964, Scoffin 1987, Yamano 2000). Over time, soil and vegetation may develop on a cay surface, assisted by the deposition of sea bird guano.

Development and stability

A range of physical, biological and chemical influences determines the ongoing development or erosion of cay environments. These influences include: the extent of reef surface sand accumulations, changes in ocean waves, currents, tides, sea levels and weather conditions, the shape of the underlying reef, the types and abundance of carbonate producing biota and other organisms such as binders, bioeroders and bioturbators (creatures which bind, erode and mix sediments) living in surrounding reef ecosystems (Harney and Fletcher 2003, Hart and Kench 2007).

Significant changes in cays and their surrounding ecosystems can result from natural phenomena such as severe El Niño Southern Oscillation (ENSO) cycles. Also, tropical cyclones can help build or destroy these islands (Scoffin 1993, Woodroffe 2003).

There is much debate and concern over the future stability of cays in the face of growing human populations and pressures on reef ecosystems, and predicted climate changes and sea level rise (Kench and Cowell 2003, Hart 2003). There is also debate around whether these islands are relict features which effectively stopped expanding two thousand years ago during the late Holocene or, as recent research suggests, they are currently still growing with significant new additions of reef sediments (Woodroffe et al. 2007).

Understanding the potential for change in the sediment sources and supply of cay beaches with environmental change is an important key to predicting their present and future stability. Despite, or perhaps because of all the debate around the future of cays, there is consensus that these island environments are very complex and somewhat fragile.

Examples

Warraber Island, Torres Strait

Examples of cays include:

- Heron Island, a coral cay on the southern Great Barrier Reef
- Warraber Island in central Torres Strait (10°12' S, 142°49' E), Australia, a small ‘vegetated sand cay’ according to the classification schemes of McLean and Stoddart (1978) and Hopley (1982). Approximately 750 by 1500 m wide, this island is situated on the leeward surface of a large 11 km^2 emergent reef platform. This cay and the surrounding reef flat are Holocene in origin, having formed over an antecedent Pleistocene platform (Woodroffe et al. 2000).
- The Florida Keys are composed primarily of exposed ancient coral reefs and oolite beds formed behind reefs. A few of the Florida Keys, such as Sand Key, are "cays" as defined above.
- Tobacco Caye, Dangriga, Belize
- Prickly Pear Cays

Chapter- 6

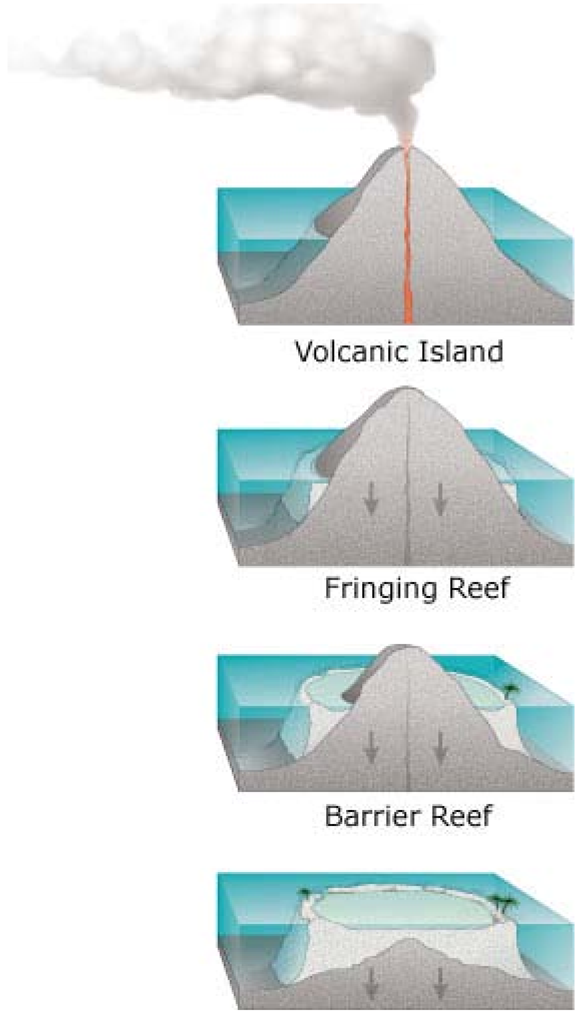
The Structure and Distribution of Coral Reefs

Kanton Island typifies the isolated coral atolls dotting the Pacific Ocean.

The Structure and Distribution of Coral Reefs*, Being the first part of the geology of the voyage of the Beagle, under the command of Capt. Fitzroy, R.N. during the years 1832 to 1836*, was published in 1842 as Charles Darwin's first monograph, and set out his theory of the formation of coral reefs and atolls. He conceived of the idea during the voyage of the *Beagle* while still in South America, before he had seen a coral island, and wrote it out as HMS *Beagle* crossed the Pacific Ocean, completing his draft by November 1835. At the time there was great scientific interest in the way that coral reefs formed, and Captain Robert FitzRoy's orders from the Admiralty included the investigation of an atoll as an important scientific aim of the voyage. FitzRoy chose to survey the Keeling Islands in the Indian Ocean. The results supported Darwin's theory that the various types of coral reefs and atolls could be explained by uplift and subsidence of vast areas of the Earth's crust under the oceans.

The book was the first volume of three Darwin wrote about the geology he had investigated during the voyage, and was widely recognised as a major scientific work that presented his deductions from all the available observations on this large subject. In 1853, Darwin was awarded the Royal Society's Royal Medal for the monograph and for his work on barnacles. Darwin's theory that coral reefs formed as the islands and surrounding areas of crust subsided has been supported by modern investigations, and is no longer disputed, the cause of the subsidence and uplift of areas of crust has continued to be a subject of discussion.

Theory of coral atoll formation



Darwin's theory set out a sequence of coral reef formation around an extinct volcanic island, becoming an atoll as the island and ocean floor subsided.
Courtesy of the U.S. Geological Survey

When the *Beagle* set out in 1831, the formation of coral atolls was a scientific puzzle. Advance notice of her sailing, given in the *Athenaeum* of 24 December, described investigation of this topic as "the most interesting part of the *Beagle*'s survey" with the prospect of "many points for investigation of a scientific nature beyond the mere occupation of the surveyor. In 1824 and 1825, French naturalists Quoy and Gaimard had observed that the coral organisms lived at relatively shallow depths, but the islands appeared in deep oceans. In books that were taken on the *Beagle* as references, Henry De la Beche, Frederick William Beechey and Charles Lyell had published the opinion that the coral had grown on underwater mountains or volcanoes, with atolls taking the shape of underlying volcanic craters. The Admiralty instructions for the voyage stated:

The circularly-formed Coral Islands in the Pacific occasionally afford excellent land-locked harbours, with a sufficient entrance, and would be well adapted to any nice astronomical observations which might require to be carried on in undisturbed tranquillity. While these are quietly proceeding, and the chronometers rating, a very interesting inquiry might be instituted respecting the formation of these coral reefs. A modern and very plausible theory has been put forward, that these wonderful formations, instead of ascending from the bottom of the sea, have been raised from the summits of extinct volcanoes.

As a student at the University of Edinburgh in 1827, Darwin learnt about marine invertebrates while assisting the investigations of the anatomist Robert Edmond Grant, and during his last year at the University of Cambridge in 1831, he had studied geology under Adam Sedgwick. So when he was unexpectedly offered a place on the *Beagle* expedition, as a gentleman naturalist he was well suited to FitzRoy's aim of having a companion able to examine geology on land while the ship's complement carried out its hydrographic survey. FitzRoy gave Darwin the first volume of Lyell's *Principles of Geology* before they left. On their first stop ashore at St Jago island in January 1832, Darwin saw geological formations which he explained using Lyell's uniformitarian concept that forces still in operation made land slowly rise or fall over immense periods of time, and thought that he could write his own book on geology. Lyell's first volume included a brief outline of the idea that atolls were based on volcanic craters, and the second volume, which was sent to Darwin during the voyage, gave more detail. Darwin received it in November 1832.

While the *Beagle* surveyed the coasts of South America from February 1832 to September 1835, Darwin made several trips inland and found extensive evidence that the continent was gradually rising. After witnessing an erupting volcano from the ship, he experienced an earthquake on 20 February 1835. In the following months he speculated that as the land was uplifted, large areas of the ocean bed subsided. It struck him that this could explain the formation of atolls.

Darwin's theory followed from his understanding that coral polyps thrive in the clean seas of the tropics where the water is agitated, but can only live within a limited depth of water, starting just below low tide. Where the level of the underlying land stays the same, the corals grow around the coast to form what he called fringing reefs, and can eventually grow out from the shore to become a barrier reef. Where the land is rising, fringing reefs can grow around the coast, but coral raised above sea level dies and becomes white limestone. If the land subsides slowly, the fringing reefs keep pace by growing upwards on a base of dead coral, and form a barrier reef enclosing a lagoon between the reef and the land. A barrier reef can encircle an island, and once the island sinks below sea level a roughly circular atoll of growing coral continues to keep up with the sea level, forming a central lagoon. Should the land subside too quickly or sea level rise too fast, the coral dies as it is below its habitable depth.

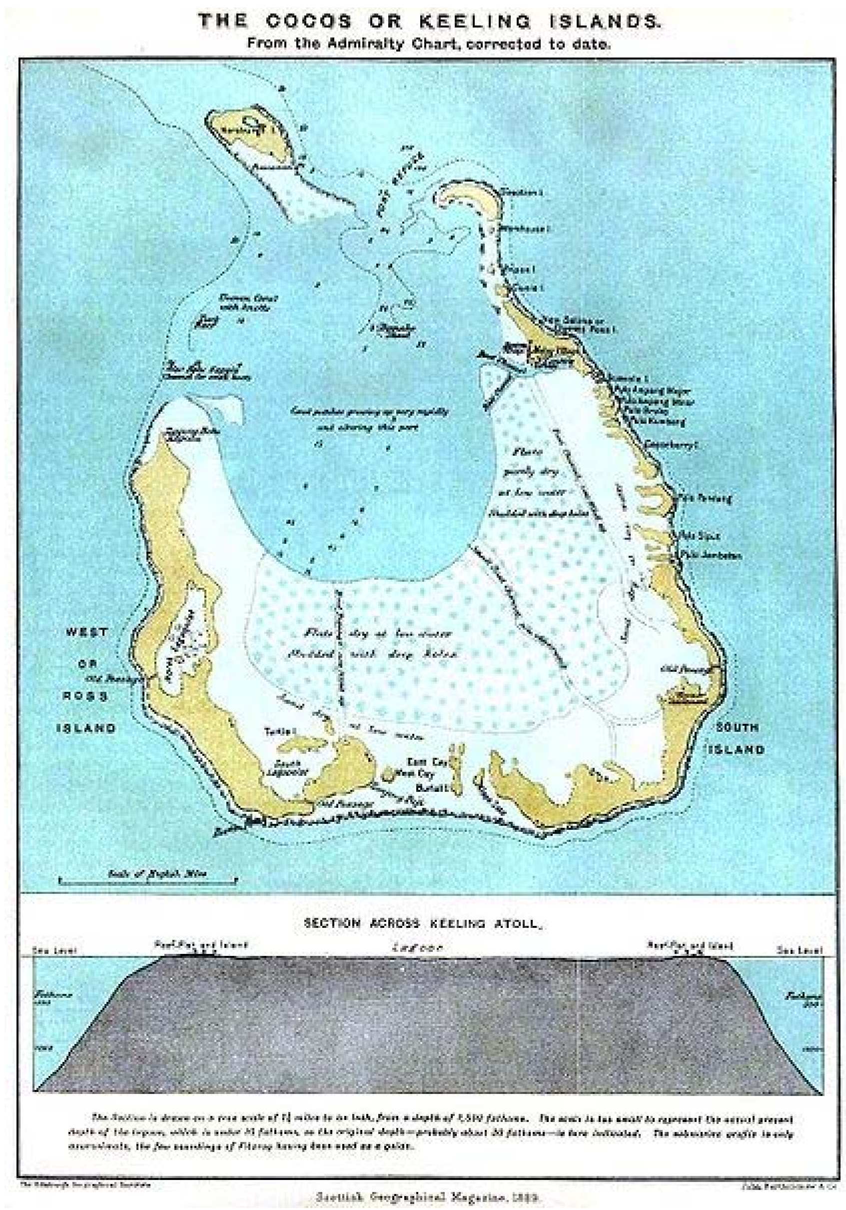
Investigation testing Darwin's theory

Darwin saw the coral reef and lagoon around Tahiti.

By the time that the *Beagle* set out for the Galápagos Islands on 7 September 1835, Darwin had thought out the essentials of his theory of atoll formation. While he no longer favoured the concept that atolls formed on submerged volcanos, he noted some points on these islands which supported that idea: 16 volcanic craters resembled atolls in being raised slightly more on one side, and five hills appeared roughly equal in height. He then considered a topic which was compatible with either theory, the lack of coral reefs around the Galápagos Islands. One possibility was a lack of calcareous matter around the islands, but his main proposal, which FitzRoy had suggested to him, was that the seas were too cold. As they sailed on, Darwin took note of the records of sea temperature kept in the ship's "Weather Journal".

He had his first glimpse of coral atolls as they passed Honden Island on 9 November and sailed on through the Low or Dangerous Archipelago (Tuamotus). Arriving at Tahiti on 15 November, Darwin saw it "encircled by a Coral reef separated from the shore by channels & basins of still water". He climbed the hills of Tahiti, and was strongly impressed by the sight across to the island of Eimeo, where "The mountains abruptly rise out of a glassy lake, which is separated on all sides, by a narrow defined line of breakers, from the open sea. – Remove the central group of mountains, & there remains a Lagoon Isd." Rather than recording his findings about the coral reefs in his notes about the island, he wrote them up as the first full draft of his theory, an essay titled *Coral Islands*, dated 1835. They left Tahiti on 3 December, and Darwin probably wrote his essay as they sailed towards New Zealand where they arrived on 21 December. He described the polyp species building the coral on the barrier wall, flourishing in the heavy surf of breaking waves particularly on the windward side, and speculated on reasons that corals in the calm lagoon did not grow so high. He concluded with a "remark that the general horizontal uplifting which I have proved has & is now raising upwards the greater part of S. America & as it would appear likewise of N. America, would of necessity be compensated by an equal subsidence in some other part of the world."

Keeling Islands



An 1889 map of the Keeling Islands based on the Admiralty Chart includes a section across the atoll showing the steep slopes FitzRoy's soundings found outside the reef.

Aerial view of the Keeling Islands.

FitzRoy's instructions set detailed requirements for geological survey of a circular coral atoll to investigate how coral reefs formed, particularly if they rose from the bottom of the sea or from the summits of extinct volcanoes, and to assess the effects of tides by measurement with specially constructed gauges. FitzRoy chose the Keeling Islands in the Indian Ocean, and on arrival there on 1 April 1836, the entire crew set to work, first erecting FitzRoy's new design of a tide gauge that allowed readings to be taken from the shore. Boats were sent all around the island to carry out the survey, and despite being impeded by strong winds, they took numerous soundings to establish depths around the atoll and in the lagoon. FitzRoy noted the smooth and solid rock-like outer wall of the atoll, with most life thriving where the surf was most violent. He had great difficulty in establishing the depth reached by living coral, as pieces were hard to break off and the small anchors, hooks, grappling irons, and chains they used were all snapped off by the swell as soon as they tried to pull them up. He had more success using a sounding line with a bell-shaped lead weight armed with tallow hardened with lime; this would be indented by any shape that it struck to give an exact impression of the bottom; it would also collect any fragments of coral or grains of sand.

These soundings were taken personally by FitzRoy, and the tallow from each sounding was cut off and taken on board to be examined by Darwin. The impressions taken on the steep outside slope of the reef were marked with the shapes of living corals, and otherwise were clean down to about 10 fathoms (18 m); then at increasing depths, the tallow showed fewer such impressions and collected more grains of sand until it was evident that there were no living corals below about 20–30 fathoms (36–55 m). Darwin carefully noted the location of the different types of coral around the reef and in the lagoon. In his diary, he described, "examining the very interesting yet simple structure & origin of these islands. The water being unusually smooth, I waded in as far as the living mounds of coral on which the swell of the open sea breaks. In some of the gullies & hollows, there were beautiful green & other colored fishes, & the forms & tints of many of the Zoophites were admirable. It is excusable to grow enthusiastic over the infinite numbers of organic beings with which the sea of the tropics, so prodigal of life, teems", though he cautioned against the "rather exuberant language" used by some naturalists.

As they left the islands after eleven days, Darwin wrote out a summary of his theory in his diary:

Throughout the whole group of Islands, every single atom, even from the most minute particle to large fragments of rocks, bear the stamp of once having been subjected to the power of organic arrangement. Capt. FitzRoy at the distance of but little more than a mile from the shore sounded with a line 7200 feet long, & found no bottom. Hence we must consider this Isld as the summit of a lofty mountain; to how great a depth or thickness the work of the Coral animal extends is quite uncertain.... Under this view, we must look at a Lagoon Isd as a monument raised by myriads of tiny architects, to mark the spot where a former land lies buried in the depths of the ocean.

Darwin's findings and modern views

Darwin's interest on the biology of reef organisms was focussed on aspects related to his geological idea of subsidence; in particular, he was looking for confirmation that the reef building organisms could only live at shallow depths. FitzRoy's soundings at the Keeling Islands gave a depth limit for live coral of about 20 fathoms (37 m), and taking into account numerous observations by others, Darwin worked with a probable limit of 30 fathoms (55 m). Modern findings suggest a limit of around 100 m, still a small fraction of the depth of the ocean floor at 3000–5000 m. Darwin recognised the importance of red algae, and he reviewed other organisms that could have helped to build the reefs. He thought they lived at similarly shallow depths, but banks formed at greater depths were found in the 1880s. Darwin reviewed the distribution of different species of coral across a reef. He thought that the seaward reefs most exposed to wind and waves were formed by massive corals and red algae; this would be the most active area of reef growth and so would cause a tendency for reefs to grow outwards once they reach sea level. He believed that higher temperatures and the calmer water of the lagoons favoured the greatest coral diversity. These ecological ideas are still current, and research on the details continues.

Darwin's investigations showed how coral eating organisms such as parrotfish controlled the growth of coral, and formed mudbanks.

In assessing the geology of the reef, Darwin showed his remarkable ability to collect facts and find patterns to reconstruct geological history on the basis of the very limited evidence available. He gave attention to the smallest detail. Having heard that parrotfish browsed on the living coral, he dissected specimens to find finely ground coral in their intestines. He concluded that such fish, and coral eating invertebrates such as Holothuroidea, could account for the banks of fine grained mud he found at the Keeling Islands; it showed also "that there are living checks to the growth of coral-reefs, and that the almost universal law of 'consume and be consumed,' holds good even with the polypifers forming those massive bulwarks, which are able to withstand the force of the open ocean."

His observations on the part played by organisms in the formation of the various features of reefs anticipated modern studies. To establish the thickness of coral barrier reefs, he relied on the old nautical rule of thumb to project the slope of the land to that below sea level, and then applied his idea that the coral reef would slope much more steeply than the underlying land. He was fortunate to guess that the maximum depth of coral would be around 5,000 ft (1,500 m), as the first test bores conducted by the United States Atomic Energy Commission on Enewetak Atoll in 1952 drilled down through 4610 ft (1,405 m) of coral before reaching the volcanic foundations. In Darwin's time no comparable thickness of fossil coral had been found on the continents, and when this was raised as a criticism of his theory neither he nor Lyell could find a satisfactory explanation. It is now thought that fossil reefs are usually broken up by tectonic movements, but at least two continental fossil reef complexes have been discovered to be about 3,000 ft (1,000 m) thick. While these findings have confirmed his argument that the islands were subsiding, his other attempts to show evidence of subsidence have been superseded by the discovery that glacial effects can cause changes in sea level.

In Darwin's global hypothesis, vast areas where the seabed was being elevated were marked by fringing reefs, sometimes around active volcanoes, and similarly huge areas where the ocean floor was subsiding were indicated by barrier reefs or atolls based on inactive volcanoes. These views received general support from deep sea drilling results in the 1980s. His idea that rising land would be balanced by subsidence in ocean areas has been superseded by modern plate tectonics, which he did not anticipate.

Chapter- 7

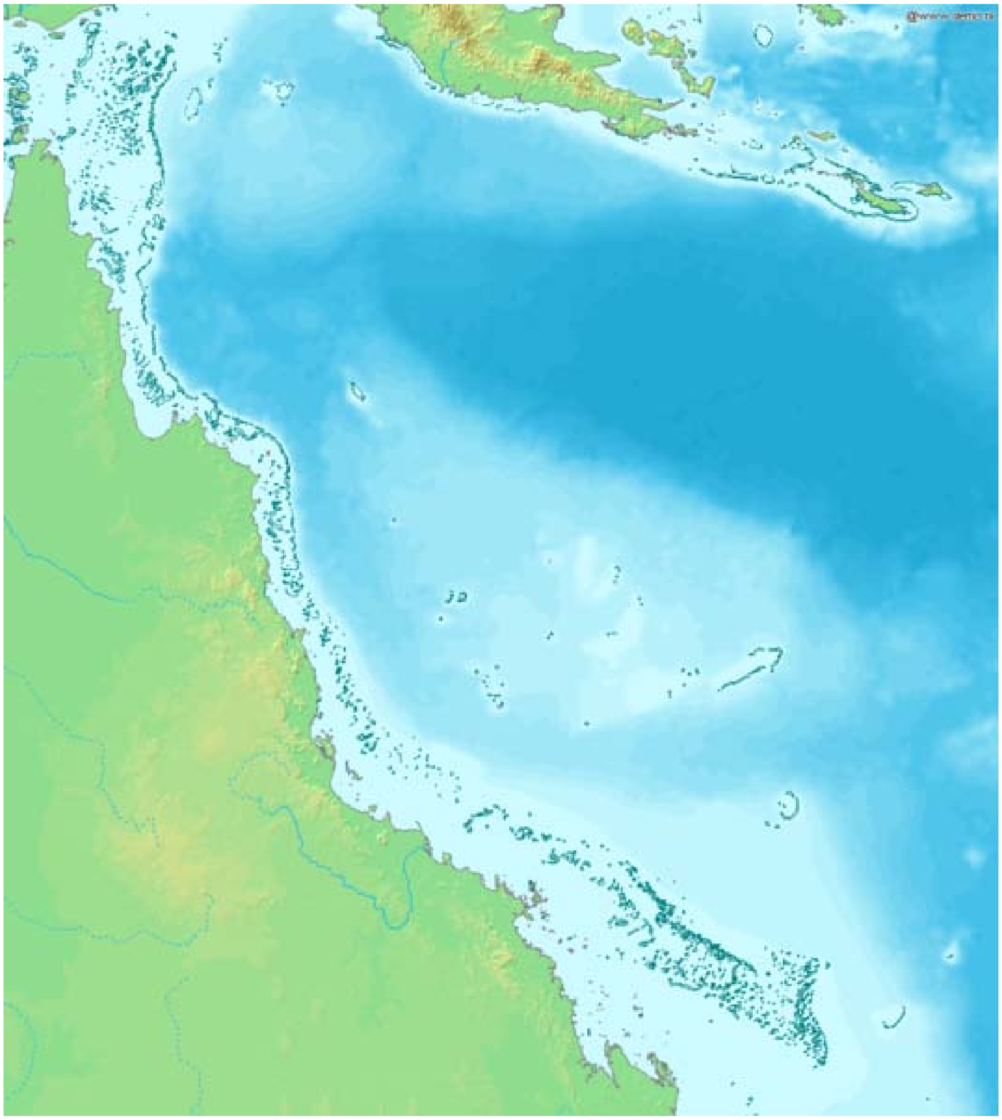
Great Barrier Reef

The Great Barrier Reef*	
UNESCO World Heritage Site	

State Party	Australia
Type	Natural
Criteria	vii, viii, ix, x
Reference	154
Region**	Asia-Pacific
Inscription history	
Inscription	1981 (5th Session)

* Name as inscribed on World Heritage List.

** Region as classified by UNESCO.



The **Great Barrier Reef** is the world's largest reef system composed of over 2,900 individual reefs and 900 islands stretching for over 2,600 kilometres (1,600 mi) over an area of approximately 344,400 square kilometres (133,000 sq mi). The reef is located in the Coral Sea, off the coast of Queensland in north-east Australia.

The Great Barrier Reef can be seen from outer space and is the world's biggest single structure made by living organisms. This reef structure is composed of and built by billions of tiny organisms, known as coral polyps. This reef supports a wide diversity of life, and was selected as a World Heritage Site in 1981. CNN labeled it one of the seven natural wonders of the world. The Queensland National Trust named it a state icon of Queensland.

A large part of the reef is protected by the Great Barrier Reef Marine Park, which helps to limit the impact of human use, such as fishing and tourism. Other environmental pressures on the reef and its ecosystem include runoff, climate change accompanied by mass coral bleaching, and cyclic population outbreaks of the crown-of-thorns starfish.

The Great Barrier Reef has long been known to and used by the Aboriginal Australian and Torres Strait Islander peoples, and is an important part of local groups' cultures and spirituality. The reef is a very popular destination for tourists, especially in the Whitsunday Islands and Cairns regions. Tourism is an important economic activity for the region, generating AU$ 1 billion per year.

Geology and geography

Satellite image of part of the Great Barrier Reef adjacent to the Queensland coastal areas of Airlie Beach and Mackay.

The Great Barrier Reef is a distinct feature of the East Australian Cordillera division. It includes the smaller Murray Islands. It reaches from Torres Strait (between Bramble Cay, its northernmost island, and the south coast of Papua New Guinea) in the north to the unnamed passage between Lady Elliot Island (its southernmost island) and Fraser Island in the south. Lady Elliot Island is located 1,915 km (1,190 mi) southeast of Bramble Cay as the crow flies.

Australia has moved northwards at a rate of 7 cm (2.8 in) per year, starting during the Cainozoic. Eastern Australia experienced a period of tectonic uplift, which moved the drainage divide in Queensland 400 km (250 mi) inland. Also during this time, Queensland experienced volcanic eruptions leading to central and shield volcanoes and basalt flows. Some of these granitic outcrops have become high islands. After the Coral Sea Basin formed, coral reefs began to grow in the Basin, but until about 25 million years ago, northern Queensland was still in temperate waters south of the tropics—too cool to support coral growth. The Great Barrier Reef's development history is complex; after Queensland drifted into tropical waters, it was largely influenced by reef growth and decline as sea level changed. They can increase in diameter by 1 to 3 centimetres (0.39 to 1.2 in) per year, and grow vertically anywhere from 1 to 25 cm (0.39 to 9.8 in) per year; however, they grow only above a depth of 150 metres (490 ft) due to their need for sunlight, and cannot grow above sea level. When Queensland edged into tropical waters 24 million years ago, some coral grew, but a sedimentation regime quickly developed with erosion of the Great Dividing Range; creating river deltas, oozes and turbidites, unsuitable conditions for coral growth. 10 million years ago, the sea level significantly lowered, which further enabled sedimentation. The reef's substrate may have needed to build up from the sediment until its edge was too far away for suspended sediments to inhibit coral growth. In addition, approximately 400,000 years ago there was a particularly warm interglacial period with higher sea levels and a 4 °C (7 °F) water temperature change.

The Great Barrier Reef is clearly visible from aircraft flying over it.

Heron Island, a coral cay in the southern Great Barrier Reef

The land that formed the substrate of the current Great Barrier Reef was a coastal plain formed from the eroded sediments of the Great Dividing Range with some larger hills (some of which were themselves remnants of older reefs or volcanoes). The Reef Research Centre, a Cooperative Research Centre, has found coral 'skeleton' deposits that date back half a million years. The Great Barrier Reef Marine Park Authority (GBRMPA) considers the earliest evidence of complete reef structures to have been 600,000 years ago. According to the GBRMPA, the current, living reef structure is believed to have begun growing on the older platform about 20,000 years ago. The Australian Institute of Marine Science agrees, placing the beginning of the growth of the current reef at the time of the Last Glacial Maximum. At around that time, sea level was 120 metres (390 ft) lower than it is today.

From 20,000 years ago until 6,000 years ago, sea level rose steadily. As it rose, the corals could then grow higher on the hills of the coastal plain. By around 13,000 years ago the sea level was only 60 metres (200 ft) lower than the present day, and corals began to grow around the hills of the coastal plain, which were, by then, continental islands. As the sea level rose further still, most of the continental islands were submerged. The corals could then overgrow the hills, to form the present cays and reefs. Sea level here has not risen significantly in the last 6,000 years. The CRC Reef Research Centre estimates the age of the present, living reef structure at 6-8,000 years old.

The remains of an ancient barrier reef similar to the Great Barrier Reef can be found in The Kimberley, a northern region of Western Australia.

The Great Barrier Reef World Heritage Area has been divided into 70 bioregions, of which 30 are reef bioregions. In the northern part of the Great Barrier Reef, ribbon reefs and deltaic reefs have formed; these structures are not found in the rest of the reef system. There are no atolls in the system, and reefs attached to the mainland are rare.

Fringing reefs are distributed widely, but are most common towards the southern part of the Great Barrier Reef, attached to high islands, for example, the Whitsunday Islands. Lagoonal reefs are found in the southern Great Barrier Reef, and further north, off the coast of Princess Charlotte Bay. Cresentic reefs are the most common shape of reef in the middle of the system, for example the reefs surrounding Lizard Island. Cresentic reefs are also found in the far north of the Great Barrier Reef Marine Park, and in the Swain Reefs (20-22 degrees south). Planar reefs are found in the northern and southern parts, near Cape York Peninsula, Princess Charlotte Bay, and Cairns. Most of the islands on the reef are found on planar reefs.

Ecology

A variety of colourful corals on Flynn Reef near Cairns

The Great Barrier Reef supports a diversity of life, including many vulnerable or endangered species, some of which may be endemic to the reef system.

Green sea turtle on the Great Barrier Reef

Thirty species of whales, dolphins, and porpoises have been recorded in the Great Barrier Reef, including the dwarf minke whale, Indo-Pacific humpback dolphin, and the humpback whale. Large populations of dugongs live there.

Six species of sea turtles come to the reef to breed – the green sea turtle, leatherback sea turtle, hawksbill turtle, loggerhead sea turtle, flatback turtle, and the olive ridley. The green sea turtles on the Great Barrier Reef have two genetically distinct populations, one in the northern part of the reef and the other in the southern part. Fifteen species of seagrass in beds attract the dugongs and turtles, and provide fish habitat. The most common genera of seagrasses are *Halophila* and *Halodule*.

Saltwater crocodiles live in mangrove and salt marshes on the coast near the reef. Nesting has not been reported, and the salt water crocodile population in the GBRWHA is wide-ranging but low density. Around 125 species of shark, stingray, skates or chimaera live on the reef. Close to 5,000 species of mollusc have been recorded on the reef, including the giant clam and various nudibranchs and cone snails. Forty-nine species of pipefish and nine species of seahorse have been recorded. At least seven species of frog inhabit the islands.

215 species of birds (including 22 species of seabirds and 32 species of shorebirds) visit the reef or nest or roost on the islands, including the white-bellied sea eagle and roseate tern. Most nesting sites are on islands in the northern and southern regions of the Great Barrier Reef, with 1.4–1.7 million birds using the sites to breed. The islands of the Great Barrier Reef also support 2,195 known plant species; three of these are endemic. The northern islands have 300–350 plant species which tend to be woody, whereas the southern islands have 200 which tend to be herbaceous; the Whitsunday region is the most diverse, supporting 1,141 species. The plants are propagated by birds.

Seventeen species of sea snake live on the Great Barrier Reef in warm waters up to 50 metres (164 ft) deep and are more common in the southern than in the northern section. None found in the Great Barrier Reef World Heritage Area are endemic, nor are any endangered.

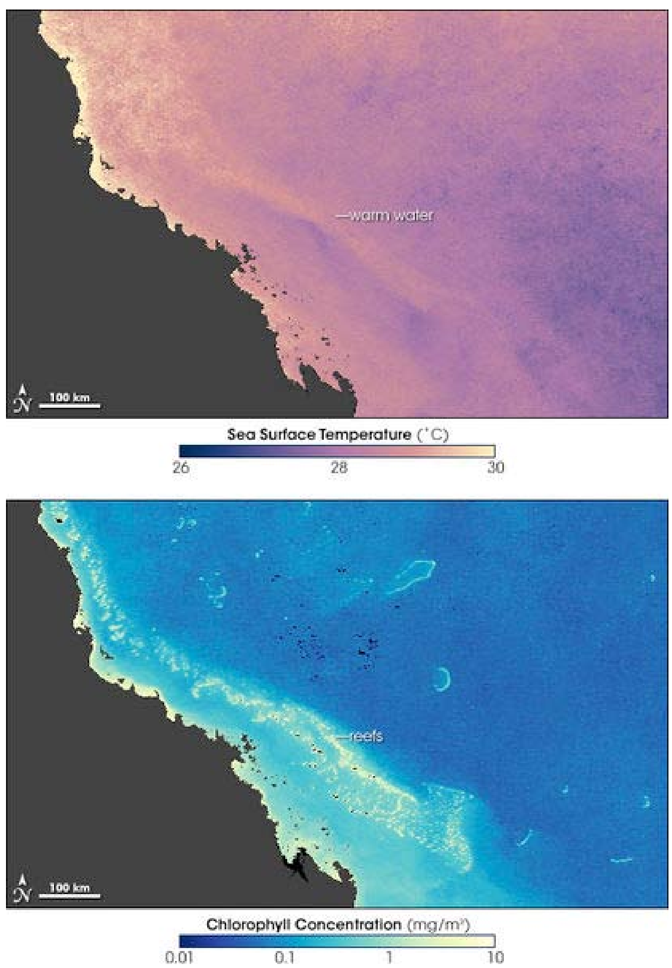
A Striped Surgeonfish amongst the coral on Flynn Reef

More than 1,500 fish species live on the reef, including the clownfish, red bass, red-throat emperor, and several species of snapper and coral trout. Forty-nine species mass spawn, while eighty-four other species spawn elsewhere in their range.

There are at least 330 species of ascidians on the reef system with the diameter of 1–10 cm (0.4–4 in). Between 300–500 species of bryozoans live on the reef.

Four hundred coral species, both hard corals and soft corals inhabit the reef. The majority of these spawn gametes, breeding in mass spawning events that are triggered by the rising sea temperatures of spring and summer, the lunar cycle, and the diurnal cycle. Reefs in the inner Great Barrier Reef spawn during the week after the full moon in October, while the outer reefs spawn in November and December. Its common soft corals belong to 36 genera. Five hundred species of marine algae or seaweed live on the reef, including thirteen species of genus *Halimeda*, which deposit calcareous mounds up to 100 metres (110 yd) wide, creating mini-ecosystems on their surface which have been compared to rainforest cover.

Environmental threats



Sea temperature and bleaching of the Great Barrier Reef

Climate change, pollution, crown-of-thorns starfish and fishing are the primary threats to the health of this reef system. Other threats include shipping accidents, oil spills, and tropical cyclones. Skeletal Eroding Band, a disease of bony corals caused by the protozoan *Halofolliculina corallasia*, affects 31 coral species.

Climate change

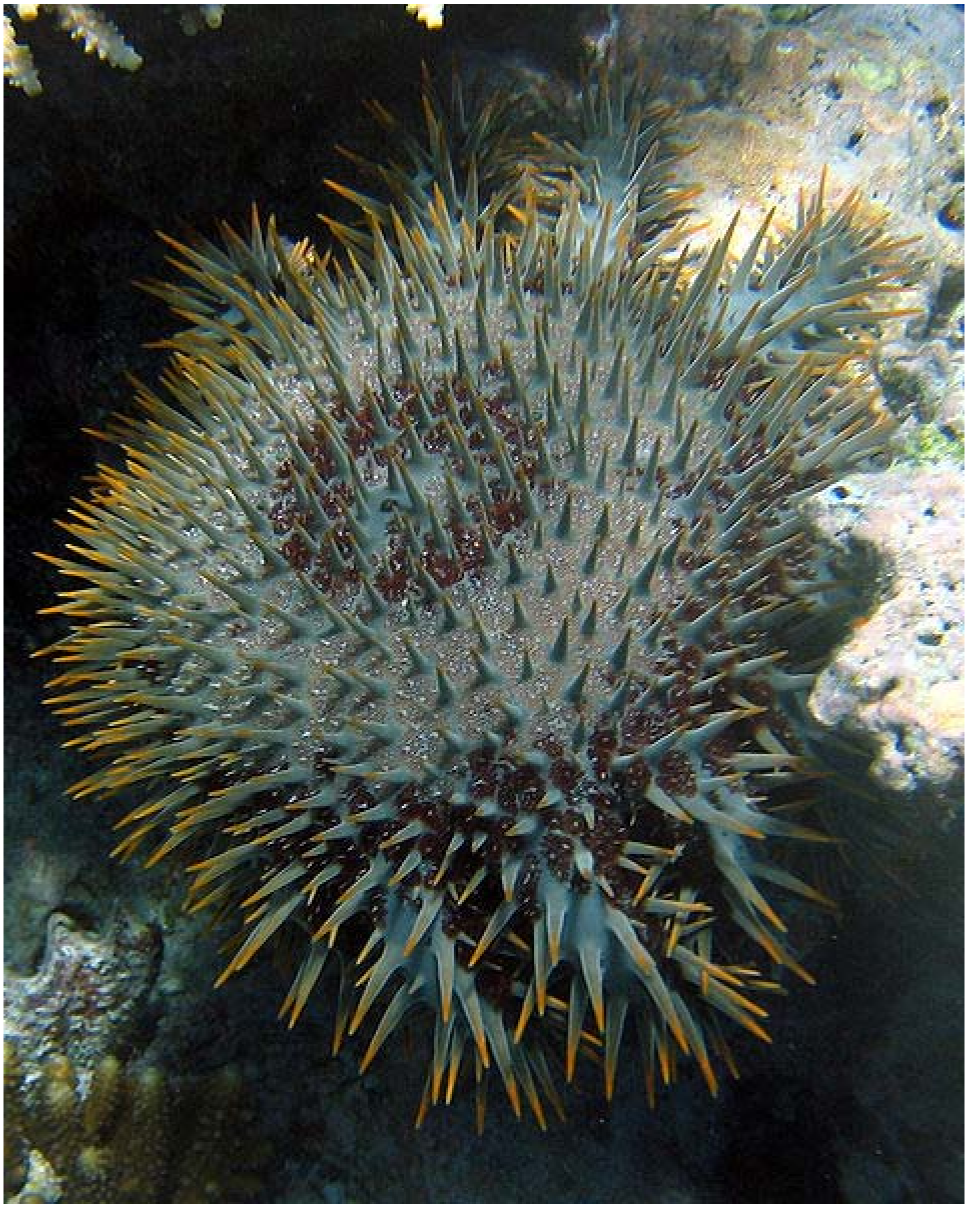
The Great Barrier Reef Marine Park Authority considers the greatest threat to the Great Barrier Reef to be climate change, causing ocean warming which increases coral bleaching. Mass coral bleaching events due to elevated ocean temperatures occurred in the summers of 1998, 2002 and 2006, and coral bleaching is expected to become an annual occurrence. Climate change has implications for other forms of reef life—some fish's preferred temperature range leads them to seek new habitat, thus increasing chick mortality in predatory seabirds. Climate change will also affect the population and sea turtle's available habitat.

Pollution

Another key threat faced by the Great Barrier Reef is pollution and declining water quality. The rivers of north eastern Australia pollute the Reef during tropical flood events. Over 90% of this pollution comes from farm runoff. Farm run-off is polluted by overgrazing, excessive fertiliser use and pesticide use.

The runoff problem is exacerbated by the loss of coastal wetlands which act as a natural filter for toxins and help deposit sediment. It is thought that the poor water quality is due to increased light and oxygen competition from algae.

Crown of thorns



Crown-of-thorns starfish

The crown-of-thorns starfish preys on coral polyps. Large outbreaks of these starfish can devastate reefs. In 2000, an outbreak contributed to a loss of 66% of live coral cover on sampled reefs in a study by the RRC (Reefs Research Centre.) Outbreaks are believed to occur in natural cycles, worsened by poor water quality and overfishing of the starfish's predators.

Fishing

The unsustainable overfishing of keystone species, such as the Giant Triton, can disrupt food chains vital to reef life. Fishing also impacts the reef through increased water pollution from boats, by-catch of unwanted species (such as dolphins and turtles) and habitat destruction from trawling, anchors and nets. As of the middle of 2004, approximately one-third of the Great Barrier Reef Marine Park is protected from species removal of any kind, including fishing, without written permission.

Shipping

The *Shen Neng 1* aground on the Great Barrier Reef, 5 April 2010.

Shipping accidents are a pressing concern, as several commercial shipping routes pass through the Great Barrier Reef. Although the route through the Great Barrier Reef is not easy, reef pilots consider it safer than outside the reef in the event of mechanical failure, since a ship can sit safely while being repaired. There have been over 1,600 known shipwrecks in the Great Barrier Reef region. On 3 April 2010, bulk coal carrier Shen Neng 1 ran aground on Douglas Shoals, spilling up to four tonnes of oil into the water and causing extensive damage to the reef.

Human use

The Great Barrier Reef has long been known to and used by the Aboriginal Australian and Torres Strait Islander peoples. Aboriginal Australians have been living in the area for at least 40,000 years, and Torres Strait Islanders since about 10,000 years ago. For these 70 or so clan groups, the reef is also an important cultural feature.

In 1768, Louis de Bougainville found the reef during an exploratory mission, but did not claim the area for the French. On June 11, 1770, the HM Bark *Endeavour*, captained by explorer James Cook, ran aground on the Great Barrier Reef, sustaining considerable damage. Lightening the ship and re-floating it during an incoming tide eventually saved it. One of the most famous wrecks was the HMS *Pandora*, which sank on August 29, 1791, killing 35. The Queensland Museum has led archaeological digs to the *Pandora* since 1983. Because the reef had no atolls, it was largely unstudied in the 19th century. During this time, some of the reef's islands were mined for deposits of guano, and lighthouses were built as beacons throughout the system. as in Raine Island, the earliest example. In 1922, the Great Barrier Reef Committee began carrying out much of the early research on the reef.

Starfish on coral. Tourists often photograph the natural beauty of the reef.

Management

Royal Commissions disallowed oil drilling in the Great Barrier Reef, in 1975 the Government of Australia created the Great Barrier Reef Marine Park and prohibited various activities. The Great Barrier Reef Marine Park does not include the entire Great Barrier Reef Province. The park is managed, in partnership with the Government of Queensland, through the Great Barrier Reef Marine Park Authority to ensure that it is used in a sustainable manner. A combination of zoning, management plans, permits, education and incentives (such as eco-tourism certification) are employed in the effort to conserve the reef.

In 1999, the Australian Parliament passed the Environment Protect and Biodiversity Conservation Act which improved the operation of national environmental law by providing guidance about regional biodiversity conservation priorities. The marine bioregional planning process came from the implementation of this law. This process conserves marine biodiversity by considering the whole ecosystem a species is in and how different species interact in the marine environment. There are two steps to this process. The first step is to identify regional conservation priorities in the five (currently) different marine regions. The second step is to identify marine reserves (protected areas or marine parks) to be added to Australia's National Representative System of Marine Protected Areas. Like protected areas on land, marine reserves are created to protect biodiversity for generations to come. Marine reserves are identified based on criteria written in a document created by Australian and New Zealand Environment and Conservation Council entitled 'Guidelines for establishing the national representative system of marine protected areas,' also known as just "the Guidelines." These guidelines are nationally recognised and implemented at the local level based on the Australian policy for implementation outlined in the "Goals and Principles for the Establishment of the National Representative System of Marine Protected Areas in Commonwealth Waters." These policies are in place to make sure that a marine reserve is only added to the NRSMPA after careful evaluation of different data. The priorities for each region are created based on human and environmental threats and the Marine Bioregional Plans are drafted to address these priorities. To assess different region's priorities, three steps are taken, first, a bioregional profile is created, second, a bioregional plan is drafted and third, the plan is finalised. After the plan is finalized, activity in different bioregions may become limited based on particular threats an activity may pose.

In 2001, the GBRMPA released a report about the declining water quality in the Great Barrier Reef and detailed the importance of this issue. In repose to this report a joint initiative between the governments of Australia and Queensland to improve the water quality of the Great Barrier Reef. In 2003, the Australian and Queensland governments launched a joint initiative to improve the quality of water entering the Great Barrier Reef. The decline in the quality of water over the past 150 years (due to development) has contributed to coral bleaching, algal blooms and pesticide pollution. These forms of pollution have made the reef less resilient to climate change. When the plan was introduced in October in 2003, it originally contained 65 actions built on previous legislation. Their immediate goal was to halt and reverse the decline in water quality entering the reef by 2013. By 2020, they hope that the quality of the water entering in the reef improves enough so that it doesn't have a detrimental impact on the health of the Great Barrier Reef. To achieve these goals they decided to reduce pollutants in the water entering the reef and to rehabilitate and conserve areas of the reef that naturally help reduce water pollutants. In order to achieve the objectives described above, this plan focuses on non-point sources of pollution, which cannot be traced to a single source such as a waste outlet. The plan specifically targets nutrients, pesticides and sediment that make their way into the reef as a result of agricultural activities. Other non-point sources of pollution that are attributed to urban areas are covered under different legislation. In 2009 the plan was updated. The updated version states that to date, none of the efforts undertaken to improve the quality of water entering the reef has been unsuccessful. The new plan attempts to address this issue by “targeting priority outcomes, integrating industry and community initiatives and incorporating new policy and regulatory frameworks (Reef Plan 5).” This updated version has improved the clarity of the previous plan and targets set by that plan, have improved accountability and further improved monitoring and assessment. The 2009 report found that 41 out of the 65 actions met their original goals, however, 18 were not progressing well according to evaluation criteria as well as 6 were rated as having unsatisfactory levels of progress. Some key achievements made since the plan’s initial passing in 2003 were the establishment of the Reef Quality Partnership to set targets, report findings and monitor progress towards targets, improved land condition by landowners was rewarded with extended leases, Water Quality Improvement Plans were created to identify regional targets and identified management changes that needed to be made to reach those targets, Nutrient Management Zones have been created to combat sediment loss in particular areas, education programs have been started to help gather support for sustainable agriculture, changes to land management practices have taken place through the implementation of the Farm Management Systems and codes of practice, the creation of the Queensland Wetland program and other achievements were made to help improve the water quality flowing into the coral reefs. A taskforce of scientists was also created to assess the impact of different parts of the plan on the quality of water flowing into the coral reefs. They found that many of the goals have yet to be reached but found more evidence that states that improving the water quality of the Great Barrier Reef will improve its resilience to climate change. The Reefocus summit in 2008, which is also detailed in the report, came to similar conclusions. After this, a stakeholder working group was formed that worked between several groups as well as the Australian and Queensland governments to update reef goals and objectives. The updated version of the plan focuses on strategic priority areas and actions to achieve 2013 goals. Also quantitative targets have been made in order to critically assess whether targets are being met. Some examples of the water quality goals outlined by this plan are that by 2013, there will be a 50 percent reduction in nitrogen and phosphorus loads at the end of catchments and that by 2020, there will be a reduction in sediment load by 20 percent. The plan also outlines a number of steps that must be taken by landholders to help improve grazing, soil, nutrient and chemical management practices. There are also a number of supporting initiatives to take place outlined in the plan to help create a framework to improve land use practices which will in turn improve water quality. Through these means the governments of Australia and Queensland hope to improve water quality by 2013. The 2013 outlook report and revised water quality plan will assess what needs to be done in the future to improve water quality and the livelihoods of the wildlife that resides there.

In July 2004, a new zoning plan took effect for the entire Marine Park, and has been widely acclaimed as a new global benchmark for marine ecosystem conservation. The rezoning was based on the application of systematic conservation planning techniques, using MARXAN software. While protection across the Marine Park was improved, the highly protected zones increased from 4.5% to over 33.3%. At the time, it was the largest marine protected area in the world, although in 2006, the new Northwestern Hawaiian Islands National Monument became the largest.

In 2006, a review of the *Great Barrier Reef Marine Park Act 1975* recommended are that there should be no further zoning plan changes until 2013, and that every five years, a peer-reviewed Outlook Report should be published, examining the reef's health, management, and environmental pressures. In each outlook report, several assessments are required. Each assessment has a set of assessment criteria that allows for better presentation of available evidence. Each assessment is judged by these criteria and given a grade. Every outlook report follows the same judging and grading process so that information can be tracked over time. No new research is done to produce the report. Only readily available information goes into the report so little of what is known about the Reef is actually featured in each outlook report.

Tourism

Due to its vast biodiversity, warm clear waters and accessibility from the tourist boats called 'live aboards', the reef is a very popular destination, especially for scuba divers. Tourism on the Great Barrier Reef is concentrated in the Whitsundays and Cairns due to their accessibility. These areas make up 7% of the Park's area. The Whitsundays and Cairns have their own Plans of Management. Many cities along the Queensland coast offer daily boat trips. Several continental and coral cay islands are now resorts, including the pristine Lady Elliot Island. As of 1996, 27 islands on the Great Barrier Reef supported resorts.

A scuba diver looking at a giant clam on the Great Barrier Reef

Domestic tourism made up most of the tourism in the region as of 1996, and the most popular visiting times were in the Australian winter. It was estimated that tourists to the Great Barrier Reef contributed $AU 776 million per annum at this time.

As the largest commercial activity in the region, it was estimated in 2003 that tourism in the Great Barrier Reef generates over AU$4 billion annually. (A 2005 estimate puts the figure at AU$5.1 billion.) Approximately two million people visit the Great Barrier Reef each year. Although most of these visits are managed in partnership with the marine tourism industry, there is a concern amongst the general public that tourism is harmful to the Great Barrier Reef.

A variety of boat tours and cruises are offered, from single day trips, to longer voyages. Boat sizes range from dinghies to superyachts. Glass-bottomed boats and underwater observatories are also popular, as are helicopter flights. By far, the most popular tourist activities on the Great Barrier Reef are snorkelling and diving, for which pontoons are often used, and the area is often enclosed by nets. The outer part of the Great Barrier Reef is favoured for such activities, due to water quality.

Management of tourism in the Great Barrier Reef is geared towards making tourism ecologically sustainable. A daily fee is levied that goes towards research of the Great Barrier Reef. This fee ends up being 20% of the GBRMPA's income. Policies on cruise ships, bareboat charters, and anchorages limit the traffic on the Great Barrier Reef.

Fishing

The fishing industry in the Great Barrier Reef, controlled by the Queensland Government, is worth AU$1 billion annually. It employs approximately 2000 people, and fishing in the Great Barrier Reef is pursued commercially, for recreation, and as a traditional means for feeding one's family.

Chapter- 8

New Caledonia Barrier Reef

Lagoons of New Caledonia: Reef Diversity and Associated Ecosystems*	
UNESCO World Heritage Site	

State Party	France
Type	Natural
Criteria	vii, ix, x
Reference	1115
Region**	Europe and North America
Inscription history	
Inscription	2008 (32nd Session)

* Name as inscribed on World Heritage List.

** Region as classified by UNESCO.

The **New Caledonia Barrier Reef** is located in New Caledonia in the South Pacific, and is the second-longest double-barrier coral reef in the world, after Australia's Great Barrier Reef.

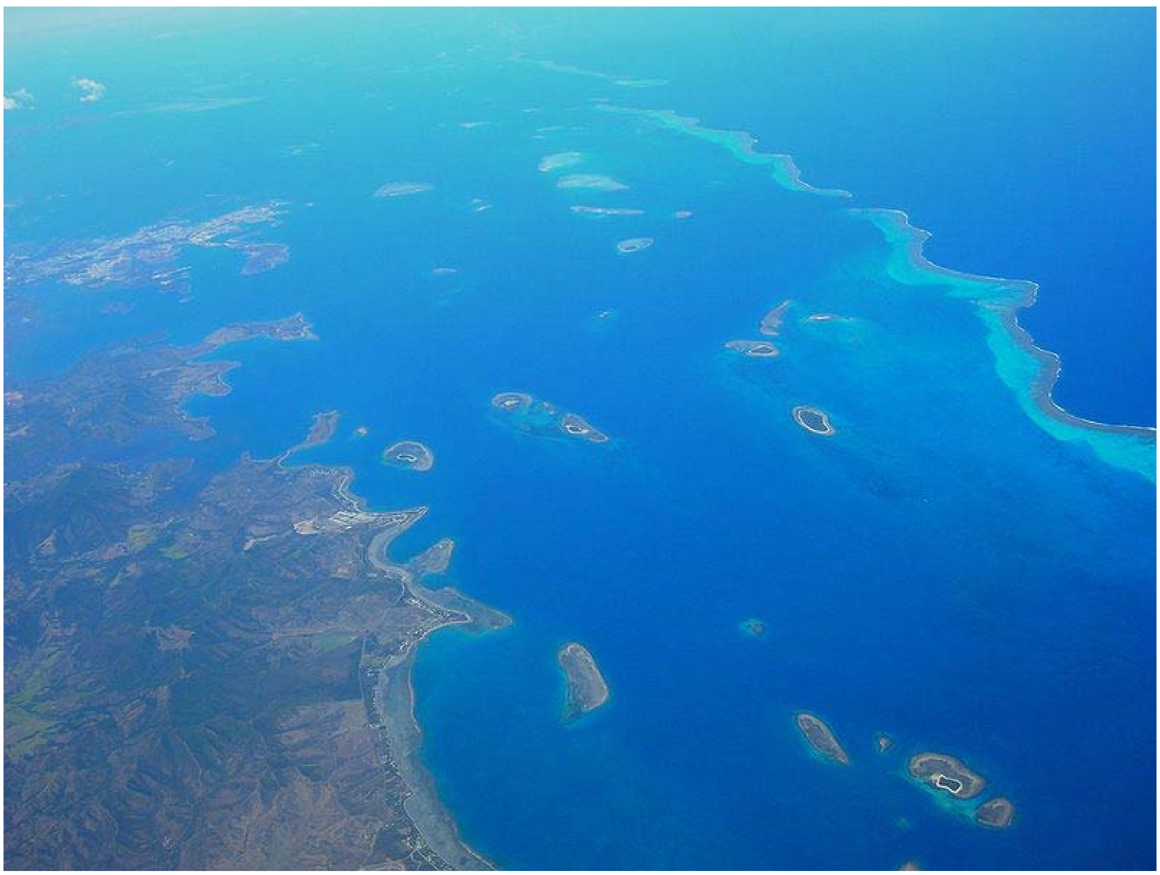
The New Caledonia Barrier reef surrounds Grand Terre, New Caledonia's largest island, as well as the Ile des Pins and several smaller islands, reaching a length of 1,500 kilometers (930 mi). The reef encloses a lagoon of 24,000 square kilometers (9,300 sq mi), which has an average depth of 25 meters (82 ft). The reefs lie up to 30 kilometers (19 mi) from the shore, but extend almost 200 kilometers (124 mi) to the Entrecasteaux reefs in the northwest. This northwestern extension encloses the Belep Islands and other sand cays. Several natural passages open out to the ocean. The Boulari passage, which leads to Noumea, the capital and chief port of New Caledonia, is marked by the Amédée lighthouse.

The reef has great species diversity with a high level of endemism, and is home to endangered dugongs *(Dugong dugon)*, and is an important nesting site for Green Sea Turtle *(Chelonia mydas)*.

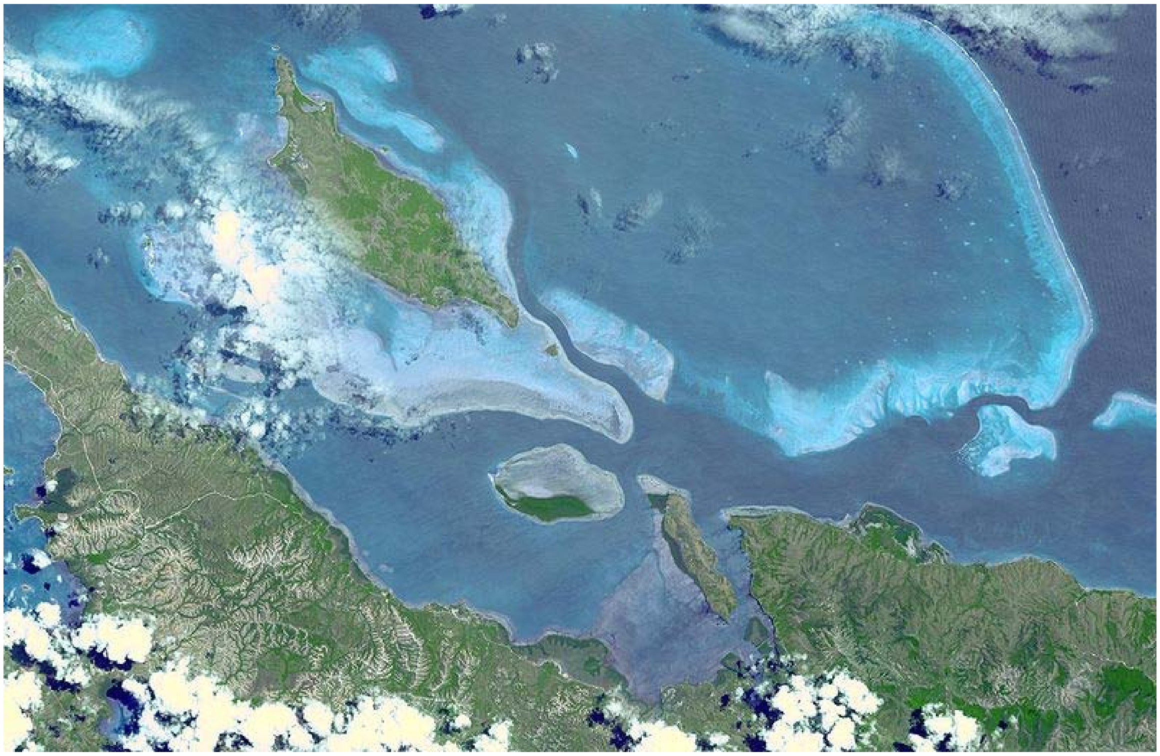
Most of the reefs are generally thought to be in good health. Some of the eastern reefs have been damaged by effluent from nickel mining on Grand Terre. Sedimentation from mining, agriculture, and grazing has affected reefs near river mouths, which has been worsened by the destruction of mangrove forests, which help to retain sediment. Some reefs have been buried under several meters of silt.

In the lagoons of New Caledonia there are many water species ranging from plankton to larger fish and even sharks.

In January 2002, the French government proposed listing New Caledonia's reefs as a UNESCO World Heritage Site. UNESCO listed New Caledonia Barrier Reef on the World Heritage List under the name *The Lagoons of New Caledonia: Reef Diversity and Associated Ecosystems* on 7 July 2008. The Lagoons were listed under three UNESCO categories: 1.Superlative natural Phenomena or natural beauty. 2.Ongoing Biological and ecological processes. 3.Biological Diversity and threatened species.



This part of the lagoon, near Dumbéa and Païta, in the North-West of Nouméa, is not included in the UNESCO world heritage sites.



ASTER image of the lagoons.

Chapter- 9

Environmental Issues with Coral Reefs

Island with fringing reef off Yap, Micronesia. Coral reefs are dying around the world.

Coral reefs are dying around the world. In particular, coral mining, pollution (organic and non-organic), overfishing, blast fishing and the digging of canals and access into islands and bays are serious threats to these ecosystems. Coral reefs also face high dangers from pollution, diseases, destructive fishing practices and warming oceans. In order to find answers for these problems, researchers study the various factors that impact reefs. The list of factors is long, including the ocean's role as a carbon dioxide sink, atmospheric changes, ultraviolet light, ocean acidification, biological virus, impacts of dust storms carrying agents to far flung reefs, pollutants, algal blooms and others. Reefs are threatened well beyond coastal areas.

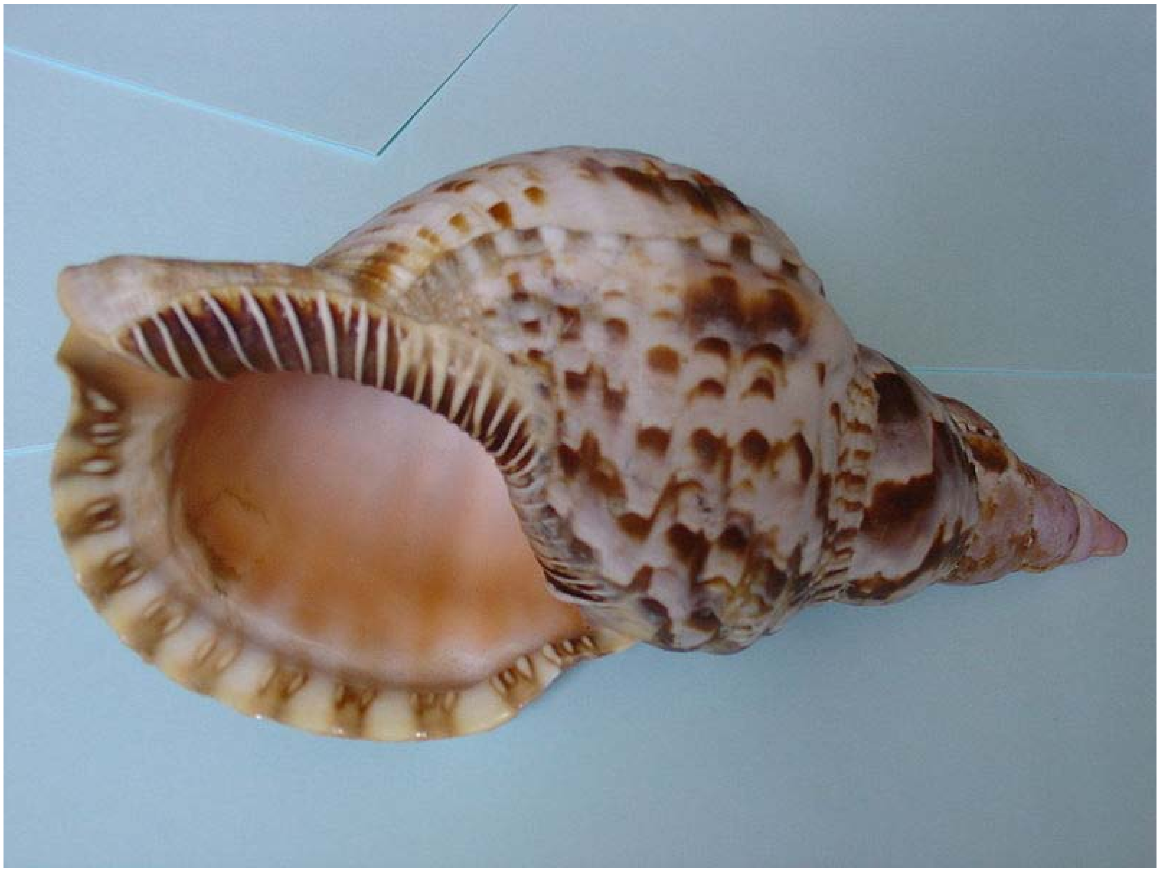
General estimates show approximately 10% world's coral reefs are already dead. It is estimated that about 60% of the world's reefs are at risk due to destructive, human-related activities. The threat to the health of reefs is particularly strong in Southeast Asia, where 80% of reefs are endangered.

Issues

Fishing practices

Many valuable fishery species live around coral reefs. Shark and reef fish are fished intensively for fish markets. Seahorses and sea cucumbers are harvested for Chinese pharmacopeia. Lobster are sought for the tourist industry, and shrimp for the export trade.

Overfishing, particularly selective overfishing, can unbalance coral ecosystems by encouraging the excessive growth of coral predators. Predators which eat living coral, such as the crown-of-thorns starfish, are called *corallivores*. Coral reefs are built from stony coral, which evolved with large amounts of the wax cetyl palmitate in their tissues. Most predators find this wax indigestible. The crown-of-thorns starfish is a large (up to one metre) starfish protected with long, venomous spikes. It has an enzyme system which dissolves the wax in stony corals, and allows the starfish to feed on the living coral. Normally the starfish are kept under control by the giant triton sea snail. However, the giant triton is valued for its shell, and has been severely overfished. As a result, crown-of-thorns starfish populations can periodically explode without check, devastating coral reefs.



The overfished giant triton eats the crown of thorns starfish

The crown of thorns starfish eats coral

Although some aquarium fish species can reproduce in aquaria (such as Pomacentridae), most (95%) are collected from coral reefs. Intense harvesting, especially in South-East Asia (including Indonesia and the Philippines), damages the reefs. This is aggravated by destructive fishing practices, such as cyanide and blast fishing. Most (80–90%) aquarium fish from the Philippines are captured with sodium cyanide. This toxic chemical is dissolved in sea water and released into fish shelters. It narcotizes fish, which are then easily captured. However, most fish collected with cyanide die a few months later from liver damage. Moreover, non-marketable species die in the field. A major catalyst of cyanide fishing is poverty within fishing communities. In areas like the Philippines where the cyanide is regularly used, the percentage of the population below the poverty line is 40%. In such developing countries, a fisherman might resort to such practices to protect his family from starvation.

Dynamite fishing is another destructive method for gathering fish. Sticks of dynamite, grenades, or home-made explosives are simply thrown in the water. This method of fishing kills the fish within the main blast area, along with many inedible and/or unwanted reef animals. The blast also kills the corals in the area, eliminating the very structure of the reef, destroying the habitat for fish and other animals important for the maintenance of a healthy reef. Other destructive fishing methods, such as muroami and kayakas, kill all fish in certain areas, causing havoc on the ecosystem of the reef.

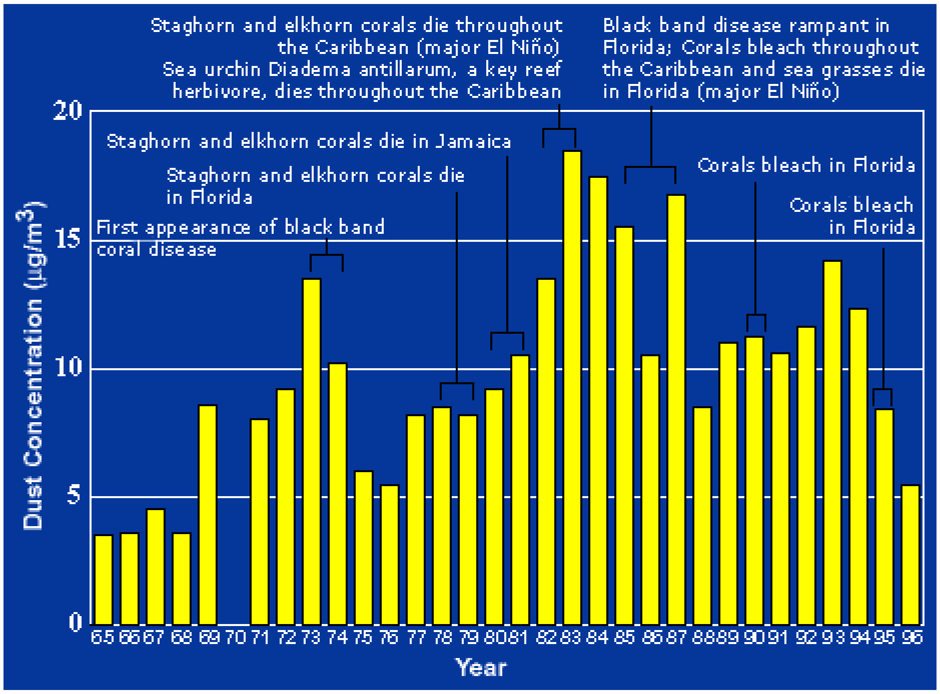
Hughes, et al., (2003), wrote that "with increased human population and improved storage and transport systems, the scale of human impacts on reefs has grown exponentially. For example, markets for fish and other natural resources have become global, supplying demand for reef resources."

Pollution

This image of an algae bloom off the southern coast of England, though not in a coral region, shows what a bloom can look like from a satellite remote sensing system

Runoff caused by farming and construction of roads, buildings, ports, channels, and harbours, can carry soil laden with carbon, nitrogen, phosphorus, and minerals. This nutrient-rich water can cause fleshy algae and phytoplankton to thrive in coastal areas, known as algal blooms, which have the potential to create hypoxic conditions by using all available oxygen. Some algae are toxic, and both plants reduce the levels of sunlight and oxygen, killing marine organisms such as fish and coral. The addition of too many nutrients such as phosphates and nitrates, a process known as eutrophication, is very damaging to reefs. High nitrate levels are toxic to corals, while phosphates slow down the growth of coral skeleton.

Reefs in close proximity to human populations can be faced with local stresses, including poor water quality from land-based sources of pollution. Copper, a common industrial pollutant has been shown to interfere with the life history and development of coral polyps. Poor water quality has also been shown to encourage the spread of infectious diseases among corals.



Barbados dust graph

In addition to soil runoff, additional soil and sand is blown in from other regions. Dust from the Sahara moving around the southern periphery of the subtropical ridge moves into the Caribbean and Florida during the warm season as the ridge builds and moves northward through the subtropical Atlantic. Dust can also be attributed to a global transport from the Gobi and Taklamakan deserts across Korea, Japan, and the Northern Pacific to the Hawaiian Islands. Since 1970, dust outbreaks have worsened due to periods of drought in Africa. There is a large variability in dust transport to the Caribbean and Florida from year to year; however, the flux is greater during positive phases of the North Atlantic Oscillation. The USGS links dust events to a decline in the health of coral reefs across the Caribbean and Florida, primarily since the 1970s. Studies have shown that corals can incorporate dust into their skeletons as identified from dust from the 1883 eruption of Krakatoa in Indonesia in the annular bands of the reef-building coral *Montastraea annularis* from the Florida Reef tract.

Climate change

Unbleached and bleached coral

Any rise in the sea level due to climate change would effectively ask coral to grow faster to keep up. Also, water temperature changes can be very disturbing to the coral. This was seen during the 1998 and 2004 El Niño weather phenomena, in which sea surface temperatures rose well above normal, bleaching or killing many coral reefs. High seas surface temperature (SSTs) coupled with high irradiance (light intensity), triggers the loss of zooxanthellae, a symbiotic algae, and its dinoflagellate pigmentation in corals causing coral bleaching. Zooxanthellae provides up to 90% of the energy to the coral host. Reefs can often recover from bleaching if they are healthy to begin with and water temperatures cool. However, recovery may not be possible if CO_2 levels rise to 500 ppm because there may not be enough carbonate ions present. Refer to Hoegh-Guldberg 1999 for more information.

Warming may also be the basis of a new emerging problem: increasing coral diseases. Warming, thought to be the main cause of coral bleaching, weakens corals. In their weakened state, coral is much more prone to diseases including black band disease, white band disease and skeletal eroding band. If global temperatures increase by 2 °C, coral may not be able to adapt quickly enough physiologically or genetically. It has been estimated that, to counter the threat of ocean acidification through global warming, a reduction of up to 40% of current emissions is needed, and up to 95% by 2050. This requires emission reductions larger than the reductions currently proposed for these dates by the EU. A 2010 report by the Institute of Physics predicts that unless the national targets set by the Copenhagen Accord are amended to eliminate loopholes, then by 2100 global temperatures could rise by 4.2°C and result in an end to coral reefs.

Ocean acidification

Bamboo coral is an early harbinger of ocean acification

Another problem related to climate change is ocean acidification. Ocean acidification results from increases in the atmospheric carbon dioxide, which increases the amount of carbon dioxide dissolved in the oceans. The dissolved carbon dioxide gas reacts with the water to form carbonic acid, and thus acidifies the ocean. This decreasing ocean surface pH is another long-term concern for the survival of coral reefs.

Ocean surface pH is estimated to have decreased from about 8.25 to 8.14 since the beginning of the industrial era, and it is estimated that it will drop by a further 0.3–0.4 units by 2100 as the ocean absorbs more anthropogenic carbon dioxide. Normally, the conditions for calcium carbonate production are stable in surface waters since the carbonate ion is at supersaturating concentrations. However, as ocean pH falls, so does the concentration of this ion, and when carbonate becomes under-saturated, structures made of calcium carbonate are vulnerable to dissolution. Research has already found that corals experience reduced calcification or enhanced dissolution when exposed to elevated CO_2.

Bamboo coral is a deep sea coral which produces growth rings similar to a tree. The growth rings picture how growth rates change as deep sea condition change over time, and can also record changes due to ocean acidification. This coral is especially long-lived. Coral specimens as old as 4,000 years old have given scientists "4,000 years worth of information about what has been going on in the deep ocean interior".

Other issues

Coral sand from a beach on Aruba

Within the last 20 years, once prolific seagrass meadows and mangrove forests, which absorb massive amounts of nutrients and sediment, have been destroyed. Both the loss of wetlands, mangrove habitats and seagrass meadows affect the water quality of inshore reefs.

Coral mining is another threat. Both small scale harvesting by villagers and industrial scale mining by companies are serious threats. Mining is usually done to produce construction material which is valued as much as 50% cheaper than other rocks, such as from quarries. The rocks are ground and mixed with other materials, like cement to make concrete. Ancient coral used for construction is known as coral rag. Building directly on the reef also takes its toll, altering water circulation and the tides which bring the nutrients to the reef. The pressing reason for building on reefs is simply lack of space.

Eroded coral

Boats and ships require access points into bays and islands to load and unload cargo and people. For this, parts of reefs are often chopped away to clear a path. Although this may seems a minor destruction of the reef, negative consequences can include altered water circulation and altered tidal patterns which result in a turnaround in the reef's supply of nutrients; sometimes destroying a great part of the reef. Fishing vessels and other large boats occasionally run aground on a reef. Two types of damage can result. Collision damage occurs when a coral reef is crushed and split by a vessel's hull into multiple fragments. Scarring occurs when boat propellers tear off the live coral and expose the skeleton. The physical damage can be noticed as striations in the reefs. Mooring also causes damage which can be reduced by using mooring buoys.

Coral in Taiwan is being threatened by the influx of human population growth. Since 2007, several local environmental groups conducted research and found that much of the coral populations are being affected by untreated sewage, an influx of tourists taking corals for souvenirs, without fully understanding the destructive impact on the coral's ecological system. Researchers reported to the Taiwanese government that many coral populations have turned black in the southeast coast of Taiwan. Potentially, this could lead to loss of food supply, medicinal sources and tourism due to the break down of the food chain.

Threatened species

The global standard for recording threatened marine species is the IUCN Red List of Threatened Species. This list is the foundation for marine conservation priorities worldwide. A species is listed in the threatened category if it is considered to be critically endangered, endangered, or vulnerable. Other categories are near threatened and data deficient. By 2008, the IUCN had assessed all known reef-building corals species as follows

Group	Species	Threatened	Near threatened	Data deficient
Reef-building corals	845	27%	20%	17%

The coral triangle (Indo-Malay-Philippine archipelago) region has the highest number of reef-building coral species in threatened category as well as the highest coral species diversity. The loss of coral reef ecosystems will have devastating effects on many marine species, as well as on people that depend on reef resources for their livelihoods.

Issues by region

A NOAA (AOML) *in situ* pCO_2 sensor (SAMI-CO2), attached to a Coral Reef Early Warning System station in Discovery Bay, Jamaica, utilized in conducting ocean acidification studies near coral reef areas

Australia

The Great Barrier Reef is the world's largest coral reef system, composed of roughly 3,000 individual reefs and 900 islands that stretch for 2,600 kilometres (1,616 mi) and cover an area of approximately 344,400 km^2. The reef is located in the Coral Sea, off the coast of Queensland in northeast Australia. A large part of the reef is protected by the Great Barrier Reef Marine Park.

The Great Barrier Reef's environmental pressures include lowered water quality from runoff including suspended sediment, excess nutrients, pesticides, and fluctuations in salinity. The effects of climate change, including increased temperatures, storms and coral bleaching. Cyclic outbreaks of the crown-of-thorns starfish, overfishing which disrupts food chains, and shipping routes which can result in oil spills or improper ballast discharge also damage the ree

Southeast Asia

Southeast Asian coral reefs are at risk from damaging fishing practices (such as cyanide and blast fishing), overfishing, sedimentation, pollution and bleaching. A variety of activities, including education, regulation, and the establishment of marine protected areas are under way to protect these reefs.

Indonesia

Indonesia is home to a third of the world's total corals and a quarter of its fish species, nearly 33,000 square miles (85,000 km^2). Indonesia's coral reefs are located in the heart of the Coral Triangle and have fallen victim to destructive fishing, unregulated tourism, and bleaching due to climatic changes. Data from 414 reef monitoring stations in 2000 found that only 6% are in excellent condition, while 24% are in good condition, and approximately 70% are in poor to fair condition (2003 The Johns Hopkins University).

The Philippines

In 2007, Reef Check, the world's largest reef conservation organization, stated that only 5% of Philippines 27,000 square-kilometers of coral reef are in "*excellent condition*": Tubbataha Reef, Marine Park in Palawan, Apo Island in Negros Oriental, Apo Reef in Puerto Galera, Mindoro, and Verde Island Passage off Batangas. Philippine coral reefs is second largest in Asia.

Taiwan

Coral reefs in Taiwan are being threatened by the influx of human population growth. Since 2007, several local environmental groups have conducted research finding many coral are affected by untreated sewage and an influx of tourists taking corals for souvenirs, not knowing that this practice destroys the coral’s habitat and causes disease. Researchers reported to the Taiwanese government that many corals have turned black in the southeast coast of Taiwan. This could lead to a loss of tourism and a decrease in food and medicinal sources that make meeting the demands of millions of people more difficult.

Chapter- 10

Coral Reef Fish

The fish that inhabit coral reefs are numerous and diverse.

Coral reef fish are fish which live amongst or in close relation to coral reefs. Coral reefs form complex ecosystems with tremendous biodiversity. Among the myriad inhabitants, the fish stand out as particularly colourful and interesting to watch. Hundreds of species can exist in a small area of a healthy reef, many of them hidden or well camouflaged. Reef fish have developed many ingenious specialisations adapted to survival on the reefs.

Coral reefs occupy less than one percent of the surface area of the world oceans, yet they provide a home for 25 percent of all marine fish species. Reef habitats are a sharp contrast to the open water habitats that make up the other 99% of the world oceans.

However, loss and degradation of coral reef habitat, increasing pollution, and overfishing including the use of destructive fishing practices, are threatening the survival of the coral reefs and the associated reef fish.

Overview

In the foreground is an orange-lined triggerfish displaying spines. Triggerfish have mouths that crush shells. Orange-lined triggerfish are particularly aggressive. The black and white fish are three-stripe damselfish and the smaller fish are blue-green chromis damselfish. If the triggerfish attacks, the damselfish will hide in the nearby pillar coral. If the triggerfish wants to hide, it will squeeze into a coral crevice and lock itself in place with its spines.

Coral reefs are the result of millions of years of coevolution among algae, invertebrates and fish. They have become crowded and complex environments, and the fish have evolved many ingenious ways of surviving. Most fishes found on coral reefs are ray-finned fishes, known for the characteristic sharp, bony rays and spines in their fins. These spines provide formidable defences, and when erected they can usually be locked in place or are venomous. Many reef fish have also evolved cryptic coloration to confuse predators.

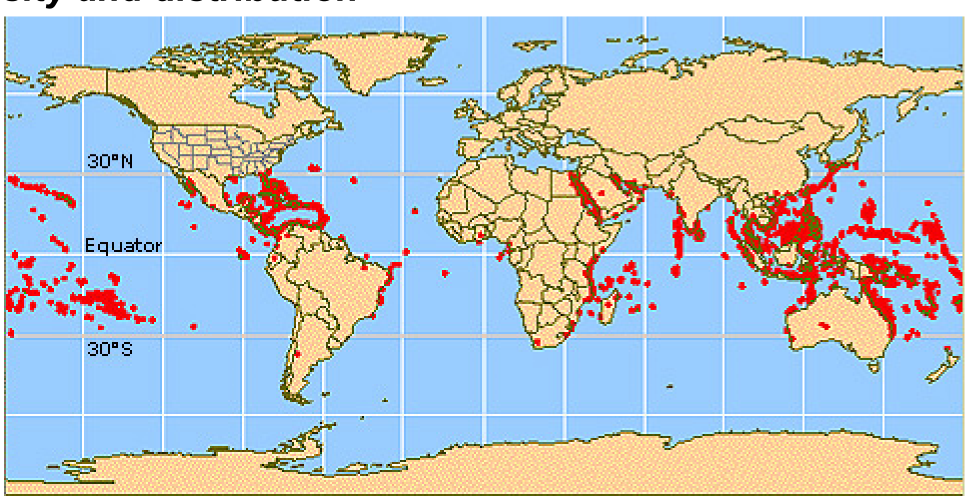
Reef fish have also evolved complex adaptive behaviours. Small reef fish get protection from predators by hiding in reef crevices or by shoaling and schooling. Many reef fish confine themselves to one small neighbourhood where every hiding place is known and can be immediately accessed. Others cruise the reefs for food in shoals, but return to a known area to hide when they are inactive. Resting small fish are still vulnerable to attack by crevice predators, so many fish, such as triggerfish, squeeze into a small hiding place and wedge themselves by erecting their spines.

As an example of the adaptations made by reef fish, the yellow tang is a herbivore which feeds on benthic turf algae. They also provide cleaner services to marine turtles, by removing algal growth from their shells. They do not tolerate other fish with the same colour or shape. When alarmed, the usually placid yellow tang can erect spines in its tail and slash at its opponent with rapid sideways movements.

Most coral reef fish have spines in their fins like this damselfish.

The usually placid yellow tang can erect spines in its tail and slash at its opponent with rapid sideways movements.

Diversity and distribution

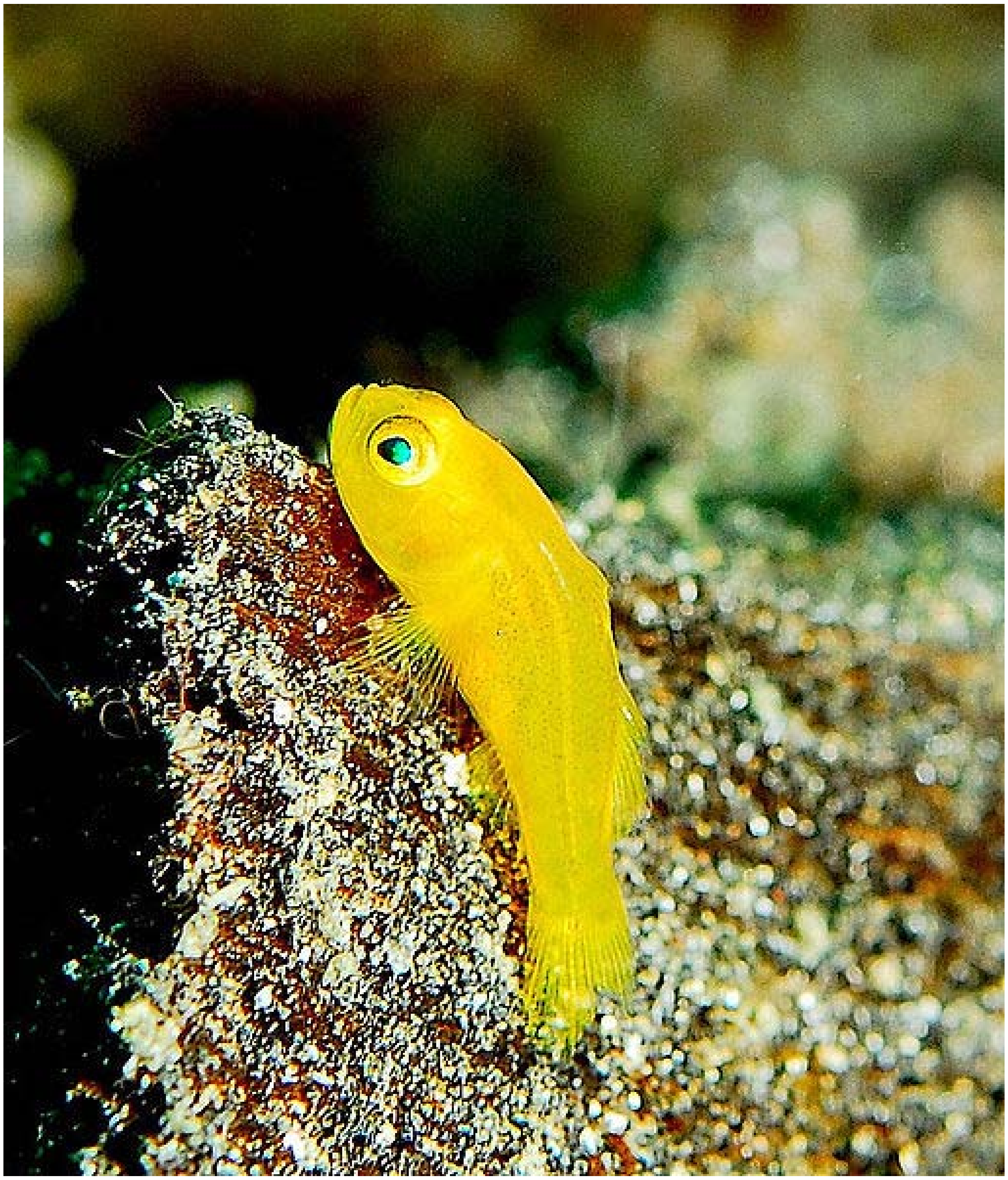


Distribution of coral reefs

Coral reefs contain the most diverse fish assemblages to be found anywhere on earth, with perhaps as many as 6,000-8,000 species that can be found dwelling within coral reef ecosystems of the world's oceans.

The mechanisms that first led to, and continue to maintain, such concentrations of fish species on coral reefs has been widely debated over the last 50 years. While many reasons have been proposed, there is no general scientific consensus on which of these is the most influential, but it seems likely that a number of factors contribute. These include the rich habitat complexity and diversity inherent in coral reef ecosystems, the wide variety and temporal availability of food resources available to coral reef fishes, a host of pre and post larval settlement processes, and as yet unresolved interactions between all these factors.

There are two major regions of coral reef development recognized; the Indo-Pacific (which includes the Pacific and Indian Oceans as well as the Red Sea), and the tropical western Atlantic (also known as the "wider" or "greater" Caribbean). Each of these two regions contains its own unique coral reef fish fauna with no natural overlap in species. Of the two regions, the richest by far in terms of reef fish diversity is the Indo-Pacific where there are an estimated 4,000-5,000 species of fishes associated with coral reef habitats. Another 500-700 species can be found in the greater Caribbean region.



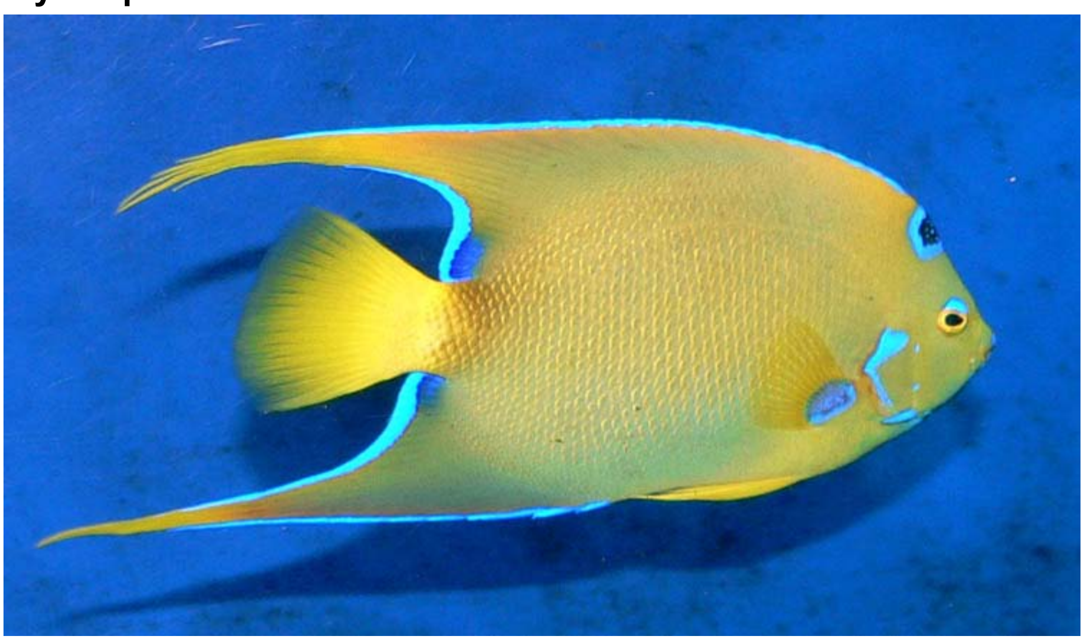
Among goby species, small coral reef-dwelling fishes, is the world's shortest lived vertebrate, the seven-figure pygmy goby, which lives for less than 60 days.

The slowest-moving fishes are the sea horses, often found in reefs. The slowest of these, the dwarf seahorse, attains about five feet per hour.

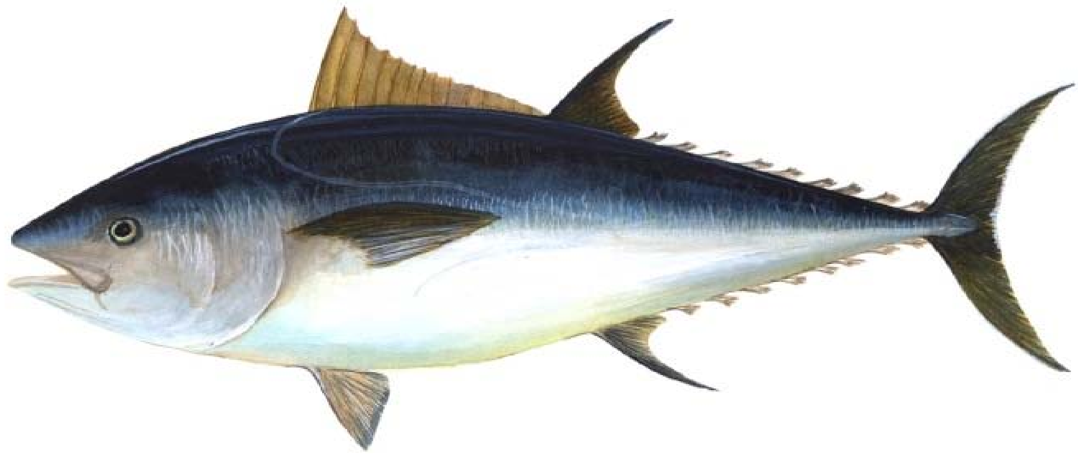
Toadfish often inhabit reefs. Male toadfish "sing" at up to 100 decibels with their swim bladders to attract mates.

Reef fish adaptations

Body shape



Many reef fish, like this queen angelfish, have a body flattened like a pancake, with pectoral and pelvic fins that act with the flattened body to maximize manoeuvrability.



Open water fish, like this Northern bluefin tuna, are usually streamlined for straightline speed, with a deeply forked tail and a smooth body shaped like a spindle tapered at both ends. They are countershaded with silvery colours.

Most reef fishes have body shapes that are different from open water fishes. Open water fishes are usually built for speed in the open sea, streamlined like torpedoes to minimise friction as they move through the water. Reef fish are operating in the relatively confined spaces and complex underwater landscapes of coral reefs. For this manoeuvrability is more important than straight line speed, so coral reef fish have developed bodies which optimize their ability to dart and change direction. They outwit predators by dodging into fissures in the reef or playing hide and seek around coral heads.

Many reef fish, such as butterflyfish and angelfishes, have evolved bodies which are deep and laterally compressed like a pancake. Their pelvic and pectoral fins are designed differently, so they act together with the flattened body to optimise manoeuvrability.

Colouration

The psychedelic mandarinfish is one of only two animal species known to have blue colouring because of cellular pigment. They are not easily seen due to their bottom-feeding habit and their small size, reaching only about 6 cm. They feed primarily on small crustaceans and other invertebrates, and are popular in the aquarium trade.

Coral reef fishes exhibit a huge variety of dazzling and sometimes bizarre colours and patterns. This is in marked contrasts to open water fishes which are usually countershaded with silvery colours.

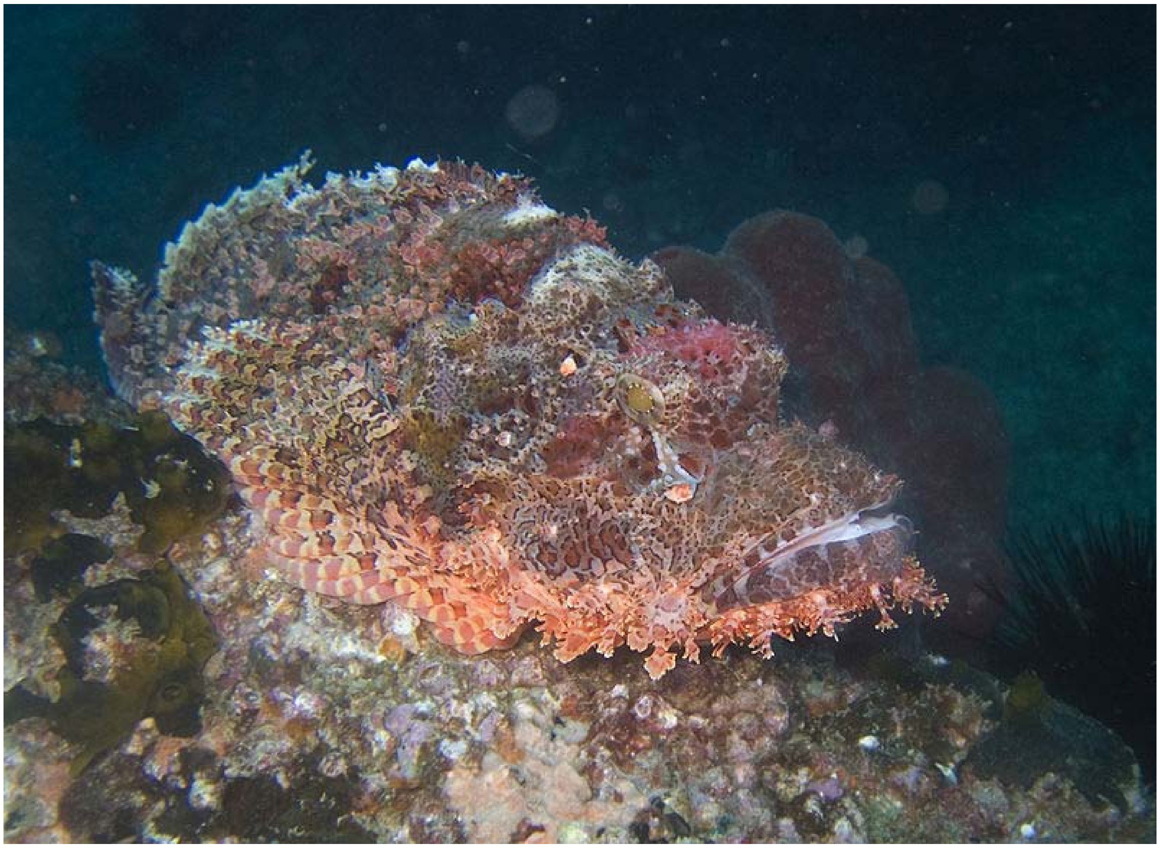
The patterns have different functions. Sometimes they camouflage the fish when the fish rests in places with the right background. Colouration can also be used to help species recognition during mating. Some unmistakable contrasting patterns are used to warn predators that the fish has venomous spines or poisonous flesh.

The foureye butterflyfish gets its name from a large dark spot on the rear portion of each side of the body. This spot is surrounded by a brilliant white ring, resembling an eyespot. A black vertical bar on the head runs through the true eye, making it hard to see. This can result in a predator thinking the fish is bigger than it is, and confusing the back end with the front end. The butterflyfish's first instinct when threatened is to flee, putting the false eyespot closer to the predator than the head. Most predators aim for the eyes, and this false eyespot tricks the predator into believing that the fish will flee tail first. When escape is not possible, the butterflyfish will sometimes turn to face its aggressor, head lowered and spines fully erect, like a bull about to charge. This may serve to intimidate the other animal or may remind the predator that the butterflyfish is too spiny to make a comfortable meal.

Just as some prey species evolved cryptic colouration and patterns to help avoid predators, some ambush predators evolved camouflage that lets them ambush their prey. The tassled scorpionfish is an ambush predator that looks like part of a sea floor encrusted with coral and algae. It lies in wait on the sea floor for crustaceans and small fish, such as gobies, to pass by.

Gobies avoid predators by tucking themselves into coral crevices or partly burying themselves in sand. They continually scan for predators with eyes that swivel independently. The camouflage of the tassled scorpionfish can prevent gobies from seeing them until it's too late.

The foureye butterflyfish has false eyes on its back end, confusing predators about which is the front end of the fish.



The tassled scorpionfish is an ambush predator camouflaged to look like part of a coral encrusted sea floor.

Gobies are very cautious, yet they can fail to see a tassled scorpionfish until it is too late.

A frogfish disguised as an algae-covered stone

The well camouflaged striated frogfish, a species of anglerfish, are ambush predators. They lie on the bottom and wave a conspicuous worm-like lure strategically attached above their mouth. Normally about 10 cm (4 in) long, they can also inflate themselves like puffers.

Clown triggerfish

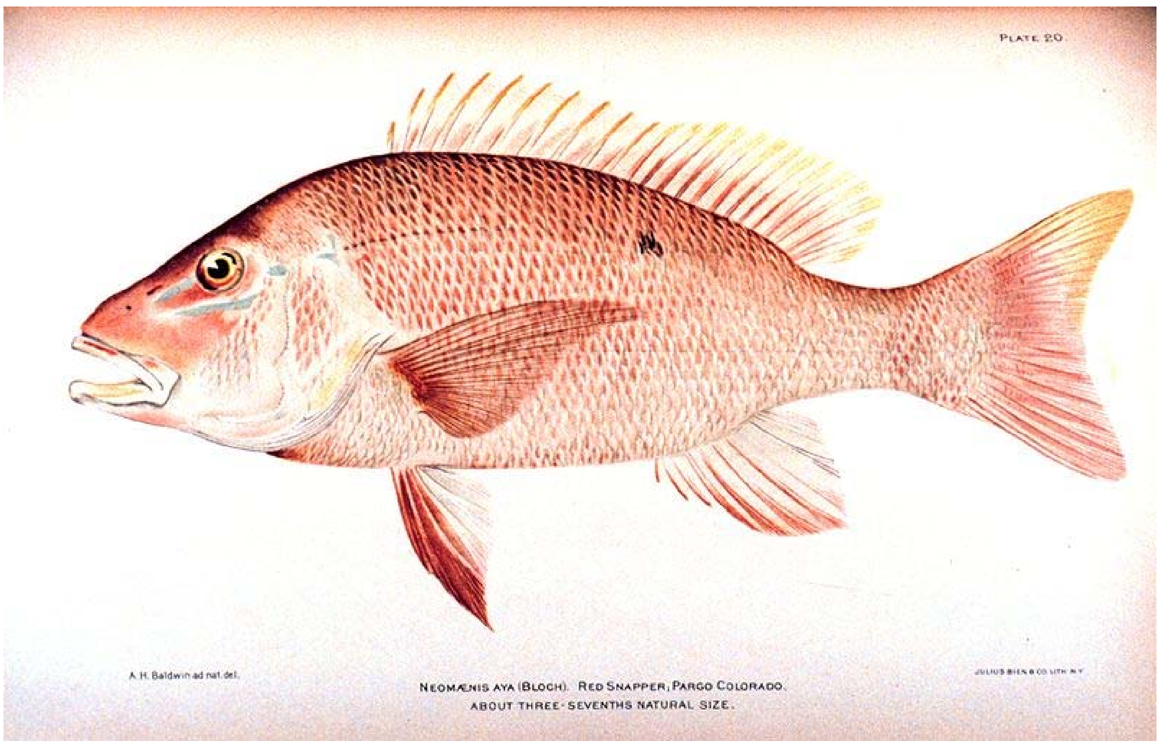
The clown triggerfish has strong jaws for crushing and eating sea urchins, crustaceans and hard-shell molluscs. Its ventral (lower) surface has large, white spots on a dark background, and its dorsal (upper) surface has black spots on yellow. This is a form of countershading: from below, the white spots look like the lighted surface of the water above; and from above, the fish blends more with the coral reef below. The brightly painted yellow mouth may deter potential predators.

Feeding strategies

Many reef fish species have evolved different feeding strategies accompanied by specialized mouths, jaws and teeth particularly suited to deal with their primary food sources found in coral reef ecosystems. This is not surprising, given the huge variety in the types of prey on offer around coral reefs.

For example, the primary food source of butterflyfishes are the coral polyps themselves or the appendages of polychaetes and other small invertebrate animals. Their mouths protrude like forceps, and are equipped with fine teeth that allow them to nip off such exposed body parts of their prey. Parrotfishes eat algae growing on reef surfaces, utilizing mouths like beaks well adapted to scrape off their food. Other fish, like snapper, are generalized feeders with more standard jaw and mouth structures that allow them to forage on a wide range of animal prey types, including small fishes and invertebrates.

Generalized carnivores



Red snapper, are generalized reef feeders with standard jaw and mouth structures that allow them to eat almost anything, though they prefer small fish and crustaceans.

Carnivores are the most diverse of feeding types among coral reef fishes. There are many more carnivore species on the reefs than herbivores. Competition among carnivores is intense, resulting in a treacherous environment for their prey. Hungry predators lurk in ambush or patrol every part of the reef, night and day.

Some fishes associated with reefs are generalized carnivores that feed on a variety of animal prey. These typically have large mouths that can be rapidly expanded, thereby drawing in nearby water and any unfortunate animals contained within the inhaled water mass. The water is then expelled through the gills with the mouth closed, thereby trapping the helpless prey For example, the bluestripe snapper has a varied diet, feeding on fishes, shrimps, crabs, stomatopods, cephalopods and planktonic crustaceans, as well as plant and algae material. Diet varies with age, location and the prevalent prey items locally.

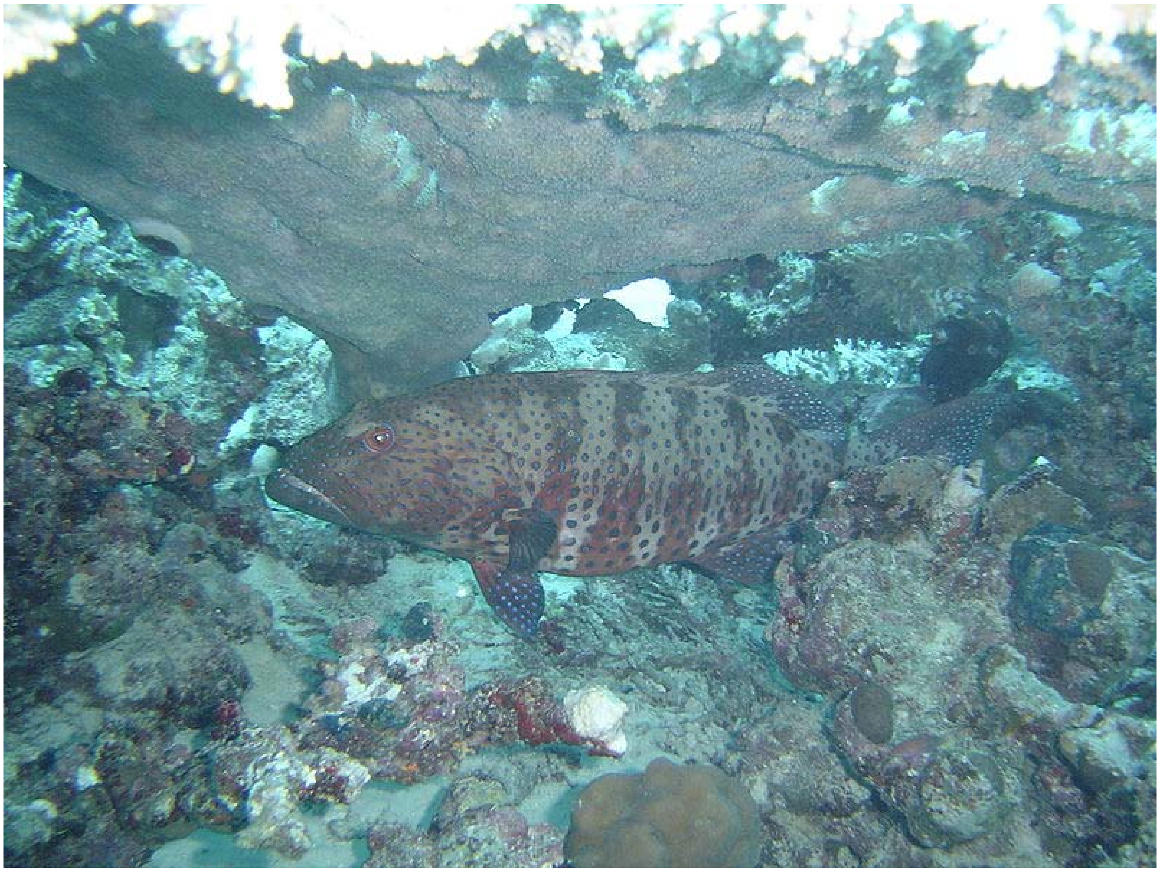
Goatfish are tireless benthic feeders, using a pair of long chemosensory barbels (whiskers) protruding from their chins to rifle through the sediments in search of a meal. Like goats, they seek anything edible: worms, crustaceans, molluscs and other small invertebrates are staples. The yellowfin goatfish (*Mulloidichthys vanicolensis*) often schools with the blue-striped snapper. The yellowfins change their colouration to match that of the snapper. Presumably this is for predator protection, since goatfish are a more preferred prey than bluestripe snapper. By night the schools disperse and individual goatfish head their separate ways to loot the sands. Other nocturnal feeders shadow the active goatfish, waiting patiently for overlooked morsels.

Moray eels and coral groupers (*Plectropomus pessuliferus*) are known to cooperate with each other when hunting. Grouper are protogynous hermaphrodites, who school in *harems* of three to fifteen females. When no male is available, the most aggressive and largest females shift sex to male, probably as a result of behavioural triggers.

Adult coral trout hunt a variety of reef fish, particularly damselfish, while their juveniles mostly eat crustaceans such as prawns.

Bluestripe snapper eat just about anything.

Yellowfin goatfish change their colouration so they can school with the blue-striped snapper.



Coral grouper sometimes cooperate with giant morays in hunting.