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Coral Reefs and Climate Change

Coral reefs are found in only a small percentage of global oceans, between 0.08 and 0.16%, but they shelter about one third of the marine species known today. This ecological success is due to a symbiosis between a coral and an intracellular microalga, commonly called zooxanthellae. "Organismic engineers", they are the source of the largest biological constructions on the planet. Genuine oases of life, they support the direct sustenance of more than 500 million people in the world from fishing, but they engage human interest also for other reasons: protection of coasts against erosion, high value tourist areas... Ecological services from coral reefs are estimated at approximately 30 billion USD per year. Their growth depends on many factors (light, temperature, pH, nutrients, turbidity...). They are therefore extremely sensitive to the current changes in our environment: water temperature variability, ocean acidification, in addition to localized disruptions (pollution, sedimentation, coastal development, overfishing, marine shipping...). An increase of less than 1 degree above a threshold value is sufficient to cause bleaching. It breaks the coral symbiosis with their zooxanthellae throughout the populations, leading to the disappearance of the reef. Similarly, ocean acidification impedes the formation of coral skeleton and many other biological functions such as reproduction. We actually estimate that approximately 20% of the global coral reefs have already disappeared completely; 25% are in high danger; and 25% more will be threatened by 2050 if positive management action is not taken.

WHAT IS A CORAL REEF?

Coral reefs are ecosystems typically found in shallow waters of the intertropical zone (approximately between 33° North and 30° South). The three-dimensional architecture of this ecosystem is formed by the buildup of calcareous skeletons of marine organisms called reef-building corals (Cnidaria, Scleractinia). They are cemented together by the biological activity of calcareous organisms (macroalgae, sponges, worms, molluscs…). Corals are named "engineering organisms", while the reef is considered "biogenic" because it is the result of biological activity. Coral reefs therefore represent ecosystems that have been built by their own inhabitants.

The total area covered by coral reefs varies, depending on the calculation methods, between 284,300 km² (Smith, 1978) and 617,000 km² (Spalding *et al.*, 2001), therefore covering between 0.08 and 0.16% of the surface of the ocean. French reefs alone cover an area of 55,557 km².

The largest reef is the Great Barrier Reef which runs along the north-eastern coast of Northern Australia over a distance of 2300 km. It is known as the only animal construction visible from space. The second largest reef is French New Caledonia Barrier, which is 1600 km long. These two barrier reefs have been included in the UNESCO World Heritage list (respectively in 1981 and 2008).

Coral reefs come in different shapes and sizes, the first published description dating from Charles Darwin during his voyage on the Beagle (Darwin, 1842):

- Fringing reefs: They follow the coastline, maintaining an active growth area offshore and an accumulation of dead coral inshore, forming a platform reef that over time turns into a lagoon.

- Barrier reefs: the fringing reef becomes a barrier reef subsequent to the progressive sinking of an island. In this way, the lagoon becomes larger and the reef can extend to 1 km from the coast.
- Atolls: these are the ultimate step in the evolution of a reef, where the island has completely disappeared below the sea surface. Atolls preserve the initial circular shape of the island. There are approximately 400 atolls in the world.

Reef growth is approximatively 4 kg of calcium carbonate ($CaCO_3$) per m² per year (Smith & Kinsey, 1976), but values can vary considerably from one reef to another, in some cases reaching up to 35 kg $CaCO_3$/m²/year (Barnes & Chalker, 1990), *i.e.* a vertical annual growth rate of 1 to more than 10 cm. Many factors influence these growth rates: light, temperature (optimal between 22° and 29°C), nutrients, currents, turbidity, pH and the saturation state of calcium carbonate in the seawater…

The formation of calcium carbonate by reef-building organisms causes the release of carbon dioxide into the surrounding environment. Hence, contrary to past belief, a reef mainly dominated by coral acts as a minor source and not as a sink of CO_2 (about 1.5mmol CO_2/m² day. Tambutté *et al.,* 2011 for a review). Nevertheless, reefs still do play an important role as a carbon sink (as $CaCO_3$), with rates of the order of 70 to 90 million tonnes of carbon per year (Frankignoulle & Gattuso, 1993).

CORALS, AT THE ORIGIN OF THE REEF

Reefs are mainly built by corals. Formerly known as stony corals, reef-building corals are now included in the Order of Scleractinians (subclass Hexacorallia, class Anthozoa of phylum Cnidaria). Among the Scleractinia, about half the amount of species (about 660 out of 1,482 species known to date, Cairns, 1999) are involved in reef construction. These are called hermatypic. They consist of polyps of variable sizes, depending on the species, and form functional units. Each polyp has a mouth surrounded by tentacles. The polyps are connected to each other by network of cavities, the coelenteron, which covers the coral tissue. The whole assemblage is known as colonial (even though the colony functions as a single organism) while individual corals are called modular animals. They present various shapes and sizes, depending on whether the species are branching coral, blade coral, encrusting, or massive coral for example, and show growth rates that can exceed 15 cm per year of axial growth in their natural environment (Dullo, 2005). The size of certain massive corals may even exceed 6 m in diameter.

The success rate for a reef to develop and to thrive is mainly related to the capability of the majority of scleractinian corals (just under 900 species, Michel Pichon, Comm. Pers.) to establish a mutual symbiosis with photosynthetic dino agellates commonly called zooxanthellae (*e.g.* Symbiodinium sp.). These microalgae reside inside the coral's gastroderm, isolated from the animal's cytoplasm by a perisymbiotic membrane that regulates the exchanges between the symbionts and the host (Furla *et al.,* 2011 for a review). To this day, 9 clades of zooxanthellae, that are potentially different species, exist (Pochon & Gates 2010). Each one presents unique characteristics, which suggests that they could condition the adaptation of corals to a given environment. These two partners have co-evolved since the Triassic (Muscatine *et al.,* 2005), developing unique abilities (*e.g.* the ability for the hosts to actively absorb CO_2 and nutrients and to protect themselves from ultraviolet rays, hyperoxia and oxidative stress; the ability of the algal symbiont to exchange nutrients with its host; Furla *et al.,* 2005, 2011). Due to the presence of zooxanthellae, the distribution of corals at depth is dependent upon light availability (generally between 0 and 30 m depth). By means of modern sequencing techniques, a large diversity in bacteria has been identi ed inside corals. These bacteria appear to play an important physiological role. The entire community of these living organisms forms a functional unit called aholobiont, often referred to as a super-organism.