CORAL REEF REGENERATION

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Contents

Summary

Reefs are degrading worldwide at an alarming rate. The causes of degradation are multiple. They include natural and anthropogenic factors. Some are acute (hurricanes, tsunamis, outbreaks of corallivorous starfish and molluscs, thermal bleaching ...) while others are chronic (eutrophication, excessive turbidity, over- and destructive fishing ...). Natural rates of recovery of coral reefs tend to be very slow, thus active measures may

need to be taken to accelerate this process. Methods for propagating and transplanting corals are currently being developed.

1. Introduction

Coral reef degradation, caused by natural or anthropogenic factors, has been reported almost world-wide in the last 2 decades. Typhoons and hurricanes often destroy extensive areas of reefs. Furthermore, human activities such as inappropriate fishing practices, vessel grounding, coastal construction, excessive sedimentation, eutrophication, and water pollution have been revealed as the main causes of reef destruction on a local and regional scale. Reefs recover naturally, once the damaging factors are removed, but usually at a very slow rate.

Factors degrading coral reefs usually outpace measures aimed at reef regeneration. Thus, the most efficient and logical approach when we start a conservation or regeneration effort of a coral reef is to identify and eliminate the damaging factors. If this is achieved, damaged reefs are expected to recover, but slowly. Several cases, however, have shown that coral reefs suffering severe damage have not recovered at least during the period of the observation. In these situations, in addition to the removal of the damaging factors, active measures become necessary. Consequently, studies and actual practices that enhance coral reef regeneration, especially the cultivation of corals in artificial environments, have received much attention.

Since the early 1980s, significant improvements in marine aquarium design and operation have enabled the cultivation of fragile organisms from coral reefs. Around one hundred species of symbiotic hard and soft coral are currently cultivated and propagated in public and private aquaria. Cultivated corals have utility not only in conservation and reef restoration, but also in areas such as scientific research, medicine, and aquarium husbandry. They are further useful in raising public awareness of the need to conserve these ecologically and economically important organisms and the communities that they support. These applications are just starting to be exploited. In order that we may understand the value of these applications, we must have an appreciation of what a coral is and what role it performs on earth.

2. The Nature of Coral Reefs

2.3. Description of a Coral Reef

Reefs are not only composed of corals; many tropical reefs are constituted mainly of calcareous algae. Nevertheless, most reef studies focus on the reefs to which corals contribute the most and sometimes play a critical role by being the frame-builder in their formation. Corals deposit $CaCO_3$ as an exoskeleton. They accumulate a large amount of carbonates as they grow. The live tissues of a coral are limited to the very surface of a colony, with a thickness of only a few layers of cells. Most of the mass of a coral is its lifeless skeleton which the coral deposits and accumulates through the years. Reef building corals, or hermatypic corals, usually harbor intracellular, single-cell algae which photosynthesize and translocate energy to the host corals. This makes zooxanthellate corals, i.e., those with symbiotic algae, deposit carbonate skeleton at a faster rate than other azooxanthellate (without symbiotic algae in the coral cells) corals. Although most hermatypic corals are zooxanthellate corals, there are also some azooxanthellate corals, e.g., cup corals, *Tubastrea* sp., which secrete skeleton fast and contribute significantly to reefs,

Besides corals, other species also contribute to reef formation. Calcareous algae, snails, bivalves, foraminifera, sea urchins, etc., all deposit large amount of carbonates and are significant contributors to reefs. However, hard corals are often considered more important than others due to their large size and 3-dimensional structures.

Non-reef-building species also inhabit coral reefs. Species like sea anemones and noncalcareous algae do not deposit hard skeleton. They compete with reef-building species for space and other resources. If these species win the biological battle, the reef will no longer accumulate carbonate. Since the erosion of reefs, both biological and non-biological, goes on all the time, a reef dominated by non-reef-building species will stop growing and become reduced in dimension.

2.4. Propagation of Corals in Nature

Corals reproduce sexually. In most species, sperm and eggs are broadcasted into water columns for external fertilization and embryo development. After being planktonic and free-living for several days, and possibly drifting hundreds of kilometers away from their parents, the planular larvae are ready to settle and become sedentary for the rest of their life. Once attaching to a suitable substrate, they metamorphose into a polyp and develop a circle of tentacles around the apical mouths. These broadcasting species reproduce once a year.

Figure 1. Broadcasting of coral's gametes.

About 25% of coral species utilize internal fertilization and brood their embryos internally. They release competent larvae that are ready to settle almost immediately after leaving their mothers. Larval development and planula release follow a lunar cycle in these species. There are usually more than several cycles of planulation per year, especially in low latitudes.

Corals grow by multiplying their polyps. This is accomplished either by budding out new polyps or by dividing an old polyp into two smaller polyps. This asexual means of growth begins on a single, tiny polyp, and works its way up to a huge colony consisting of thousands and thousands of polyps. Since individual polyps perform all life functions, fragments or part of a colony consisting of from one to many polyps can survive and grow just like an intact colony. As long as the fragments can secure themselves without rolling on the bottom, or being buried by sediment, the survival rates may be high, especially in large fragments. Parts of polyps also have the potential to regenerate and grow again.

Corals do not senesce, i.e., their metabolism does not slow down, and mortality rates do not increase with age. Thus, there is great potential for a coral to reach a large size with many polyps. For example, a poritid coral found in Green Island (west of Taiwan), has reached 12 m in height and 31 m in circumference. This coral is estimated to be 1200 years old. Since the top of the colony is 8 m from the surface, there is still enough space for the coral to extend for hundreds of years.

As a hemispheric coral colony grows, its annual increment in diameter remains the same (approximately 1 cm). Therefore, if we compare the specific growth rate (increase per unit of tissue), the value of a small colony would be much higher than that of a large colony. In other words, it is possible to achieve a higher overall growth by breaking a large colony into many small pieces. However, small colonies often suffer higher mortality rates than large colonies found in nature. This is especially pronounced when a recruit starts at the very small size of several millimeters in diameter. Small colonies are likely to be eaten by fishes or snails, or to be covered by sediment or other benthic organisms. The same risk also applies to a large colony, but the damage is only a scratch, or a small wound that can be healed by regeneration. Thus, the most life-threatening stage of a coral is when they are young and small. Most coral recruits to a reef do not survive their first year in nature. Once they reach a large size, however, their mortality may be extremely low. A coral reef, then, consists mainly of large, long-lived colonies, when the biomass or the accumulated skeleton is used as a unit of calculation.

3. Destruction of Coral Reefs

3.1. Degrading Factors

The source of much reef damage is easy to identify. Fish blasting, for example, generates large, round craters on the reefs. Fragments become unconsolidated spreading around the holes. Coral mining, on the other hand, results in bare reefs in their late stages when no large colonies can be seen. Species with market value in the aquarium trade, e.g., *Euphyllia ancora,* are often among the first to disappear. High sedimentation can be observed on shore when belts of murky water appear after storms or heavy rains along the coast. This is often a serious factor for fringing reefs that are close to the shore. Bleaching may be caused by many environmental factors, but high temperatures seem to be the cause in most cases. The source of small scale bleaching is sometimes easy to trace. Hot water from plants near the shore may cause bleaching in very shallow water, since these events are often limited to 1-2 m, and do not always result in mass mortalities. Large scale bleaching, like that of 1998, which affected 75% of world's reefs is associated with the warming of seawater. Besides affecting large areas, it also affects corals in relatively deep water. The mortality of corals is species-specific, and is related to the thermal tolerance of different species.

Some other damage may be difficult to distinguish. For example, the overgrowth of macroalgae may be caused by excessive nutrification of reef waters, or, on the other hand, by the disappearance of herbivores. In many reefs, macroalgae dominance is seasonal, and lasting damage is done during the alga-growing season. Thus, it is difficult to find the culprits out of season. We need to understand the basic ecology of coral reefs in order to come up with a way to confront this damage.

3.2. Mechanisms of Destruction and their Alleviation

3.2.1. Storms

Storm damage is characterized by mostly physical destruction caused by projectiles moving in the water. Branching and platy corals often suffer the most. They may be broken into small fragments scattered in crevices of the reefs. Exposed substrates are later covered by fast-growing algae or sea anemones that inhibit recruitment of reef-building species. Some bottoms are covered by unconsolidated fragments that are unsuitable for coral recruits. Since this is a natural process, human intervention may be controversial. On the other hand, some reefs suffering from storm damage have yet to recover after decades.

3.2.2. Over- and Destructive Fishing

Both types of fishing practices result in the reduction of fish diversity and sizes. The removal of herbivores (e.g., parrotfishes, sea urchins) may result in macroalgae dominance, which in turn inhibits the growth of existing corals and the recruitment of corals. Since both corals and algae require light and space, expanded algae cover may cause the partial or total mortality of corals. Some fishes feed on the sea anemones that compete with corals. Thus the removal of, for example, angel fish may result in an over-abundance of certain sea anemones. Over-fishing involves complicated social-economic situations that can hardly be resolved by scientists. Various approaches have been tried in different parts of the world, for example, awareness programs which educate people in the value or economic potential of healthy reefs. Alternative livelihood training teaches fishermen to farm in the sea or to operate a business using the sea. Marine Protected Area (MPA) is a solution when there is consensus among people, or when law can be enforced.

3.2.3. Nutrification of the Sea

Macroalgae respond to nutrients in seawater much faster than corals do. While corals maintain a similar growth rate, macroalgae can really accelerate their growth rates under eutrophic conditions. Both macroalgae and corals require sunlight for energy and substrate for space. The algae are superior competitors compared to corals when there are nutrients in seawater. Nutrients also accelerate multiplication of phytoplankton in the seawater. Since phytoplankton lives in water columns, they intercept sunlight before it can reach the bottom where the corals live. Excessive nutrients usually come from the land, thus a solution has to start there. Water treatment plants that remove inorganic nutrients can be tried in small villages or facilities. Marine outfall pipes are exploited when sewage from cities is the source of nutrients.

3.2.4. Excessive Turbidity

Reef corals need ample sunlight so their endosymbiotic algae can photosynthesize and translocate energy to the hosts (the corals themselves). The turbidity of water effectively prevents sunlight from reaching the bottom. Fine particles in water columns eventually settle. When they fall on corals, excessive mucus is secreted by the organisms. Some corals are easily smothered by sediment accumulating on their surface. There are also corals that can tolerate turbid waters better than others. These corals usually have vertical-shaped colonies resulting in less accumulation of sediments. Furthermore, some species can expand their tissues to expel sediments on their surface.

Excessive turbidity on coral reefs usually has a terrestrial origin. This may be derived from the construction of buildings or agricultural activities on land. Therefore, coastal construction should be required to use sediment traps or trenches. Outcrops, due to land development, should be covered with plants. Generally, the particle sources from a small area can affect a large area in the sea. Moreover, one season of high loading of particles into the sea can effectively wipe out a reef which may require decades to recover.

3.2.5. Thermal Bleaching

Bleaching of corals is usually caused by high water temperatures. A temperature as high as 29-30 degree Celcius is a critical point when zooxanthellae starts to leave the host corals and bleaching occurs. Corals can recover if the environmental conditions improve; otherwise mortality ensues. There are many studies on the physiology and ecology of coral bleaching, although very little can be done to reverse the trend of bleaching, or to accelerate the recovery, at present. There is now multi-regional monitoring of the status of reefs and the ranges of affected areas. Using this opportunity to raise public awareness about coral reefs seems to be the only consolation.

3.2.6. Tourists

Destruction due to tourists occurs at popular areas and from the demands of souvenir shops and restaurants. This involves both tramping and collection. While the collection of specimens can be outlawed, a prohibition of tramping is hard to enforce. Route planning to guide tourists, following a fixed track, may be the way to limit the range of destruction. Tour guide training works when tourists are well-educated. Providing facilities for tourists has the effect of gathering tourists and concentrating damage. Assigning exclusive diving rights to local diving shops offers great incentives for dive masters to educate their customers. Floating buoys for boats can eliminate damage from anchorage at popular sites.

3.2.7. Coral mining and Aquarium Trade

Corals, like many colonial organisms, are long-lived. It takes more than 10 years for a massive coral to reach palm size. Colonies reaching 1 m in radius are usually a century old. Thus, the collection of these organisms results in long-term changes. Besides direct removal, the collection of fishes often involves poisons that kill many other species, including corals. Sustaining fisheries of commercial scale in coral reefs is difficult, despite the high abundance and high biological diversity. The discouraging and banning of routine collection from coral reefs are necessary.

After resolving the factors degrading coral reefs, some active measures can be considered to enhance the rate of recovery.

4. Coral Reef Regeneration

4.1. Assessing Coral Recruitment

Densities of coral recruits may vary by several orders of magnitude in different reefs. Plastic plates or other natural or artificial substrates can be used to monitor the amount of recruits. Since coral spats are selective, the material, orientation, lighting, size, etc., of plates need to be considered if data from different locations are compared. The timing as well as duration of plate immersion also make a difference. For broadcasting corals, the settling may be more seasonal, since spawning is limited to a short time of the year. For example, in the Great Barrier Reefs, hundreds of species spawn in October- November. In the Red Sea, corals spawn in the summer. Brooding species usually have a longer season of recruitment than broadcasting species. This may occur year-round at low latitudes.

The rates of the natural recruitment of corals are often highly variable over the years, especially in broadcasting species. Thus, results from one year may not be a good indicator of the situation in other years. Coral recruits settling on monitored surfaces are often lower in species diversity than that of existing communities. At present, many settled larvae can be identified to the family level. More exact identification is possible only in a few species. Continuous cultivation and serial recording are time-consuming, but are the only ways to distinguish the juvenile stages of corals..

In nature, coral recruits settle on hard and secured substrate. Some destruction, e.g., ship grounding, renders the bottom a loose substrate that further inhibits successful recruitment. Coral fragments also become projectiles and cause further damage when there are strong waves. Bottom consolidation, thus, has been tried in a few cases to prevent the damage from further intensifying and to provide suitable space for new recruits.

New recruits are small, usually smaller than 3 mm when first observed in the field. They may be difficult to see on natural habitats, since they do not prefer exposed surfaces which tend to be covered by sediments or fast-growing algae. Recruits or juveniles smaller than 1 cm, i.e., in their first few years, are relatively few for most massive species which reach large colony sizes in nature. So it is the branching and the plate-forming species that are expected to "return" to a damaged site within a few years.

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Biographical Sketches

Jean M. Jaubert - Professor of Marine Biology at the University of Nice, France and Director of the European Oceanographic Center of Monaco, Principality of Monaco

Jean Jaubert studied biology at the University of Poitiers and specialized in Marine Biology at the University of Marseille. He obtained a Ph.D. in Biological Oceanography in 1971 and a Doctorate in Science in 1987. He has been working at the University of Nice, France as Associate Professor from 1972 to 1987 and then as Professor of Marine Biology. Various occupations have led him to teach, organize overseas scientific expeditions and write widely. From 1970 to 1989, he founded successively the group of Ocean Technology and the Laboratory of Experimental Ecology at the University of Nice, France. In 1990, he was commissioned by H.S.H. Prince Rainier III to establish the Scientific Center, European Oceanographic Institute of Monaco, a research organization affiliated to the Council of Europe with laboratories located within the building of the Oceanographic Museum. Investigations carried out by Jean Jaubert and his collaborators aim to better assess ecological risks and rehabilitate degraded ecosystems. One of their most important findings is that marine organisms that precipitate huge amounts of calcium carbonate, such as reef-building corals and calcareous algae, transfer carbon dioxide from the oceans to the atmosphere. Since carbon dioxide is a major greenhouse gas this transfer can, over geological time scales, modify the climate of earth. Another important finding made by Jean Jaubert and his collaborators is that high concentration of carbon dioxide and high temperature inhibit calcification. This latter finding show that the global Warming and the rising concentration of carbon dioxide in the atmosphere due to the burning of fossil fuels are now more clearly appearing as both major causes of the worldwide spread bleaching and mortality of reef-building corals. To better understand these processes and enable researchers to carry out laboratory experiments Jean Jaubert has developed an innovative biological water purification technique that permits the propagation of corals in closed-circuit aquaria and the reconstruction of coral reef models. This simple but efficient technique is patented in Europe, the United States and Japan. Its is becoming popular among aquarium hobbyists as the Jaubert Natural Nitrate

Reduction system. In acknowledgement of this contribution to Marine Biology Jean Jaubert was decorated with the Palmes Académiques in 1988 and was the recipient of the Medal of the Society of Oceanography in 1994. He is currently member of the New York Academy of Sciences; the Interdisciplinary Academy of Sciences of Paris; the European Academy of Sciences; the American Association for the Advancement of Science; the board of directors of the International SeaKeeper Society. To relax Jean Jaubert enjoys scuba diving, photography, video and gliding planes. He also has his own coral reef aquarium.

Keryea Soong - Professor of Marine Biology at the National Sun Yat-sen University, Taiwan, Republic of China.

Keryea Soong studied zoology at National Taiwan University and specialized in Marine Biology at the University of Texas at Austin. He obtained a Ph.D. in Biology in 1990. He has been working at the National Sun Yat-sen University as Associate Professor from 1990 to 1994 and then as Professor of Marine Biology. His research interest is in reproduction and sex of marine invertebrates. With various types of marine habitats around Taiwan, there are many research opportunities to study a variety of organisms. Population biology in the coral reefs and soft bottoms, has attracted much of his attention. Due to the degradation of coral reefs around the world, the focus of his studies has been shifting from pure science to more applicable aspects of conservation biology.