Marine Ecology of La Reunion: An Overview of Recent Research

Reunion Island (Fig. 1), which is part of the Mascarene archipelago, is located between 21°07'S and 55°32'E. It is a volcanic island 2.1 million years old, with the first reef colonization as a reef bank, dating back to 8500 BC, when the sea level was 20 m lower than it is today (1). The highest point is the Piton des Neiges 3069 m a. s. l. while the active volcano, the Piton de la Fournaise, is 2631 m high. The surface area of the island is about 2512 km² and the diameter 70 km.

The rainfall regime of the island is controlled primarily by the southeast trade winds. During the cool season (from June to October), the winds produce ocean swells of 1-2 m while during the hot season (from November to May) weak winds generate swells of 0.5 m. Occasional hurricanes and storms generate very rough conditions. The tidal range varies from 0.9 m (springs) to 0.1 m (neaps).

The first human settlers arrived around 1650, but with today's population of over 700 000 inhabitants, the island is considered overpopulated. Due to the steep topography, the population is concentrated close to the coast (82%).

There are 3 main categories of coastal environment in Reunion namely: coral reefs with sandy beaches, volcanic rubbles, and steep cliffs. The common reef geomorphology includes an outer slope, outer and inner reef flats and a back reef. The fringing reefs are discontinuous and narrow (less than 550 m wide) and they only cover 7.3 km². The reef flats are exposed at low water.

Large volcanic rubble is mostly found on the north and northeastern coasts; with increasing depth this is followed by volcanic sands. Volcanic cliffs are found on the south and southeast, due to the recent volcanic activity. Natural harbors and coves are rare.

Since the volcano is young and the continental shelf is narrow, the depth increases very rapidly near the shore. The Exclusive Economic Zone (EEZ) surrounding Reunion Island is about 320 000 km². With the exception of a few seamounts the ocean is very deep and possibilities for bottom fishing are few. Being situated at the southern limit of the South Equatorial Current, sea surface temperature varies between 22° and 28°C. At the depth of 200 m the temperature is around 20°C throughout the year.

Environmental conditions are not favorable for the concentration of large tuna schools, however tunas are abundant

in the area and are the target of the long-line fishery. The management of the EEZ and its resources is governed by the European Union.

RESEARCH IN REEF ECOLOGY

Reunion reefs have been studied by the Marine Ecology Laboratory since the 1970s. During this period when the reef were considered to be healthy, the first studies were of a more taxonomic and descriptive nature (1). However, in recent years the focus of research activities has changed to examine: i) function, degradation and restoration of reefs; and ii) reef biodiversity and resource management.

Coral Function, Degradation, and Restoration

The reef communities constitute dynamic assemblages, with thousands of species interacting biologically, and with the physicochemical environment. Thus, the function of a "normal" reef, if it still exists, was examined at different levels: ecosystem, community, and species. At the ecosystem level, reefs are shallow and their metabolism is intense. The overall metabolism was studied by the flux method that quantifies the primary production and calcification (2, 3). Particular attention was given to nutrients, derived from terrestrial inputs as well as from community metabolism. At the community level, diversity, trophic structure, and percentage cover of the main constituents were quantified and monitored over time at a few referenced stations (4, 5). Species level functions were examined through studies of the dynamics and biological activity of populations of key species. Corals, fishes and echinoderms are the major taxonomic groups, with keys species on La Reunion reefs. Mechanisms such as growth, bioerosion by fish and echinoids (6), and recruitment (7) can contribute to understanding reef function.

From 1985, coral reef degradation has been observed through studies aimed at monitoring physicochemical and benthic

Figure 1. La Réunion Island.

parameters to determine the level of pollution in reef flats. As benthic community structure is well-known and is permanently monitored, changes to the benthic communities are more easily detected and could be interpreted in terms of their responses to natural and/or anthropogenic stresses (5, 8). The principal factors of perturbation on the reef flats were analyzed and it was found that natural events, such as hurricanes, have been responsible for up to 100% coral mortality (9). Other factors that have impacts on reefs included excess nutrients through groundwater seepage, sedimentation (from soil erosion inland) lowered salinity due to surface water flow, and industrial wastes. Some communities on the outer slopes are also degraded by sedimentation in areas close to rivers, but also due to fishing, anchoring, and by ground water seepage. The ecological response of a reef to different impacts can be shown at different levels. At the ecosystem level, the degree of alteration of the benthic communities was determined by analyzing the health and the percentage of mortality of corals, as well as the relative

abundance of potential competitors like cyanophytes, algae, and sponges (5). Other factors that accentuate the stress on corals remain to be quantified. These include: human activities such as reef walking and fishing; coastal constructions which modify sand dynamics and contribute to silting-up of lagoons; and coral bleaching which occurs sometimes in summer when coinciding with very low tides during the day.

The comparison of specific metabolic parameters such as net production and calcification-the difference between dissolution and precipitation-reveal large differences between normal and degraded reefs. For example, lower calcification rates and Pb/R ratio values < 1 were recorded in degraded areas (3). Bioerosion, determined as an index, is also useful in evaluating carbonate budgets for reefs. Echinoids can be major bioeroders of coral reefs when their populations are dense and/or composed of large individuals. Sea urchins *Echinometra mathaei*, very abundant on the fringing reefs in La Reunion, have been sampled to determine their contribution to the carbonate budgets of the reef flats and the back reef. They are very effective bioeroders on the outer reef flat ($23 \text{ g CaCO}_3\text{m}^{-2}\text{day}^{-1}$) in the control nondegraded zone (6, 10). On other

sites, with different degradation levels the populations are very different and bioerosion is much lower (11). In addition, the replacement of coral-dominated by algae-dominated reef communities has been recorded in several reef sites on the Saint-Gilles La Saline reef over the last 20 years. Most of our studies have focused on 3 areas of the reef flat, Planch'Alizes (PL) Trois-Chameaux (TC), and Trou d'Eau (TE). Their benthic communities, algal biomass, abundance of herbivorous fish, bioerosion by *Echinometra*, and gross primary production to respiration ratio, reflect the oligotrophic state of TC and TE and the dystrophic state of PL. This condition was early attributed to a combination of natural and anthropogenic factors such as accidental events (e.g. very low tides), nutrient-enriched groundwater discharges into the back reef, and lack of sea urchins. Furthermore, patterns of inorganic nutrient flux and food processing by the fish *Stegastes* and sea urchin

Tripterygion, 2 dominant herbivores on these reefs, suggest that recycling might increase nutrient availability at PL (12, 13). Some worrying features of PL compared to TC and TE are a low fish species richness (43 vs 65 at TC), a decreasing number of juvenile fish, and a low net calcification ($1.5 \text{ kg CaCO}_3\text{m}^{-2}\text{day}^{-1}$ vs 5.8

at TC).

The coral bleaching event of 1997/1998 prompted the development of a multi-disciplinary team, in 1998 from the Reunion university in collaboration with the French Ministry of Overseas to conduct studies to better understand the causes, patterns, and consequences of the bleaching event in La Reunion. Temperature maxima and high mean monthly values have been shown to correlate with the onset of bleaching. Three approaches have been used in this study:

- i) Remote-sensing images of the entire island, using the NOAA-A VHRR satellite data, provide various thresholds for analysis and comparison with subsurface temperatures recorded hourly since 1993.
- ii) Local reefs and colonies of different species, data were collected from observations and through enquiries to determine the stages of bleaching, their progression and the sensitivity of the different species. An "Alert form" was used for the purpose.
- iii) Following the death of corals, different stages of colonization by filamentous algae have been identified and characterized, in order to identify the epiphytic succession of the microalgal assemblage. Their prevalence is favorable to the growth of toxic dinoflagellates and an increase of ciguatera may occur as a possible consequence of bleaching.

These complementary approaches have provided the tool, for a better understanding of future events (14). Recently, in 2001, signs of bleaching have been observed which corresponded to a long period of warmer than average water temperature (15) (Fig. 2).

Restoration is a more applied theme. The analysis of the imbalance of degraded reefs in different types of environments (from the physicochemical point of view, as well as from biotic interactions) helps to form an understanding the natural coral restoration. Concerning reef restoration, first experiments, by coral cuttings or

Bleached *Acropora* colonies. Photos: M. Rard.

nubbins, sponsored by the Regional Council have given promising results. Coral transplantation, with their associated fish on artificial DCF (Fauna Aggregating Device), has been sponsored by the French Ministry of Environment and the multidisciplinary program (PPF) of the university (16, 17).

Reef Biodiversity and Resources Management

Biodiversity is currently being studied by several zoological groups using different approaches. Hydrozoans from different habitats have been collected as part of a long-term study. More than 90 species have already been identified (18,19). Corals have been extensively studied (20), and the university laboratory hosts a referenced collection for the Mascarenes. These data and information have been put into databases, which can be accessed by different experts for their research work and taxonomic needs. A collaborative program has been initiated to bring together French scientists from different institutions to access data and information on coral in their archives (21). The aim is to promote utilization of computer-aided systematic tools for describing, classifying, and identifying coral specimens. Coral, reef fish and echinoderms species have been catalogued and will be included in databases soon (22).

Biodiversity studies also include examining population strategies in reproduction (18). For example, fission rates in different sea cucumber populations have been studied. Asexual reproduction by fission, followed by regeneration is found in 3 species of holothurians in La Reunion (23-25). Fission may be controlled by different factors, generally inducing stress. On La Reunion reefs, man-made changes like eutrophication and other anthropogenic disturbances are possible triggers of this phenomenon (23).

Reef resources are very diverse. They are economically important and of value to the expanding ecotourism industry. The Marine Ecology Laboratory (ECOMAR) is involved in the Indian Ocean Commission Environment Program and has produced a manual for use in monitoring the reefs of the region (26, 27). Fish and holothurians are among the fishery resources that have been studied extensively. The colonization of fringing reefs by fish larvae has also been studied. Essentially, it takes place from August to February with 2 peaks, in August-September when the water temperatures are the lowest and to February when the water temperature is at a maximum. The number of individual fish, as well as the number of sampled species, presented similar values over 2 consecutive years with, nevertheless, a strong variation in

Figure 3. Trophic relationships in pelagic ecology (modified from Le Corre, pers. comm.).

DCF: Fauna Aggregating Device
 SPC: Secretariat of the Pacific Community
 IFREMER: French Institute for Exploitation of the Sea
 IRD: Research Institute for development
 CPER: Contrat de Plan Etat-Region
 CRPME: Regional Committee for Marine Fisheries
 FAD: Fish Aggregating Device
 ARDA: Regional Association for Aquaculture Development
 ICRI: International Coral Reef Initiative
 CORDIA: Coral Reef Monitoring Network
 PPF: Programme Pluriformations Mer
 WIOMSA: Western Indian Ocean Marine Science Association

the species involved. The number of postlarvae which colonize the reef is lower than on larger and more structured reefs. This phenomenon could be explained by the geographical characteristics of the island. The stock control of the adult fish in Reunion could be mostly explained by the arrival of post-larvae on reefs and would correspond to the model of "recruitment limitation" (7).

Sea cucumbers have been exploited for many years by Chinese populations who consume the dried tegument. Sea cucumber fisheries in tropical countries are intended for export to international markets. Most of these fisheries are currently showing signs of overexploitation and their rational management is a priority for many countries (28-30). In 1988, the laboratory in collaboration with SPC started the production of the *Beche-de-mer Information Bulletin* which is now widely distributed worldwide to raise awareness on sea cucumbers. Facing the current overexploitation problems, research initiatives to farm sea cucumber are encouraged.

MAIN PROGRAM IN MARINE ECOLOGY

There are several ongoing research programs undertaken by different organizations. ECOMAR in collaboration with IFREMER and the Research Institute for Development (IRD) is implementing a project on the dynamics of coastal and high seas of tropical ecosystems, which includes 2 main research areas: i) impact of artificial reefs on communities; and ii)

trophic relationships in tropical high seas environment. This collaboration will run for 6 years through an agreement between the French State and the Reunion Region (CPER).

Given the overexploitation of the reef resources, artificial reefs have been developed by professional fishermen (CRP- I MEM) since 1995. They are set up in large bays where the fish fauna are limited. Their aggregating effects have been analyzed by visual and video observations of fish and other fauna. Functional relationships between the benthic and pelagic communities are being monitored.

The study of the trophic relationships in a tropical high seas environment has recently been initiated (31, 32). The Figure 3 shows the interactions between seabirds and fish near the coast (less than 10 miles) and offshore.

The IRD formerly ORSTOM, is active in large-scale oceanographic and the satellite observations and interpretation. In 2000, IRD implemented the THETIS program, which amongst others focused on the predator-prey interactions in some high seas pelagic ecosystems of the Atlantic and Indian Oceans (33). These interactions are based on stomach-content analyses, carbon and nitrogen stable isotope ratios and acoustic surveys. The implementation of these research activities will lead to a better knowledge of the trophic ecology of apex predators and will provide an ecosystem point of view that is necessary in high-seas fisheries management. The predator-prey interactions cannot be studied over the whole oceanic

basin, therefore, some representative areas will be selected for sampling. In the Indian Ocean, studies are conducted in 4 areas; Somalia, Seychelles-Chagos, Mozambique Channel, and Mascarenes. The results may allow for development of a trophodynamic model and analysis of the functionalities of the studied ecosystems.

Other research focuses on the relationships between environmental variability, the exploitation and the spatial dynamics of tuna populations (in cooperation with IRD-IREMIA/UR). The ACTIVE program also conducted by IRD, focuses on research concerning the behavioral ecology of pelagic fish. It studies the behavioral mechanisms which lead fish to school or to form aggregations around fish aggregating devices (FADs). Furthermore, acoustic and video observations are planned under the artificial reefs built in shallow water near the reef coast. As they aggregate small pelagic fish and oceanic larvae, these small attractive structures are of interest for both programs (IRDECOMAR).

The IFREMER station is involved in several research programs. The study of long-line fishing is currently implemented jointly between ECOMAR and IRD and consists of 6 components:

- i) Fisheries statistics of Reunion fishery using the information in the database;
- ii) *Xiphias gladius* (swordfish) reproductive biology and growth.
- iii) Behavior of the main fish in response to the use of hooks.
- iv) Relations between the fishery resource and the oceanographical conditions studied by the IRD Seas station.
- v) Fishery management strategies.
- vi) Growth of *Thunnus obesus* (34, 35).

A local center, CEDTM in collaboration with ARDA, is currently developing an intensive marine fish culture in land-based facilities and in floating cages. Fish Aggregating Devices (FAD) are important for La Reunion fisheries and have been studied (36, 37). In 2000, IFREMER with the help of CPER initiated a program on the high-sea resources, focusing mainly on *Coryphaena hippurus*, which aggregate around epipelagic devices. Migration patterns of marine turtles (*Chelonia mydas*) is another aspect that has been studied for a long time.

CONCLUSION

The research on coastal and marine environment of La Reunion over the years has been conducted by different university laboratories, institutions, associations and administrations. The multidisciplinary program of the university PPF (Littoral Pole, biodiversity, and marine resources) has provided an opportunity for collaboration and development of joint research activities (38). Research on high seas

through the Contrat de Plan Etat-Region (CPER), has also provided another opportunity for collaborations between ECOMAR, IRD and IFREMER teams.

Regional and international programs on coral reefs (ICRI, CORDIO, and GCRMN) have also been implemented in La Reunion, leading to generation of use

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