Part 3

Coral reefs: impacted but resilient

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The coral reefs of New Caledonia are threatened by human activity, especially mining. Globally, human emissions of greenhouse gases are leading to global warming and acidification of the oceans. Locally, warming and acidification cause coral bleaching. The coral cays and islets of New Caledonia are also exposed to the effects of rising sea levels. These direct or indirect human impacts add to existing natural stresses, such as invasions of the coral-eater starfish Acanthaster. While geographers, geologists, physicists, chemists and biologists warn us about these pressures and the risks that reefs can face, they also retain a cautious optimism about the resilience of New Caledonia's coral reefs.

Chapter 22

Reefs and anthropogenic pressures: from mine to lagoon

Gilbert David

Aerial view of the Nakéty mining massif (east coast), where red contrasts with green vegetation and blue ocean. © P.-A. Pantz

New Caledonia from the sky, the clash of red and blue

Seen from the sky, New Caledonia's Grande Terre is a colorful composition dominated by the green of the mountain chain forests in the center and mangroves along the coast, the blue of the lagoon around it and the patches of red of the mining massifs. These colors can be interpreted in two different ways. Where the dominant color is red, open-pit nickel mines are the defining elements of the landscape and the lagoon is perceived as a threatened ecosystem that receives the terrigenous pollution generated by mining. In contrast, one can choose to focus on the "world's largest lagoon", according to LABOUTE *et al.* (1999). In this interpretation, New Caledonia is then essentially surrounded by the blue of its marine environment. This red and blue conflict often structures political debates about the economic future of the country. Today, everyone acknowledges the exceptional natural assets that represent the reefs and lagoons of New Caledonia. With a total surface of approximately 23,500 km^2, New Caledonia harbors significant marine biodiversity, accounting for over 15,000 known species. However, many areas and biological groups are still poorly known (PAYRI and RICHER DE FORGES, 2007). For more than a century, nickel mining and the associated metallurgical industry have dominated New Caledonia's productive economy. During the 2006-2016 decade, they accounted for 90% of the value of exports, reaching 1,040 billion euros in 2016 despite the very low world market price of nickel (8,500 dollars per ton in January 2016 when it was twice as much in 2011). This sustained export value is due to record levels of ore and nickel metal production in 2016. Mining has never been so intense in New Caledonia's history and, as a consequence, viewed from the sky over New Caledonia, each year the red patches become more visible.

Pressures are dominated by human action: Catchment areas and urban centers

Although New Caledonia is affected by climate change, like the rest of the region, the future of the reefs also largely depends on human activities that occur along the coasts and catchment areas. These anthropogenic pressures include urban or agricultural pollution and environmental disturbances caused by nickel mining. Since the opening of the first metallurgical plant in Nouméa in 1877, open-pit mines have proliferated and left open wounds on the sides of the mountains. Meanwhile, New Caledonia's Grande Terre is one of the southwestern Pacific regions most affected by tropical cyclones (8 to 9 tropical cyclones and storms per year), daily rainfall is close to world records and the catchment areas are often steep. In this context, limiting the erosion of mining sites is a priority. It requires the management of runoff and revegetation[8] by planting either fast growing native species such as *Acacia spirorbis* and *Casuarina collina*, or a combination of species from the local flora on mining massifs (L' HUILLIER *et al.*, 2010). Soil erosion resulting from poor agricultural practices, overgrazing of livestock (cattle) and overpopulation by non-endemic wild deer, or wildfires[9] can also impact the lagoons locally. During periods of frequent and intense rainfall, the use of fertilizers and pesticides can create further local problems, especially in the South Province, where most farms of more than 100 ha, including vegetable farms, are located.

In urban areas, poor wastewater treatment is the major issue. Over 70% of the population lives in Grand-Nouméa, the capital and its three neighboring municipalities (Paita, Dumbéa and Mont-Dore), and in the urban conurbation of the North Province, which spreads over the Voh-Koné-Pouembout area (DAVID *et al.*, 1999; BOUARD *et al.* 2016). Outside these main urban areas, municipalities that have more than 1,000 inhabitants are relatively rare and developing collective waste water treatment is very expensive.

Pressures from the lagoon

Due to the size of the fishable area (7,280 km^2, including 5,490 km^2 of coral reefs and 1,800 km^2 of lagoon soft bottoms), the overall impact of fishing on reef formations is limited. However, there is a local risk of overfishing. This is particularly true in areas close to urban centers, mainly because of the high recreational fishing activity and the quotas authorized by public authorities (JOLLIT *et al.*, 2010). Species valued on the international market are also highly vulnerable to overfishing. These are mainly trochus (or top-shaped sea snails, used for button manufacture in the high-end textile industry) and holothurians (sea cucumbers or bêche-de-mer). Bêche-de-mer is highly valued on the Chinese market, and fishing for this marine invertebrate has increased sharply since 2006. The annual international demand for 70,000 tons of dried product is difficult to supply, and prices can reach 2,000 euros per kilogram on the international market. As a result, there is increasing pressure on the countries that still have resources, and illegal fishing by Vietnamese vessels occurred in 2016 and 2017 in the New Caledonian lagoon (chap. 31).

In many countries around the world, aquaculture is a very environmentally significant activity. In New Caledonia, the small size and low number of prawn farms (18 companies with an average surface area of 40.2 ha), the low densities of prawns (average yield is 2.5 t/ha/yr) and the ban on chemical fertilizers and pesticides work together to limit the impact of effluents on coastal waters. Ponds are located on 723 ha of saltmarshes (salted grounds at the back of mangroves) which prevents the degradation of mangrove cover, unlike what is found elsewhere in the world for extensive prawn farms. The preservation of the environment is also essential to the quality standards of the New Caledonian product and an important asset for export to foreign markets. Besides prawn farming, aquaculture is still underdeveloped.

[8] Where the sites were built before 1975, their rehabilitation is the responsibility of the French State and where they were built after that date, the responsability is that of the Government of New Caledonia.
[9] Depending on the year, fires can destroy tens of thousands of hectares of land.

Shrimp farm, west coast of Grande Terre. © P.-A. Pantz

In 2017, it was limited to two caged farms, one for the emperor red snapper *(Lutjanus sebae)* and the other for the golden-lined spinefoot *(Siganus lineatus)*. Due to the small size of these farms, their impact on the lagoon is minimal.

Apart from fishing and aquaculture, the recreational use of the lagoon and islets can also affect the quality of ecosystems, especially around Nouméa (chap. 33). In rural areas, the extraction of sand from shallow waters can significantly increase coastal erosion

World Heritage inscription and pressure reduction

The year 2008 is a remarkable date for New Caledonia's reefs with the inscription on UNESCO's World Heritage List of 15,808 km^2 of reef barrier and lagoon, an increase by 35 of the protected area which previously stood at 446 km^2. Six sites were listed, two in each of the three provinces and two buffer zones were also included. The first covers 8,206 km^2 of the Southern Lagoon and adjacent waters. It includes the coastal zone near the Goro metallurgical plant where a 26 km long pipe discharges waste water offshore at a controlled toxicity level.

The second covers most of the catchment areas of the municipalities of La Foa, Moindou and Bourail and one third of the land area to the north-east of Grande Terre, a total of 5,146 km^2. Besides Grand Nouméa, these drainage basins are the areas of the South Province most affected by man. Their designation as buffer zones is an opportunity to develop integrated drainage basin and coastal zone management.

Ultimately, listing the reefs of New Caledonia as heritage sites, such as the creation of the Marine Park of the Coral Sea in 2014, represents a valuable opportunity for more environmentally friendly public policies. This includes the generalization of wastewater treatment, and changes to individual behavior in order to reduce pressures on the reef environment. The ambition is that within 20 to 30 years New Caledonia will be established as one of the rare places on the planet where the reef ecosystem is in good condition.

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Chapter 23

Metals and their impact on corals

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Soils exposed by mining in the north of Grande Terre (New Caledonia). © Koniambo Nickel SAS/ A. Wright

Pollution by metals, a global problem

Coral reefs have significantly declined globally over the last decade as a result of anthropogenic activities (HUGHES *et al.*, 2003). They face many threats including disease, overfishing, habitat destruction and water quality degradation. This water quality degradation is due to several factors: deforestation and mining operations, which increase soil erosion; agricultural and domestic pollution; and dredging operations, which develop along the coast. Metal inputs are also a form of pollution. They are released through soil leaching, industrial effluents, in the form of atmospheric particles and also mainly from mining. Car emissions, sewage sludge, dredged material and antifouling paints also contribute significant quantities of metals to the oceans. This pollution by metals affects many reefs around the world. (e.g., Costa Rica, Panama, the Red Sea, Thailand, Tuvalu, Puerto Rico). Among them, the reefs of New Caledonia are particularly exposed. New Caledonia is one of the five major nickel producers in the world and its open-pit mines require extensive excavations which considerably expose the soil to water and wind erosion. This increases the contribution of metal-rich particles to the lagoon via sediment-rich runoff or atmospheric pollution, threatening the functioning of reefs and their biodiversity.

When there are too many metals in seawater...

The effects of high sedimentation on corals are now well known. High sedimentation decreases the amount of light available for *Symbiodinium* to photosynthesize and generally results in lower growth rates. In extreme situations, high sedimentation can even cause the bleaching of colonies and lead to their partial or total death (FABRICIUS, 2005).

The effects of dissolved metals associated with these high sediment loads are much less studied. It is known that corals have an exceptional capacity to bioaccumulate metals in both their tissue and skeleton. However, experimental studies on the effects of metals on corals have only focused on their reproduction and early life stages. These studies demonstrated that high metal intake resulted in: lower reproductive success; lower larval fixation and survival rates (REICHELT-BRUSHETT and HARRISON, 2005); a change in photosynthesis rates leading to a reduction in the calcification and growth of corals during their early life stages; a loss of *Symbiodinium* in coral tissues and eventually an increase in coral mortality. However, it is very important to note that all these experimental studies used exceptionally high levels of metals: 100 or 1,000 times higher than *in situ* concentrations.

Incubation of coral colonies in benthic chambers to test (directly on the reef) the effect of nickel or cobalt on coral calcification and photosynthesis. © CNRS/E. Amice

What about the corals of the New Caledonian lagoon?

In New Caledonia, additional studies have been carried out to understand the effects of the regular exposure of near-shore reefs to pollution by metals. A series of field and laboratory experiments revealed the effects on coral metabolism of concentrations "characteristic" of those measured in the lagoon. The effects of two metals were tested: nickel and cobalt, which are particularly abundant in coastal waters because of mining activities.

For nickel, concentrations in seawater are generally around 0.1 to 0.5 µg L^{-1}, but concentrations exceeding 20 µg L^{-1} can be measured in some areas along New Caledonia's coastline. Surprisingly, coral colonies exposed to moderate concentrations of nickel (3.5 µg L^{-1}) were not negatively affected, but instead their metabolism was stimulated with increased calcification (BISCÉRÉ *et al.*, 2017). This is the first time that a beneficial effect of nickel on corals has been recorded. One possible hypothesis that may explain the positive role of nickel is related to the activity of urease, an enzyme whose active site contains nickel (Fig. 1).

This enzyme is responsible for the transformation of urea into ammonia and carbon, two elements that are then used in the process of coral calcification. A temporary exposure to a moderate amount of nickel would have stimulated the activity of this enzyme, boosted carbon dioxide production and then increased coral calcification.

In the case of cobalt however, with a minor increase (around 0.2 µg L^{-1}, which is in the range of maximum concentrations found along New Caledonia's coastline), the growth rates of the two species of coral tested dropped by one third and even by 70% when cobalt levels reached 1 µg L^{-1} (BISCÉRÉ *et al.*, 2015).

Metals and corals, friends or enemies in a changing climate?

In addition to local stresses, the coral reefs will now have to cope with global climate change. Climate models forecast an atmospheric warming of 2 to 4°C over the next 30 years (IPCC, 2014). This warming has already triggered massive bleaching events (i.e., when coral tissues lose their symbiotic algae, see chap. 25) in all the world's reefs over the past 30 years. The simultaneous increase in CO_2 concentration (pCO_2) in the oceans also alters the chemistry of water by lowering pH (by 0.1 pH units in the 20th century) and carbonate concentrations (IPCC, 2014).

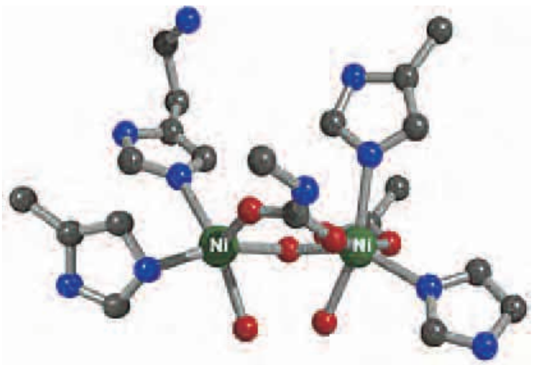


Figure 1: Chemical representation of urease showing the active site containing a double nickel nucleus. Adapted from www.rcsb.org

The scientific community expects that coral reef calcification rates will have decreased by between 17% and 37% by the end of the century. To date, the impacts of climate change on corals have been investigated in isolation (only an increase in CO_2 and/or temperature), assuming that the corals were located in areas free from anthropogenic pollution. Unfortunately, this assumption falls far short of reality, and it is essential to study the synergy between the multiple factors and their cascading effects in order to identify and prevent future threats to coral reefs.

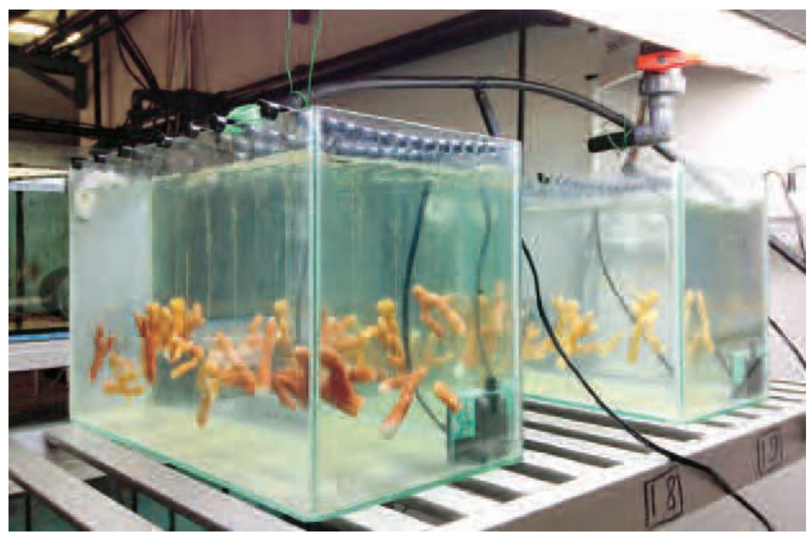
Nowadays, it is difficult to know whether regular inputs of metals, as is the case in New Caledonia with mining operations, will exacerbate the adverse effects of climate change on corals or not. To answer this question, laboratory experiments were carried out to test the combined effects of acidification and warming on several coral species, previously exposed to higher levels of cobalt and nickel.

Results indicated that, even if at "normal" temperatures, nickel stimulates coral calcification, when temperatures increase, nickel amplifies the negative effects of water warming and reduces coral growth by up to 37%. In contrast, colonies incubated for one month at higher pCO_2 (lower pH) and higher cobalt concentrations were less sensitive to acidification and were able to maintain calcification at levels equivalent to controls (maintained at normal pH and cobalt concentrations).

Complex responses to multiple stresses

These studies highlight the complexity of coral responses to multiple stresses. Although under "normal" temperatures a few metals may be useful to specific physiological mechanisms, these effects are offset or even reversed when corals are exposed to an increase in ocean temperatures such as those predicted for the end of the century.

These works only focused on the two most common metals found in the New Caledonian lagoon, but several other metals are being discharged in the lagoon from mining operations and runoff. Furthermore, very little data is available on interactions between metal. A combination of metals can increase or decrease their toxicity or bioavailability to corals. Corals, for which growth rates already declined by 37% when exposed to chronic and moderate nickel supply and temperature stress, will also likely be further compromised when exposed to other threats such as other types of pollution or ocean acidification.



Coral colonies exposed to different cobalt concentrations and temperatures in the laboratories of the *Aquarium des lagons* in Nouméa. © IRD/V. Meunier

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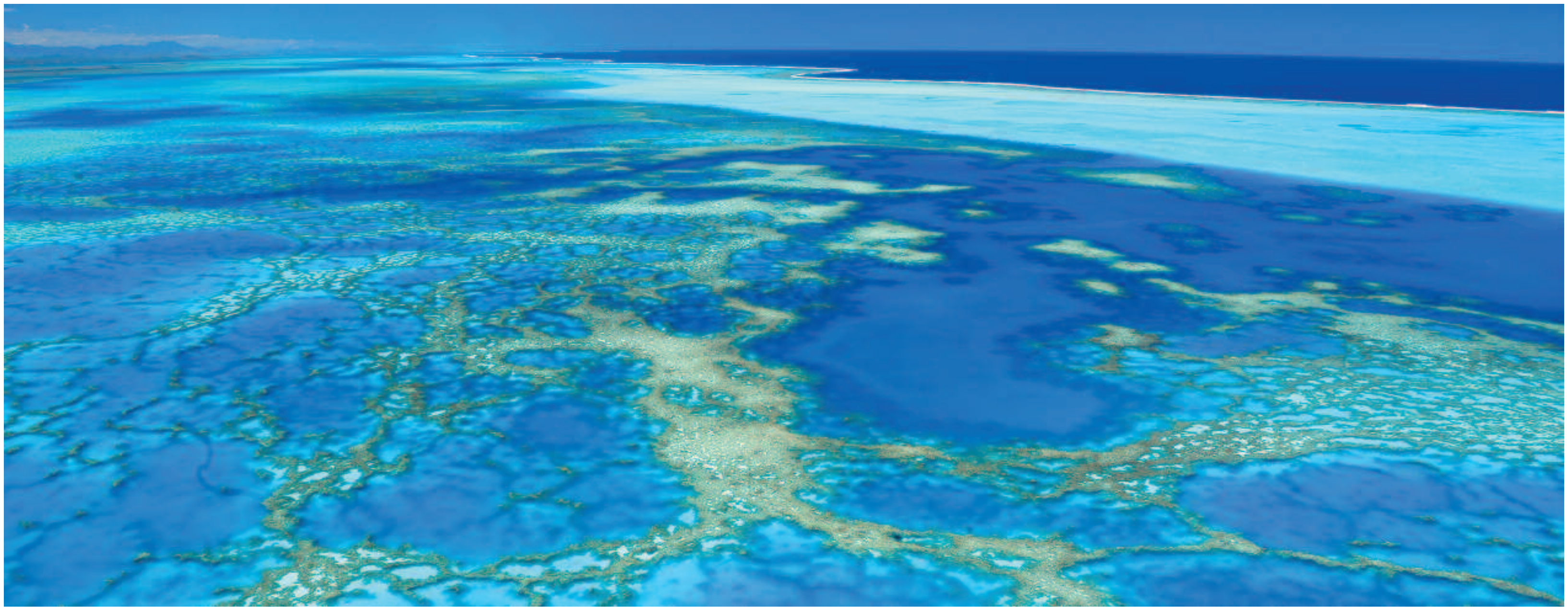
Soil erosion brings metal-rich sediments to the lagoon. © P.-A. Pantz

Chapter 24

Super corals in New Caledonia can resist climate change

Riccardo Rodolfo-Metalpa, Fanny Houlbrèque and Claude E. Payri



Reticulated lagoon, Nessadiou. © Province Sud/M. Dosdane

Coral reefs under threat from climate change

Coral reefs are already significantly impacted by climate change (GATTUSO *et al.*, 2015). Since the industrial revolution, atmospheric CO_2 levels have almost doubled, leading to global warming and ocean acidification. The effects of climate change on coral reef organisms have been extensively studied in recent decades, and experiments have been mainly conducted in tanks.

Calcifying species, such as reef-building corals, which host a substantial portion of the world's ocean biodiversity, are likely to be among the most affected by ocean acidification. This is because their calcification and dissolution rates appear to be related to the chemistry of carbonates in the oceans (box. 19). Several studies thus show a decline in coral calcification rates and, at the same time, an increase in dissolution rates of carbonate skeletons when the pH of seawater decreases. Ocean warming is also a major threat to marine life, and coral reefs have already been severely affected in recent decades. Sea surface temperatures which rise only 1°C above the maximum summer temperatures for at least two to three days, result in the loss of the coral's symbiotic algae (known as coral bleaching, chap. 25). Several studies indicate that most corals are able to recover from bleaching if temperature anomalies persist for less than a month, but the stress generated by high temperatures can cause permanent damage to coral metabolism.

Massive coral mortality, following bleaching events, was reported worldwide in 1998 and 2016. Although the majority of studies have shown a decrease in coral calcification rates with the reduction of pH in seawater, and massive mortality from bleaching due to higher temperatures, it appears that some corals are capable of acclimatizing to ocean warming and acidification. These divergent results reflect the difficulty of adequately and consistently reproducing complex environmental and ecological interactions in laboratory experiments. The scientific community has made considerable efforts over the past 15-20 years to understand the impact of global change on coral reefs and to more accurately predict how these ecosystems will change in the future. However, most conclusions about the impacts of climate change on corals and extrapolations to the ecosystem level are based on short-term laboratory experiments carried out on isolated individuals exposed to artificial conditions.

These experiments are useful, because they identify the effects of one or more parameters in isolation, but they are unable to take into account the acclimatization (and adaptation) of species in their natural environment. Laboratory experiments are not ecologically realistic because they do not take into account the effects of species interactions, natural food supply, or fluctuations in key environmental parameters. In addition, almost all of these studies have neglected the role of adaptation, as they have only tested responses to global change within the same generation of individuals and during very short periods of stress exposure.

In addition to ocean acidification and warming, the oxygen saturation rate of seawater decreases due to higher temperatures and coastal eutrophication. Little is known about the consequences of this for organisms, but they are likely to be negative. Deoxygenation, together with ocean acidification and warming form a "deadly trio", which could permanently affect the oceans by 2100.

In order to better predict the fate of marine organisms in response to climate change, it is time to scale up and address ecosystem-level effects. This requires finding coral reefs that are already exposed to environmental conditions that have been predicted for the end of this century. One might think that this is impossible, but there are several examples in nature. Some of these places are far from us, in Papua New Guinea, others are much closer and can be found in New Caledonia!

Studying extreme environments for the prediction of coral reefs' futurees

Populations of corals currently living at the margins of their optimum environment and acclimatizing to extreme environmental conditions have become models for predicting the future structure and functioning of coral reefs. Natural systems such as volcanic CO_2 vents (HALL-SPENCER *et al.*, 2008, FABRICIUS *et al.*, 2011) offer unique opportunities to study the future of coral communities exposed to global change. To date, no perfect natural systems have been discovered, but the data from the existing ones are of fundamental ecological relevance for providing realistic and natural scenarios. For example, at CO_2 vents in Papua New Guinea, pH varies over time, depending on environmental conditions (e.g., changes in prevailing currents and atmospheric conditions) and its effect is usually limited in space (about 100 square meters of the reef). In addition, at these sites, only the effect of ocean acidification can be observed because only "cold" resurgences of CO_2 have been discovered, although it is clear that warming will be the most influential factor in the future. The French National Research Institute for Sustainable Development (IRD) started a long-term research program at three volcanic sites in Papua New Guinea (CARIOCA project). A series of physiological and molecular analyses, coral transplants and multigenerational experiments will provide more reliable predictions on the responses of organisms and ecosystems to ocean acidification.

In February 2016, a collaboration between the IRD and the University of Technology Sydney (Australia) led the first field work at an exceptional site in Bouraké, 150 km from Nouméa (CAMP *et al.*, 2017). At this site, lagoon waters flow into the mangrove with high tide, circulate inside the system and exit at low tide. The depth of the system varies from a few centimeters to more than 6 m. The channel, which is more than 80 m wide, penetrates into the mangrove and creates large pools over a total area of more than 60,000 m^2.

The first measurements of the daily pH fluctuations (Fig. 1), during a 24-hour cycle, revealed the value of this unique site for studying the capacity of corals to acclimatize and adapt to extreme conditions. At each high tide, new lagoon water enters through the channel into the vast inner basin of the mangroves. During this journey, the water chemistry changes, due to metabolic reactions in the sediment, coral reefs and mangrove habitats, and it mixes with more acidic, hot and deoxygenated seawater. Even at high tide, the water in the system never returns to "normal" values. For example, the maximum pH values are around 7.9 (the normal pH of the ocean is currently 8.05 and is predicted to decrease to 7.7-7.8 in 2100). At low tide, seawater becomes more acidic and oxygen-depleted as the system begins to drain. The large volumes of water that were inside the mangrove forest enter the system and are then discharged into the lagoon. At low tide, near corals, the pH reaches the extreme value of 7.3 and O_2 reaches a concentration of 2 mg L^{-1} (the normal concentration of O_2 at the coast is 4-6 mg L^{-1}).

All these parameters exhibit clearly detectable fluctuations over a 24-hour cycle, which is extremely important in assessing the amount of stress that corals experience over time. This makes this site much more interesting than other natural laboratories in which the duration and intensity of stress (e.g., volcanic vents) are not consistent in time or space.

According to recent literature on the effects of climate change on coral reefs, the persistence of corals and calcifying organisms in general is likely to be seriously compromised. Yet, the IRD experiments at Bouraké revealed the presence of more than 50 different species of corals, which form very well-preserved reefs similar to other fringing reefs of New Caledonia.

There is no doubt that this site offers new opportunities to better understand the future of coral reefs in response to global change. The main hypothesis, which has yet to be verified, is that many marine species, considered by previous laboratory studies to be sensitive to

Study site at Bouraké showing the main channel through which seawater from the lagoon enters the mangrove. © IRD/J.-M. Boré

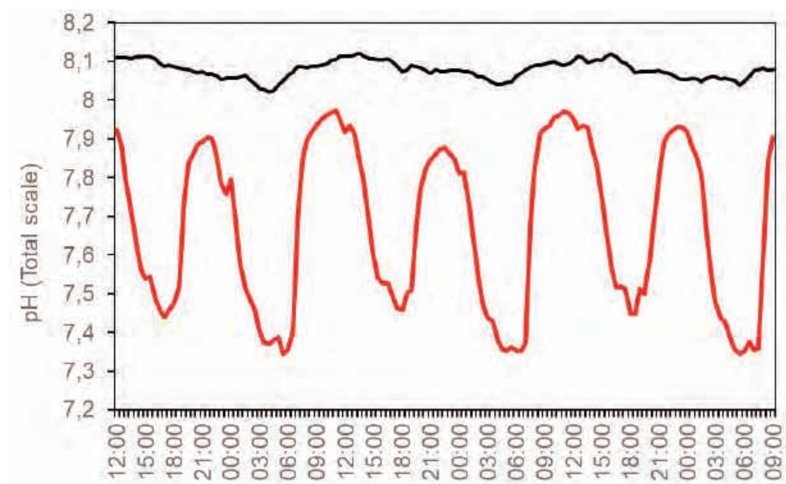


Figure 1: Tidal pH changes at the study site (red) and at a control site, outside the mangrove system (black). © IRD/R. Rodolfo-Metalpa

Box 19

Ocean acidification, a threat to corals?

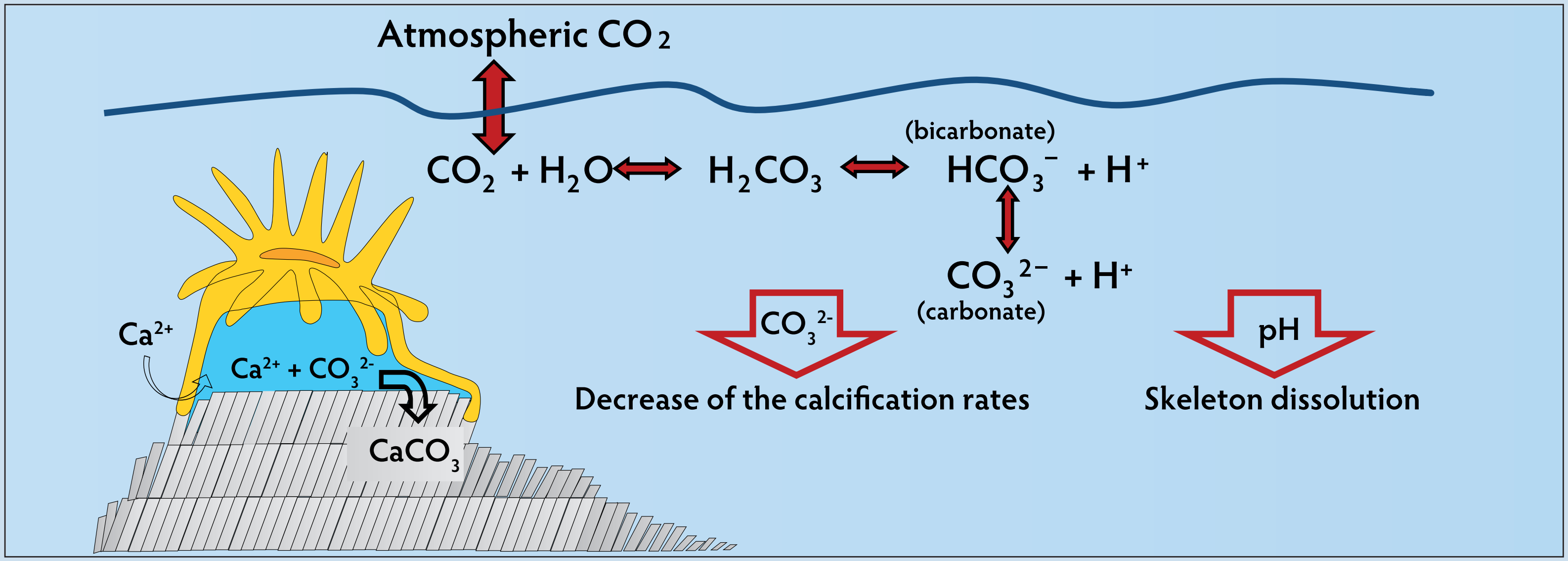


Diagram of calcification and decalcification (dissolution): Dissolved carbon dioxide (CO_2) reacts with water (H_2O) to produce carbonice acid (H_2CO_3): $CO_2 + H_2O \leftrightarrow H_2CO_3$
Carbonic acid is then uncoupled in bicarbonate: $H_2CO_3^- \leftrightarrow HCO_3^- + H$
The bicarbonate ion is also uncoupled in carbonate ion: $HCO_3^- \leftrightarrow CO_3^{2-} + H^+$
In water, the three compounds CO_2, HCO_2^-, and CO_3^{2-} are in stable proportions depending on pH conditions.

Will oceans be more acidic in the future?

Ocean acidification is about chemistry. Carbon dioxide (CO_2), released into the atmosphere by human activities, contributes to global warming (greenhouse effect). About 25% of this carbon dioxide is absorbed by the oceans. Oceans thus contribute in the reduction of the greenhouse effect. In return, this gas increases the acidity of oceans. In fact, the dissolution of CO_2 in seawater causes an increase in its acidity, which corresponds to a decrease in pH. This leads to a decrease in the amount of carbonate ions (CO_3^-), which are one of the necessary elements for some marine organisms to build their skeletons, shells and other calcareous structures.

What will be the impacts on the coral ecosystem?

With more acidic waters, animals with calcareous skeletons or shells such as corals will experience difficulties in producing calcified structures because the carbonate ions they use will be less abundant. Organisms will need more energy to calcify, and their skeletons and shells will be more fragile. Responses differ depending on species and some seem to be more resistant to a decrease in pH. Responses also vary depending on life history stages, physiology and the capacity of species to regulate pH at the cell level. Ocean acidification can also facilitate the dissolution of reefs and make them more vulnerable to storms and tropical cyclones.


Aerial view of the Bouraké fringing reef. © IRD/J.-M. Boré

ocean acidification and warming, are in fact capable of acclimatizing to, or even adapting to, future climatic conditions. The main support for this hypothesis is the presence of many coral species in this mangrove system, where pH, temperature and pO_2 conditions are close to (or above) the values predicted for the end of the century.

Our aim is to acquire a better understanding of the physiological changes that corals use to adapt to extreme conditions (phenotypic elasticity), which is already an innovative approach. Our ambition is to assess whether these species, which have grown in these extreme conditions, can reproduce and how they potentially have adapted to future-like conditions (for example with transgenerational acclimatization).

Current research aims at investigating i) how changes in metabolism and zooxanthellae allow corals to thrive in extreme environments? and ii) what is the role of microbes and photosynthetic algae (i.e., *Symbiodinium*) living in symbiosis with the corals in the resistance capacity of corals to extreme conditions?

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Chapter 25

The 2016 coral bleaching event

Claude E. Payri, Francesca Benzoni, Laure. V. André and Fanny Houlbrèque

Massive colony of the genus *Porites*, d'Entrecasteaux Reefs, March 2016. © IRD/F. Benzoni

Coral reefs: a fragile and threatened ecosystem

Coral reefs are among the most diverse ecosystems in terms of species diversity and economic importance. Colorful, diverse and rich, they form a protective interface between land and ocean, which attracts and concentrates human activities. While they cover less than 0.2% of the world's ocean surface, they support almost 30% of the known marine biodiversity and provide resources upon which 500 million people depend directly or indirectly. In addition to their ecological value, coral reefs provide essential ecosystemic, economic and cultural benefits to industries and human societies through fishing, coastal protection, tourism and access to new natural molecules.

Entirely bioconstructed by biological organisms such as corals and calcareous algae, coral reefs are natural structures, which are particularly sensitive to changes in the environment. Their fragile equilibrium is threatened by a combination of factors including overexploitation of the environment and resources, and the overall degradation of the physical environment (sedimentation, pollution, etc.), all of which are exacerbated by population growth, the emergence of specific coral diseases and climate change. Their decline is observed worldwide. The situation is unquestionably clear today: 20% of the reef communities have totally changed, 15% have been seriously affected and are at risk of disappearing within a decade, and 20% are threatened with extinction within the next 40 years. Climate change affects the circulation, temperature, pH, salinity and nutrients of the seas. Warming of surface waters, either progressive or as a result of severe weather or climatic anomalies, has resulted in coral bleaching in many coral reefs around the world and this, has occurred on several occasions in recent decades.

Coral bleaching

Reef-building corals, as well as some other taxa (sea anemones, giant clams), live in symbiosis with unicellular microscopic algae belonging to the genus *Symbiodinium* and commonly referred to as "zooxanthellae". These algae live in polyps, the soft parts of corals, and contribute to their hosts' energy budget by accelerating the calcification of their skeleton. With their green and brown photosynthetic pigments, zooxanthellae also contribute to the color of living coral tissues. The substantial or complete loss of symbiotic algae by animal tissue and/or decreased concentrations of photosynthetic pigments in algae result in a discoloration of the host. It is this phenomenon of polyp depigmentation that is known as coral bleaching. Visually, the animal tissue becomes translucent, revealing the white calcareous skeleton. While this may be reversible, it has consequences for the life of corals as it affects their growth, fertility and reproduction. If the symbiosis is not re-established, then bleaching leads to coral death (Fig. 1).

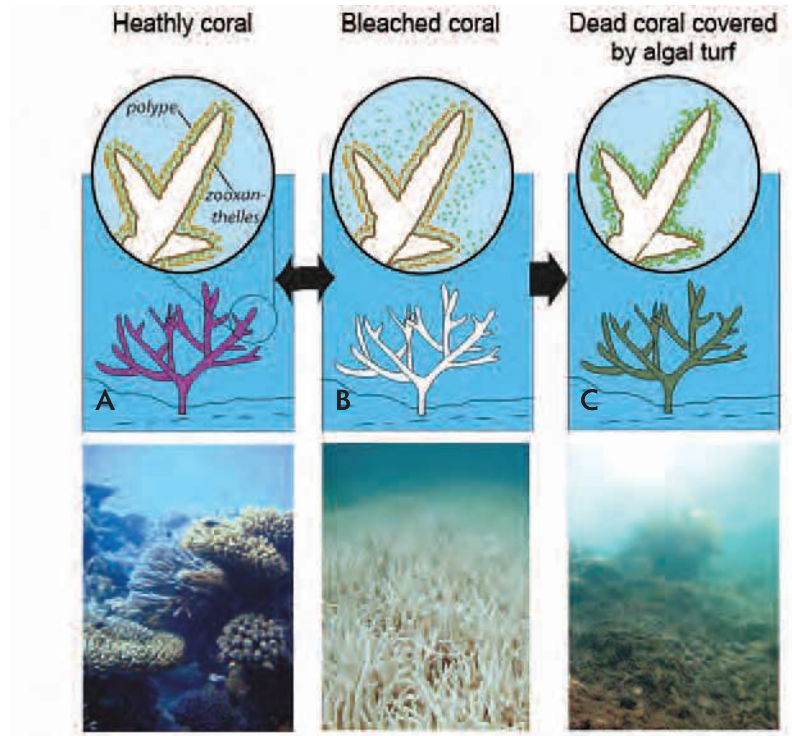


Figure 1: Diagram of coral bleaching at colony level (top) and community level (bottom).
A: Healthy coral with zooxanthellae and normal coloration.
B: Bleached coral after expelling zooxanthellae.
C: Algal turf on dead coral skeleton.
Adapted from http://www.gbrmpa.gov.au/managing-the-reef/tareats-to-the-reef/climate-change/what-does-this-mean-for-species/corals/what-is-coral-bleaching,

Coral bleaching is usually caused by abrupt environmental changes to which the coral is unable to adapt, such as increased seawater temperature, high UV radiation, desalination or bacterial infection. However, most large-scale massive bleaching events seem to have occurred due to an increase in mean maximum surface temperatures of only 1-2°C but which have lasted for several weeks in a row.

A major event in New Caledonia during summer 2016

Until the austral summer 2016, the reefs of New Caledonia had been spared by massive bleaching events. Only one earlier bleaching event had been reported and documented in January 1996, but limited data were available for only two sites of Grande Terre and did not suggest a major event. In February 2016, an unprecedented event of massive bleaching was observed.

In New Caledonia, sea surface temperatures were unusually high during the austral summer 2016. This period was also marked by an estimated 10% increase in UV radiation due to the absence of wind and cloud cover. Temperatures ranged from 27°C to 31°C between January and May 2016, with the warmest recorded temperatures in February at 1-2°C above the region's climatic maximum (Fig. 2). Values of 1°C for this index (Coral Bleaching Hotspot) and 4°C-Weeks (Degree Heating Week) for cumulation over time are considered to be thresholds that can lead to coral bleaching and are used for predicting risk areas. The 4°C-Weeks threshold was exceeded between February and mid-May 2016, with the highest values (above 8°C-Weeks) occurring in March and April 2016 (Fig. 2).

This meteorological anomaly, making this period the warmest season recorded in New Caledonia for the last 30 years, would be the cause of an exceptional bleaching event. It has already been established that 2015 was the warmest year ever recorded worldwide. It is not surprising that the combination of global warming and regional weather events had an impact on coral reefs.

Many observations made by IRD researchers (BLANCO and SUR-BLANCO programs[10]) and by a participative monitoring organized by the Pali Dalik association, among others, indicated that the event had affected almost all the fringing reefs of Grande Terre and intermediate reefs and islets of the lagoon. Bleaching was also observed at the Loyalty Islands and d'Entrecasteaux Reefs, but no data is available for the remote reefs of the Chesterfield Islands. In total, over 300 observations were made between March and April 2016, either by diving or aerial surveys. The presence or absence of bleaching is generally in good alignment with the Degree Heating Week map (Fig. 3).

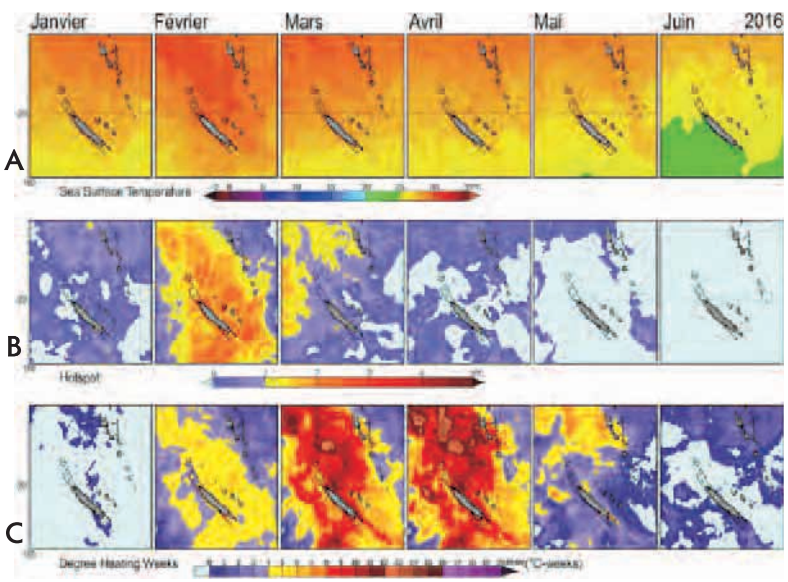


Figure 2: Sea surface temperature maps
A: of the Coral Bleaching Hotspot.
B: of the Degree Heating Week around New Caledonia during first semester 2016.
C: Data for 15th day of each month.
https://coralreefwatch.noaa.gov/satellite/bleaching5km/index.php

A variable impact

While most of the reefs were impacted, the extent of the damage varied between severe, moderate and mild depending on the species and types of coral communities. A bleached coral is not a dead coral, but without symbiotic algae its energy supplies are severely limited and in the event that stress conditions persist, corals will eventually die. While moderate and mild impacts may allow for a rapid return to normality, severe damage results in a much higher chance of death.

In general, coastal and lagoon reefs with a majority of branching corals were more affected than barrier reefs and external reef slopes, with bleaching rates reaching 90% of the coral cover. For the d'Entrecasteaux Reefs, bleaching affected the entire reef complex, with more severe damage inside the atolls' lagoons than outside. Massive corals, which exist in the form of balls and are usually less vulnerable, have been particularly affected on coastal reefs making this event particularly remarkable.

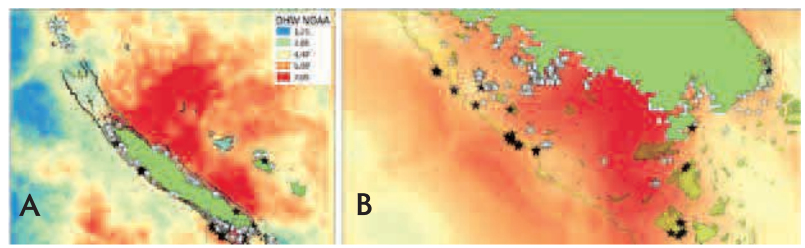


Figure 3: Location of observations (stars) made between March and April 2016.
A: Around Grande Terre.
B: In the Southern Lagoon and compared to Degree Heating Week map in °C-weeks, mid-February 2016 (NOAA 50-km SST Anomaly Product). The presence or absence of bleaching is marked by white (observed bleaching) or black (no bleaching) stars, respectively. Adapted from BENZONI *et al.*, 2017

A dynamic event

Thanks to a monthly monitoring carried out since February 2016 at several sites in the lagoon of New Caledonia, researchers have been able to demonstrate the dynamics of the event. They mapped the sensitivity of species from several thousand colonies which had been observed and monitored during an annual cycle. The event lasted from February 2016

[10] The BLANCO program is funded by MOM, IFRECOR New Caledonia and the IRD. The SUR-BLANCO oceanographic campaign aboard the Amborella is funded by the New Caledonia government.

to the end of March 2016, gradually decreased with the arrival of austral winter and lower temperatures and disappeared completely in August 2016. Two months after bleaching started at sites in the Nouméa lagoon, 70 to 80% of the bleached colonies had fully recovered their zooxanthellae and vitality, 10 to 20% were partially dead and less than 10% had died.

Reef monitoring after the 2016 event

Apart from the event reported during the austral summer 1995-1996, other events did not affect New Caledonia, even those of 1998 and 2002, although they had a major impact on the Great Barrier Reef. However, the 2016 event will remain a massive and global issue, having severely affected many different parts of the world.

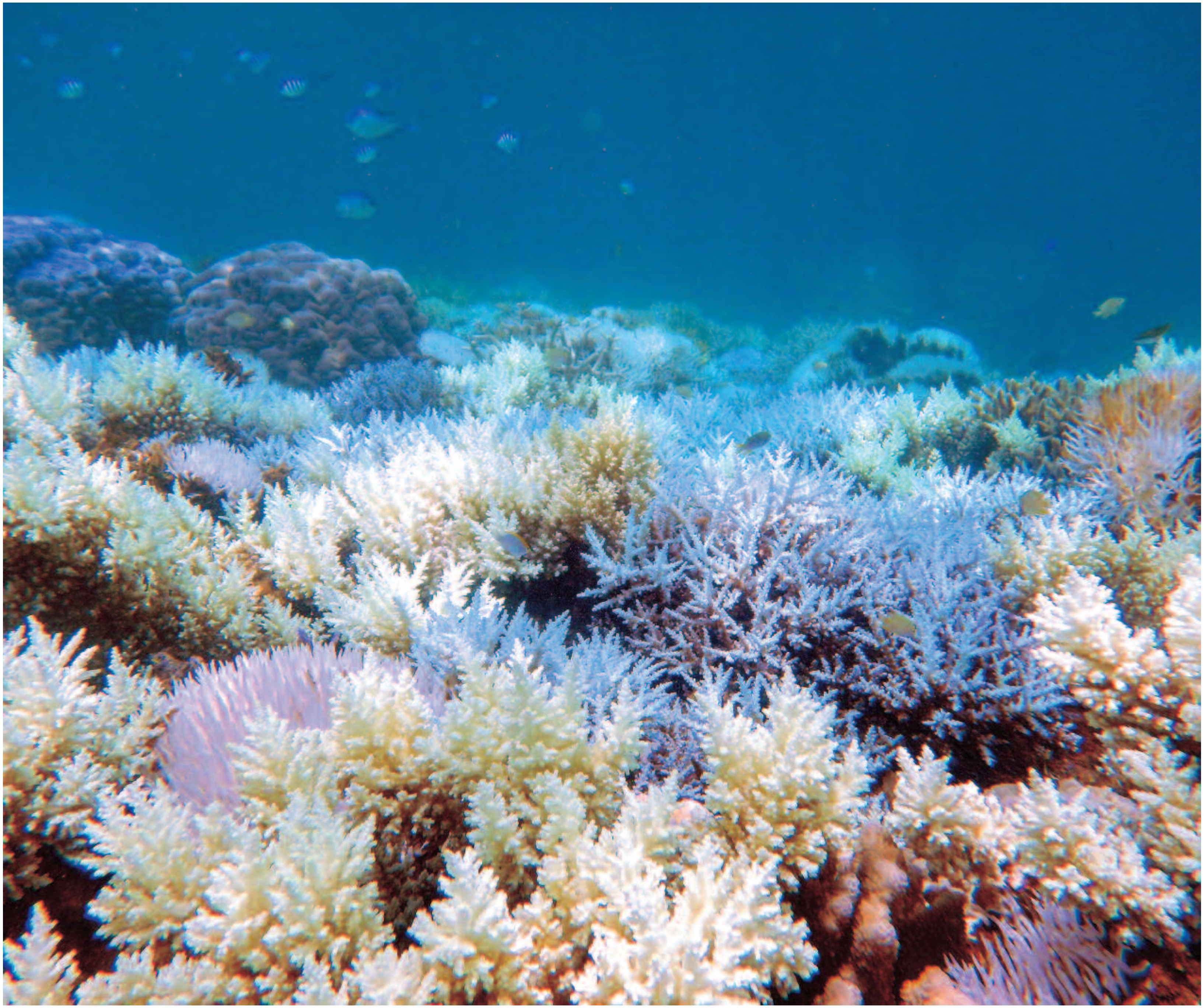
While in January 2017, several areas of the Great Barrier Reef were experiencing a consecutive year of coral bleaching, the vast majority of New Caledonia's reefs were spared. During the February 2017 monitoring (POST-BLANCO campaign[11]), researchers reported a higher mortality rate for coral communities at d'Entrecasteaux Reefs and on the east coast of Grande Terre. These were attributed to the 2016 bleaching event and the fact that the waters are warmer at these sites than on the rest of the coast of Grande Terre. Meanwhile, the monitoring carried out in the Chesterfield Islands in April 2017 (POST-BLANCO-2 campaign) revealed some signs of recent bleaching, the origin of which remains to be established.

What are the solutions?

Global warming and the associated rise in sea surface temperatures over the coming decades are no longer in question according to IPCC forecasts. Australian researchers have estimated that given the scale of the reef, it will take 10 years for the damaged corals to recover their vitality. Although they cannot control climate change, the mobilization of researchers is essential to warn others about environmental degradation, investigate its various aspects and ultimately study the resistance, or even resilience, of relevant species. Scientists are also working on combining the observations of the 2016 event with those available for regional coral communities. Their objective is to provide coral sensitivity maps that could be used by decision-makers when prioritizing conservation areas.

Comparison of two aerial views of Kuendu Beach Bay in Nouville, Nouméa, at the end of January 2016 (left) and at the end of February 2016 (right). The white spots visible in the right photograph correspond to the massive bleaching of corals. © IRD/F. Benzoni

[11] http://umr-entropie.ird.nc/index.php/home/actualites/depart-imminent-de-la-campagne-post-blanco-suivi-de-letat-des-recifs-apres-lepisode-de-blanchissement-massif-de-2016



Coral community of fully bleached branching corals. Roche Blanche Reef, south coast of Grande Terre, February 2016. © IRD/ F.Benzoni

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Chapter 26

Islet mobility in the New Caledonian lagoon: vulnerability or resilience?

Myriam Vendé-Leclerc and Manuel Garcin

Aerial view of Larégnère Islet; an islet in the middle of the lagoon. © province Sud/M. Dosdane

Unique geomorphological structures

Many coral islets of various sizes, ranging from a few square meters to several hectares, are present in the lagoon of New Caledonia. These more or less vegetated sandy formations, also called coral cays, rest on reef platforms within the lagoon or on the barrier reef. These islets are the result of an accumulation of biodetritic sediments produced by the degradation of coral reefs under the action of waves and storms.

These islets are places where the environment, culture, society and economy are interconnected. They play a key role in the rich and unique ecosystems of the lagoon of New Caledonia as nesting sites for turtles and seabirds, for example. Some benefit from environmental conservation measures and are classified as provincial, or governmental (for remote islets), reserves.

Islets are also very important in New Caledonia's culture and lifestyle. They are popular places for boating, fishing and water sports and attendance by New Caledonians, as well as tourists, has increased steadily in recent years. This has led to the development of an economy based on recreational activities with specific facilities and services.

People of New Caledonia and the local authorities continually debate their current development and their future, particularly in the context of climate change and sea level rise. The understanding of islet dynamics is of interest to decision-makers and the agencies managing these areas, but also to scientists, particularly those working on the impacts of climate change on coastal zones.

Twenty one islets under surveillance

In 2013, the New Caledonia Coastal Observatory (OBLIC, Observatoire du littoral de Nouvelle-Calédonie) initiated a study on the recent and future evolution of 21 New Caledonian islets. The objective was to facilitate the understanding of their morpho-dynamic functioning, the links between forcing factors (wind, waves,

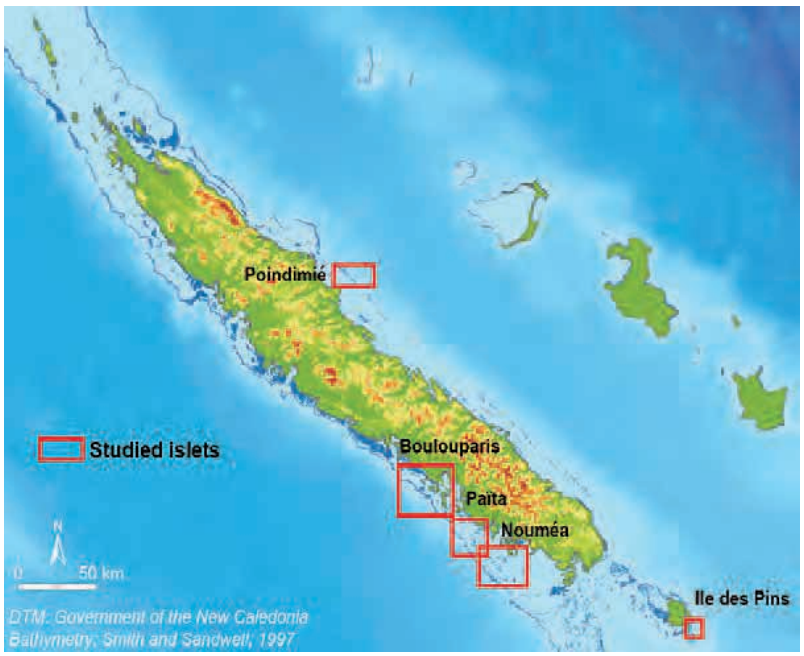

Figure 1: Location of the 21 islets in the New Caledonian lagoon. Altimetry: Government of New Caledonia; bathymetry: SMITH and SANDWELL, 1997

sea level, etc.) and their evolution, as well as to provide clues as to their future evolution.

Most of the investigated islets are located in the western lagoon, four are in the eastern lagoon and one is south of the Isle of Pines (Fig. 1). These islets are located in different and diverse environments, particularly in terms of their position in relation to the barrier reef or passes and wave exposition. Most of them have little or no facilities and some of them can be very busy. Only three islets are moderately to very strongly anthropized, with actions aiming at containing the erosion of their shoreline.

Between 2013 and 2016, field surveys have investigated the geomorphology and sedimentology of these islets. These surveys provided data to identify the geomorphological characteristics of the islets and to map the active morpho-sedimentary processes affecting the coastline of each islet (erosion, accretion, stability) in order to compare and classify them.

These observations were supplemented by the analysis of the islets' temporal evolution using satellite images and early aerial photographs. The time frame covered by the reconstitutions of each islet varies according to the availability of these media: satellite images are available for the last decade, while historical aerial photographs cover a period of 10 to 70 years. A conventional method was implemented whereby the permanent vegetation line was used as a reference and indicator of coastline mobility. Based on this work, coastal erosion and accretion rates, shape and surface area changes, and long-term trends of coastline changes have been modelled for each islet and a pluri-annual to pluri-decadal analysis of the islet dynamic and evolution trajectories has been performed.

Forcing factors were analyzed to understand the interactions and links between them and the geomorphological dynamics of islets. Changes in local and regional hydrodynamics (wave climate, currents) and cyclogenesis (intensity and frequency of extreme events such as tropical storms and cyclones) are possible factors in the degradation or regeneration of islet morphology. The variation in mean sea level can also affect their natural evolution. This is linked to the interannual climatic phenomenon ENSO (El Niño-Southern Oscillation), and to the relative rise in sea level (under the influence of climate and vertical ground movements).

Islets with various characteristics

Analyses show a large diversity of characteristics depending on the surface area (from 360,000 to 180 m^2) and shape (oval, oblong, triangular, etc.) of each islet. Very different trends of evolution have also been highlighted in recent decades, including for islets located in the same geographical area. The distribution of processes affecting the coastline of each islet (erosion, accretion, stability) is as follows: 54% of the cumulative coastline length of the islets is currently eroding, 30% is stable and 16% is accreting. The situation for each islet is, therefore, very variable with some remaining relatively stable over time while others evolve very fast and experience a significant decrease in their surface area.

All islets currently experience erosion on at least 50 % of their coastlines, and for many of them 100 % of their coastlines are affected. However, this erosion may also indicate a migration of the islet or an adaptation of its geometry. In fact, islets are much more

Temporal evolution of Larégnère Islet from 1982 to 2012. Adapted from GARCIN and VENDE-LECLERC, 2015 mobile than the coastlines of Grande Terre or the Loyalty Islands. Over the last few years, islets with a significant tendency to accretion and increasing surface area were very rare, and those in a stable situation accounted for less than one-third of all the islets studied.

Beachrocks, an essential component of many islets

Beachrocks (box. 20) which provide natural protection against receding coastline were also mapped. This is particularly true when several generations are present in the form of successive beds. Islets with beachrocks that are higher in elevation than the current sea level (probably formed during the high Holocene sea level between 6,000 and 2,800 BP) are often less prone to shoreline erosion. These islets generally have significantly larger areas and mean altitudes compared with other islets. However, in a few cases, the presence of beachrocks did not prevent erosion and the partial or even total destruction of the islet. Most of these cases are islets of relatively modest surface area, low altitude and are therefore probably younger than those mentioned above. Changes in sea level make these them much more vulnerable to erosion.

The life cycle of islets, from birth to disappearance

These analyses lead us to propose an islet life cycle diagram composed of several evolutionary stages. These stages are controlled by environmental parameters such as local hydrodynamic conditions, changes in wind and wave climates over time, and changes in reef and relative sea levels. Six stages make up the life cycle of New Caledonian islets: nucleation, growth, maturity, decay, relic and disappearance (Fig. 2). One stage was allocated to each of the islets studied. Changes in forcing factors as well as current or inherited geomorphology lead the islets to evolve from one stage to another. However, these stages do not necessarily follow one another sequentially and a reversal to an earlier stage is possible.

Box 20
What the beachrocks tell us

Beachrocks are sedimentary rocks formed at the intertidal zone by the carbonate cementation of beach sands and bioclastic and biodetritic sediments. This early hardening occurs only during periods of beach stability and is parallel to the shoreline. Therefore, over time, beachrocks have fossilized the islet shoreline providing evidence of the location, orientation and shape of the former beaches and the paleo-morphology of the islet. They allow us to assess the past surface area of the islet, to detect areas where the coastline has receded and thus provide valuable information on the evolution of the islet over time.

Several generations of beachrocks that result from the fossilization of successive former beaches, southeast of Larégnère Islet. © M. Vendé-Leclerc

The future of islets: disappearance or adaptation?

The future of an islet can be anticipated using several criteria that can be factors of resilience or vulnerability: its past evolution, its current stage, the intensity of current morpho-sedimentary processes and its morphological characteristics.

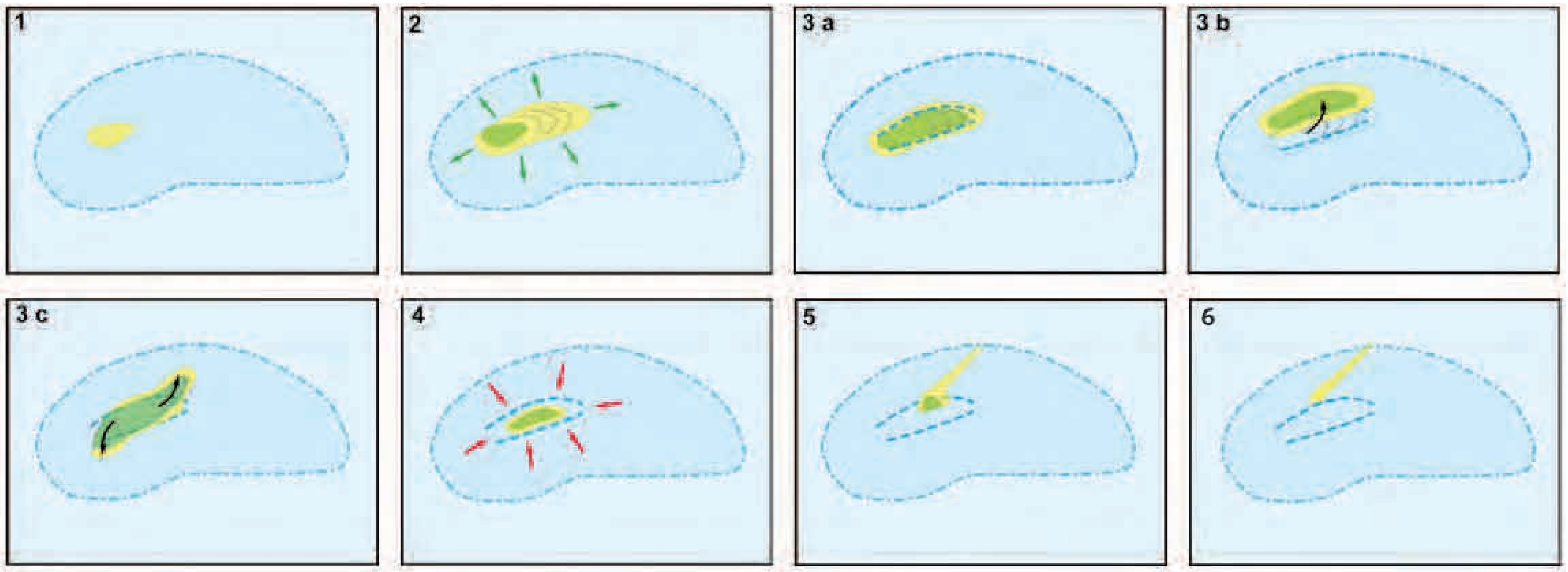

Figure 2: The different evolutionary stages of New Caledonian islets.
Stage 1: Nucleation. Stage 2: Growth. Stage 3a: Stable maturity. Stage 3b: Migration maturity. Stage 3c: Adaptation maturity. Stage 4: Decay. Stage 5: Relic. Stage 6: Disappearance.

Consideration should also be given to the future evolution of environmental parameters such as, for example, ENSO climatic oscillations, which influence mean sea level in the southwest Pacific, or extreme events (tropical cyclones, southern swells), which can have a severe impact on islet morphology over the very short term with sometimes permanent effects. These natural processes are exacerbated by climate change and human-induced sea-level rise.

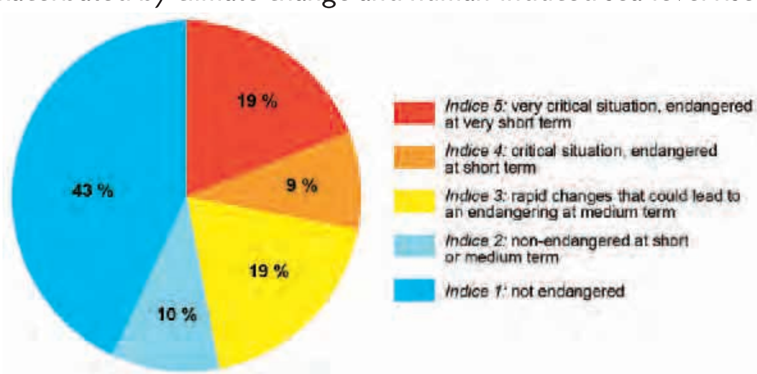

Figure 3: Distribution of islets according to their likely future evolutions (in %). Adapted from GARCIN *et al.*, 2016b

Using these data and information, a life expectancy index was defined to indicate the plausible future of each islet. This index is ranked from 1 to 5, where 1 is the most stable, and 5 is the most critical situation. Based on this classification and assuming that the current environmental situation remains stable, it was determined that: 19% of the 21 islets are in a very critical situation which could lead to their very probable disappearance in the near future (a few years) (index 5); 9% of the islets are in a critical situation with a probable disappearance in the near future and a very probable disappearance in the mid-term (next decades) (index 4); 19% of the islets exhibit rapid morphological changes which could be a threat in the mid-term (over a decade) but not in the near future (index 3); 10% of the islets are not threatened on the short and mid-term due to their medium size and altitude, and moderate increase or decrease in surface area (index 2); and 43% are not threatened as they are stable or growing, with large surface areas and relatively high elevations (index 1) (Fig. 3). These findings indicate that situations can be highly contrasting from one islet to another, even for neighboring islets.

Uncertainties are also more substantial over the medium and long term due to the future rate of sea level rise. Uncertainties are linked to a threshold which, if it was reached, would lead to a change in the resilience capacity of islets. Changes in ocean temperature and acidity also significantly affect the health and growth of reefs, modifying their protective role within coastal zones and their function as producers of biodetritic sediments which contribute to the sediment budget of islets.

In the future, the evolution of the islets of the New Caledonian lagoon will be highly variable and will rely greatly on their resilience to the various threats of global climate change.

Islets: indicators of the effects of climate change

Islets are characterized by a high sensitivity to changes in weather and climate conditions. The number of forcing factors that play a role in their evolution is smaller and their impacts on coastal dynamics are more direct and easily detectable than on the mainland. Understanding such processes at the scale of islets provides a better understanding of the events happening at a larger scale. The islets of the lagoon thus provide indicators of environmental change for New Caledonia and can serve as a reference site for monitoring the impacts of sea level rise and climate change.

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Chapter 27

Managing Acanthaster outbreaks: a challenge for the Pacific

Pascal Dumas and Mehdi Adjeroud

Acanthaster planci is a corallivorous starfish, which feeds on coral polyps by extruding its stomach over corals, leaving behind only the white calcareous skeleton of its prey. Large adults (30 to 40 cm in diameter on average) can consume up to 12 m^2 of coral per year. © IRD/P. Dumas

A voracious predator

Sea stars of the genus *Acanthaster* are echinoderms, a group which also includes sea urchins, holothurians, crinoids and ophiuroids, all found in Indo-Pacific coral reefs. Their color varies considerably depending on the region. They usually have 10 to 20 arms with long spines on their upper face, which are coated with a particularly painful and highly toxic steroid venom. Their common name reflects their morphology: "Crown of thorns". Besides *Acanthaster brevispinus*, a species mostly found in deep habitats, recent genetic studies suggest that there are at least four distinct and geographically separate species along a Red Sea - Indian Ocean - Pacific Ocean *continuum*. Once part of the unique species *A. planci*, the populations found in Pacific reefs are now classified as *A.* cf. *solaris*, but their taxonomic status (and the possible existence of several distinct species within the Pacific) is still controversial.

Some specimens can be over 70 cm in diameter and weigh up to 3 kg, but the reputation of acanthasters is mainly due to the effects of their diet on coral ecosystems. Adult acanthasters are voracious predators of coral, which they eat by extruding their stomachs over the coral colonies. Once they have digested the polyps on site, they leave behind them clean and intact calcareous skeletons. These white feeding scars are often one of the first indicators of the presence of numerous acanthasters.

Acanthasters have existed on reefs throughout geological times and they are a natural component of tropical ecosystems. They are relatively scarce on a "healthy" coral reef (only a few individuals per hectare) and their predation has no negative impact on the abundance, cover and diversity of coral assemblages. They even contribute to the maintenance of coral diversity due to their pronounced dietary preferences. In general, fast-growing corals such as *Acropora* and *Montipora* are preferred over slower-growing corals such as *Porites*, leaving more room for less opportunistic species. An adult acanthaster consumes about 10 m^2 of coral per year and has only few regular predators. Out of about thirty recorded species of fish and invertebrates, only a handful (the giant triton *Charonia tritonis* or "Triton's trumpet", the stellate puffer *Arothron stellatus*, the humphead wrasse *Cheilinus undulatus*, and some triggerfish, emperor or boxfish) are known to prey on healthy adults.

Outbreaks of acanthaster populations

While in normal conditions, acanthasters are rather inconspicuous, their populations can, sometimes, explode to extreme levels. They can reach up to several thousand, or even tens of thousands of individuals per hectare, which can persist for months or years over vast reef areas. These unpredictable blooms are one of the most serious biotic disturbances to coral reefs, and their impact is comparable to that of tropical cyclones. Coral mortality can exceed 90% in the most severely affected reef areas, resulting in a profound restructuring of the ecosystem structure and ability to function. The cascading effects of coral disappearance include the physical alteration of habitat, the depletion of prey, and the displacement and relocation of species. These can affect the entire reef community and sometimes lead to a phase-shift where the system becomes totally dominated by algae.

Although fossil records suggest a much older history, the first outbreaks of acanthasters and their consequences were not reported and studied quantitatively until the 1960s. More than a third of the Pacific reefs have been affected by these outbreaks: the Ryukyu archipelago in southern Japan, Palau, Guam, Samoa, the Great Barrier Reef, Vanuatu, Fiji and Kiribati. French coral reefs have not been spared. The Society Islands in French Polynesia experienced a major event between 2006 and 2009. New Caledonia, which had had been

In some years, and for reasons that are not yet well known, acanthasters start to proliferate, with densities reaching several individuals per square meter. After a few months, they can destroy large portions of reefs. The Great Barrier Reef of Australia, French Polynesia, southern Japan, and more recently the Vanuatu archipelago and New Caledonia have experienced these sad outbreaks! © IRD/P. Dumas spared by large-scale outbreaks, was affected in 2000 and more recently in 2012. Despite sustained research efforts by the scientific community, the causes of these proliferations are still insufficiently understood. Some researchers believe that one factor could be the increasing scarcity of acanthasters' natural predators due to the overfishing of commercial species such as tritons, humphead wrasses, emperors, etc. The overall deterioration in water quality, linked to human activities, is also highlighted, but this hypothesis alone cannot explain all outbreaks, especially those observed on unpolluted reefs. For other authors, these demographic explosions could be part of the biological cycle of the species, which is naturally predisposed to large fluctuations as a result of its extraordinary fertility: a single spawning adult female can produce over 100 million eggs in a single breeding season. With hindsight, and thanks to recent scientific advances in genetics, molecular biology and modelling, the highly complex, multifactorial and multi-scale nature of these outbreaks is becoming increasingly evident.

"Acanthaster threat" and global change

In the Indo-Pacific region, the frequency and intensity of outbreaks appears to be increasing, especially in recent decades, with growing awareness of the global changes that are affecting the region. Acanthasters develop best in warm waters (26 to 30°C) in the presence of phytoplankton, and can therefore be particularly sensitive to the effects of climate change. Increased sea surface temperature and nutrient enrichment in coastal waters are the main contributing factors to the survival of larvae, thus increasing the number of adults potentially reaching the reefs at the end of their development. Given the large dispersal capacities of the species, whose swimming larvae can settle several hundred kilometers from their original reef, the growing regional "acanthaster threat" is a real problem in the context of current climate change scenarios. Although there is historical evidence that coral reefs can recover after an outbreak, recovery is generally slow (several decades) and not guaranteed. Acanthaster outbreaks are yet another pressure on ecosystems, which are increasingly weakened by other natural (coral bleaching, tropical cyclones, coral diseases, etc.) and anthropogenic (pollution, overfishing, coastal developments, etc.) disturbances. In the Australian Great Barrier Reef, a recent study reports a 50% decline in coral cover over the last 30 years, half of which is due to recurrent acanthaster outbreaks alone.

In New Caledonia, we have only limited knowledge of these outbreaks and their quantitative impacts on reefs. In line with studies and occasional observations dating back to 1980-1990, the assessment of 18 sites was carried out in 2012 by IRD scientists. Results revealed the existence of localized, potentially mobile, outbreaks with, at times, very high acanthaster densities (up to 500 individuals/ha). The Southwestern Lagoon is the most studied area, where proliferations are restricted to a few sites. Often ephemeral, these outbreaks generally go unnoticed by environmental managers, but they are likely to cause significant damage to corals in the medium and long term, especially to *Acropora* and *Pocillopora*. However, the information provided by users of the lagoon raises concerns about the existence of many outbreaks that are almost totally ignored, both in the South Province (e.g., Boulouparis, Ouaco, South Horn) and in the North Province (e.g., Hienghène, Poindimié, Poum), on the east coast (Côte oubliée, etc.) or on the islands.

Management of the "Acanthaster threat"

In the majority of Pacific countries, where coral resources form the basis of traditional fisheries, acanthaster outbreaks threaten the food security and livelihoods of coastal populations. The issue is also of concern to the tourism industry (diving clubs, hotels, etc.) whose activity can be seriously impacted by uncontrolled proliferation, and environmental managers for whom it is now a conservation issue.

Currently, only human actions can combat the proliferation of acanthasters, more or less successfully, depending on the extent of the phenomenon, the characteristics of the impacted reefs (size, isolation, vulnerability, etc.), the context (socio-economic, environmental) and the available resources (human, financial). The most common methods generally aim at limiting coral losses by minimizing the number of individuals feeding on reefs during an outbreak. The oldest method is the manual collection of acanthasters using a variety of tools such as hooks, sticks, spear guns, bags, etc. to bring them back to shore and destroy them. This method, which requires a large workforce and a long-lasting commitment, has a limited effect in the face of massive, widespread and/or recurrent outbreaks, especially since it requires a good knowledge of the species' biological and ecological specificities (particularly its local spawning period). The injection method, which is more cost-effective, is increasingly replacing collection methods. It involves inoculating a toxic solution that causes the death of acanthasters. However, these treatments have some drawbacks, and the use of several chemicals (e.g. copper sulfate, sodium bisulfate, formaldehyde, ammonia, bleach, etc.) had to be discontinued due to their toxic effect on the environment and other species as well as their high cost. A new approach based on the injection of natural and cheap acidic substances has recently been developed by the IRD. Tests were carried out both in the lab under controlled conditions and in the field and demonstrated the lethal properties of some fruit juices (different varieties of lime and passion fruit), white vinegar and some powdered acids from the agri-food industry. These substances, which cause high mortality even at low doses, are now a highly credible ecological alternative in fighting acanthaster outbreaks. Tested in Vanuatu since 2014, this method was first used in New Caledonia in 2017. A pilot field operation was carried out at Vua islet with the participation of volunteer divers and the IRD's research vessels. It resulted in the eradication of more than a ton of acanthasters over two days and confirmed the efficiency of the method under real conditions.

The unpredictability of these outbreaks makes their management particularly complex, especially for reefs that are frequently exposed to these events, sometimes several years in a row. But as effective as they may be, these methods of control are merely a symptomatic treatment of the phenomenon - much like scooping water out of a punctured boat. They require that any proliferation is detected at the earliest possible moment. This task may seem overwhelming for countries with extensive reef formations, as long-term monitoring requires considerable resources. Alternatives are required to face the difficulty of ensuring the funding of long-term scientific monitoring covering the whole territory. An interesting alternative is the creation of "citizen" monitoring networks, where data collection is provided by the lagoon users themselves. This is the purpose of the participative monitoring program OREANET[13] (Oceania Regional

The methods for controlling acanthaster outbreaks are limited. In some Pacific island states, fishermen and divers organize campaigns during which acanthasters are collected manually. They are often timely but limited in space, and their efficiency is usually not sufficient to stop severe outbreaks. However, they do help to mitigate damages and involve local populations in the preservation of their reefs. © IRD/P. Dumas

[13] http://oreanet.ird.nc

Recently, more sophisticated techniques have been developed that attempt to reconcile field efficiency, low environmental impacts and low costs. For example, lethal vinegar injection kits have been successfully tested, here, around Vua Islet in the Southwestern lagoon of Grande Terre. © B. Preuss

Box 21

The Oreanet program

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The IRD project, OREANET (Oreanet Regional Acanthaster Network) was officially launched in July 2015 with financial support from the Pacific Fund (Fonds Pacifique), the Government of New Caledonia and GOPS (Grand observatoire de la biodiversité terrestre et marine du Pacifique sud et sud-ouest). This project aims at building an operational monitoring network for the "acanthaster threat" in New Caledonia, Vanuatu and Fiji. The success of this network is based on a participative approach, where observations are relayed by lagoon users, with user-friendly tools that allow rapid reporting of acanthasters from a computer, tablet or smartphone.

To date, the OREANET network has recorded over 16,000 acanthasters through more than 300 participative reports from fishermen, coastal communities, boaters, divers, NGOs, diving clubs and associations, scientific organizations, etc. Standardized procedures for the verification of the threat and control in the field have also been developed and validated. The objective is to establish a mapping of threats and provide an operational response framework when an outbreak is reported via the surveillance network.

Acanthaster Network), set up in New Caledonia since 2015. It is based on the voluntary participation of fishermen, boaters, diving clubs, environmental consultants, associations and scientists in monitoring the outbreak (box. 21).

The "acanthaster phenomenon" is now recognized as a major conservation issue. However, the late realization of its magnitude and the existence of recurring controversies regarding the relevance of human intervention, have severely hampered the response capacities of affected countries. Despite their efficiency over the short to medium term, current management strategies are only a temporary solution, treating symptoms rather than the origin of a complex phenomenon whose underlying causes are still largely unknown. The next step requires the development of a global approach, integrating a better understanding of the processes that control the onset, maintenance and spread of acanthaster outbreaks with relation to climate change affecting marine ecosystems: a major scientific challenge.

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