NEW CALEDONIA
World of Corals

Scientific direction: Claude E. Payri

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"The samples of drawings selected to illustrate the chapters of this book come from my artistic residence on board Tara during the Tara Pacific expedition (2016-2018) which studied coral reefs and their evolution while faced with climate change and anthropic pressures. The drawings in part 1 ("Exchanges and symbioses / photosynthesis and nutritional radiation of Symbiodinium from corals to other reef animals / shared gelatinous overproduction"), part 2 ("What is exchanged from air to water to air") and part 3 ("Planche N et blanc, site Chesterfield") were made using pencils, while drawings in part 5 ("Exchange Iconographies II Organisms Machines") were made using a ball-point pen. Part 4 starts with a sample of a black lithography ("Exoskeleton of Tara in planktonic gleams under the Milky Way").

All the artistic work carried out during this residence can be seen at noemiesauve.blogspot.fr under the chapter TARA PACIFIC."

Noémie Sauve

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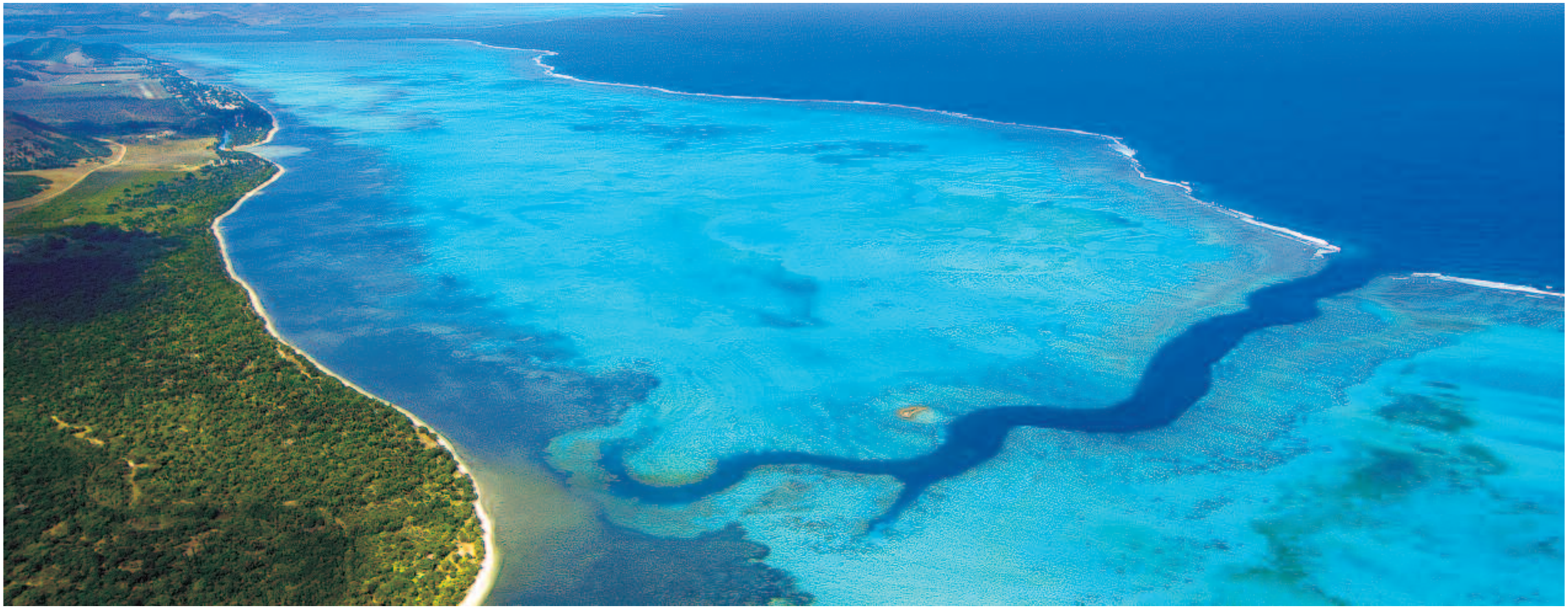
Preface

A compelling urgency

Prof. Jean-Paul Moatti, Chairman of the Board and Chief Executive Officer of the French Research Institute for Development (IRD)



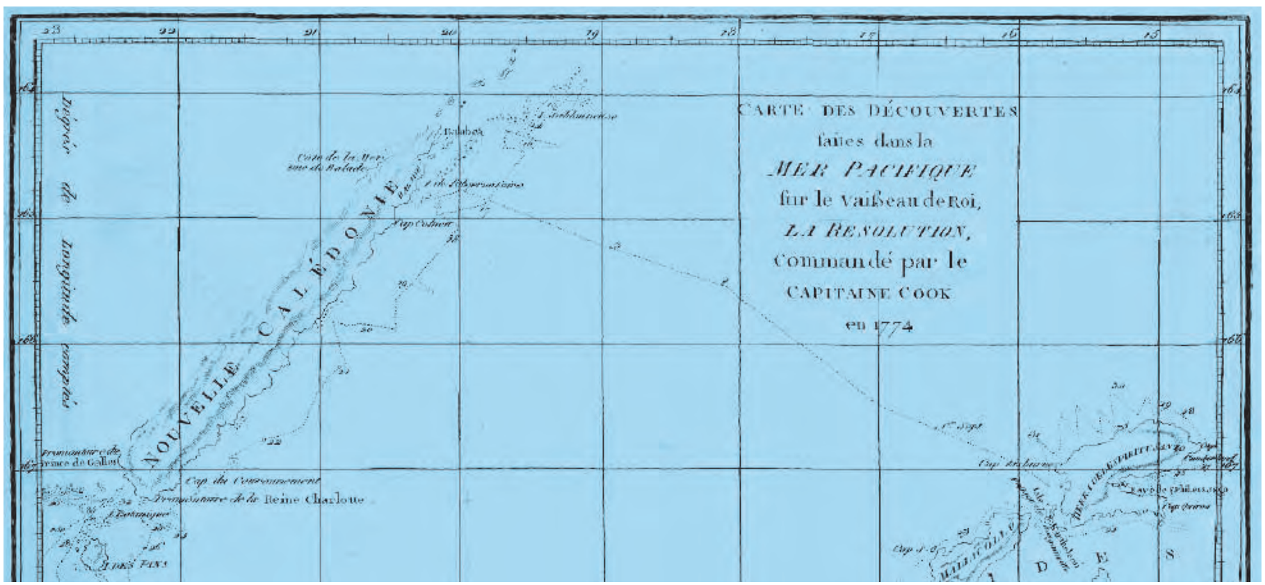
Aerial view of the barrier-reef at Poé, west coast of Grande Terre. © P.-A. Pantz

An exceptional reserve for marine biodiversity, a barrier protecting the coastline against the fury of the ocean, a key economic resource and a precious cultural heritage for many island and coastal populations, coral reefs are today one of the most threatened ecosystems of our planet. Under the combined weight of global warming and the accelerated urbanization of coastal areas, 20% of the world's coral reefs have already been destroyed without hope of recovery, and an additional 70% could disappear in the short to medium term. Protecting these ecosystems and implementing sustainable management methods for these vulnerable environments is an urgent priority at the core of the 2030 agenda for Sustainable Development Goals (SDOs) adopted by the United Nations and all its member states.

Home to the second largest coral reef barrier in the world after Australia, New Caledonia is at the forefront of this international challenge. Research on the reefs and lagoons of the New Caledonian archipelago has a long historical tradition, that began with Captain Cook's expeditions in the 18th century. Research in these areas has accelerated over the last half century as the scientific community have started to mobilize for the preservation of coral reefs, alongside many other stakeholders, NGOs and management agencies responsible for the protection and conservation of the environment and heritage. Thanks to its long-standing presence in the intertropical zone and in French overseas territories, particularly in the Pacific zone of New Caledonia and French Polynesia, the French National Research Institute for Sustainable Development (IRD) is committed to this field of research, which calls for an interdisciplinary approach combining biological, physical, environmental, human and social sciences.

Bringing together approximately a hundred experts from research organizations, universities and institutions in charge of preserving both New Caledonian and metropolitan environment and heritage , this book offers the most up-to-date knowledge of New Caledonia's coral reefs. It provides an insight into the extraordinary diversity of these coral reefs in relation to geological history and the marine environment, the way that they function and the interactions between the multitude of organisms that they are composed of or which they host. The book also outlines how, over the past 3,000 years, these lagoons and reefs have provided New Caledonian populations not only with resources but also a place of life and expression and can be found at the heart of the Kanak culture. Finally, the authors examine the capacity of these ecosystems for resilience, given their exposure to threats from global warming and other global environmental changes and discuss the tools available for their preservation.

The publication of this work is timely in two ways: 2018 has been declared the "International Year of the Reefs", at the same time as the tenth anniversary of the inscription of 15,000 km^2 of reefs and lagoons of New Caledonia on the UNESCO World Heritage List. In addition, in an international context where science is increasingly challenged by irrational or politically guided motives, this book illustrates, in an exemplary manner, how rigorous multidisciplinary research can contribute to the sustainable management of an exceptional natural heritage, not only for the people of New Caledonia and the Pacific, but for humanity as a whole.



Map of New Caledonia, Captain Cook's voyage, 1774. © Gallica/BNF

[1] The Institute for Research for Development (IRD), the University of New Caledonia (UNC), IFREMER, the Lagoon Aquarium (ADL), the Geological Department of New Caledonia (SGNC), the Archaeological Institute of New Caledonia and the Pacific (IANCP), the Kanak Culture Development Agency (ADCK), the services of the three provinces in charge of the management of reefs and lagoons, the Conservatory of the Natural Areas of New Caledonia (CEN), The Office of New Caledonian Maritime affairs (DAM) in charge of the Natural Park of the Coral Sea.

Foreword

Lagoons and coral reefs: foundation of a society and source of bioinspiration

Édouard Hnawia, chemist and ethnopharmacologist, Delegate Representative of the IRD in New Caledonia

Bay of Sandal, Lifou. © P.-A. Pantz

This book on New Caledonian reefs and lagoons is of particular importance to me, both as a child of the country and as a chemist and ethnopharmacologist. At the interface between several scientific domains, ethnopharmacology studies all materials of plant, animal or mineral origin that traditional societies use to live in harmony with their environment. In New Caledonia, pharmacochemical research began to focus on reef and lagoon organisms well before studies of biodiversity. The study of molecules of interest for the development of new drugs then gave a notable boost to biological inventories, thanks in particular to the curiosity, dynamism and enthusiasm of the IRD's scientific divers (formerly ORSTOM).

For several decades now, understanding and recognizing the links that human societies maintain with the lagoon, describing the way that they function and the marine biodiversity they contain, have been the foci of the IRD's researchers, in partnership with researchers from other research institutes and universities.

However, long before them, the inhabitants of New Caledonia, and more particularly Kanak people, produced knowledge related to reefs and lagoons. This knowledge is the foundation of a vision of society that links the land and sea, the visible and invisible worlds, people and their environment. Although over time, political, economic and societal

Highly diverse gorgonian community, typical of the coral reef photic zone in Lifou. Depth: 20 m. January 2008. © Andromède Océanologie/ L. Ballesta

changes have led to the disappearance of some ancient practices, reefs and lagoons still remain a source of the expression and production of traditional ecological knowledge. As a result, medicines produced using terrestrial plants to treat humans can be informed by what is observed in the marine environment. One of the stories that particularly struck me in this regard was told by a grandfather from my clan. He recounts how he witnessed an unusual event along the shore which involved both marine and terrestrial species, and allowed him to discover a cure for scorpionfish and jellyfish stings.

Symbolically as well as physically, land and sea form a continuum. In the minds of many people of New Caledonia, just like the land, the lagoon represents a "larder", a place where it is always possible to find food for one's family. Wildlife associated with reefs and lagoons is also relied upon to ensure the smooth unfolding of a customary event, or more frequently, to welcome guests. Consequently, environmental pollution can affect social organization, which we witnessed just this year with an oil spill caused by the stranding of the container ship *Kea Trader* in Maré. A few weeks before the yam festival, an essential event in the Kanak life cycle, which must be celebrated with valuable marine animals, the fishermen feared that they would not be able to do their duty and that this would compromise the ceremony. Some marine organisms are also used to guide people in their work and decision-making, to "command" the sea or fish, or for their healing properties. Therefore, taking care of the lagoon also means taking care of the people.

This work, alongside the oral tradition which conveys many stories and legends recalling the links between the marine world and mankind, is intended to be one further way to perpetuate the knowledge and know-how of an entire population, which today relies on both the oral and the written word. The following chapters reflect the interest that scientists have shown in the lagoon and the people who have relied on it for nearly 70 years. The results of their research contribute to a greater knowledge that serves to better manage this natural and cultural heritage, which has been inherited from the Elders and that we wish to pass on to future generations. We hope that our children will find a source of inspiration in this book and that they will not forget to take the time to observe their environment.

Introduction

New Caledonia: Land of Nickel, World of Corals

Claude E. Payri

Ouen Island. © P.-A. Pantz

Reef ecosystems are an important part of the coastline of many countries in the intertropical zone. Some of these countries are even made exclusively of coral islands or atolls, such as the Maldives and Chagos archipelago in the Indian Ocean, and the Marshall Islands, Kiribati, Tuvalu and Tokelau in the Pacific Ocean. Coral reefs, and the lagoons they delimit, are like fortifications that shelter and feed a profusion of species. They are highly productive and represent the main source of protein for millions of people, while simultaneously protecting coastlines. In the Western imagination, coral reefs embody the peaceful, turquoise blue waters of the southern seas, their beautiful white sandy beaches and the wonder of brightly colored fish – all of which attract numerous tourists.

Coral reefs are among the few ecosystems to grow and develop on their own substratum. They are built up by the accumulation of calcareous coral skeletons and consolidated by other organisms such as red calcareous algae. They shelter a multitude of different life forms and create a complex network of biological functions and interactions.

Their continuity in time and space critically relies on the ability of these organisms to live, persist and thrive so that the whole structure continues to grow. This is also what contributes to their vulnerability. The increase and extension of reefs is perpetually counterbalanced, not only by physical and mechanical erosion due to tropical storms and cyclones, but also by bioerosion due to organisms that perforate and erode the calcareous skeletons, breaking them down into debris and sand.

« Reefs are as old as the world ». However, in the past they were built by other organisms, most of which disappeared during major biological extinction periods and different types of reef formations have succeeded one another over geological time. Precambrian stromatolites, built by blue-green algae or cyanobacteria, were replaced during nearly 250 million years by bryozoans, stromatoporoids (a sort of primitive sponge), and primitive corals, most of which disappeared during the great Permian extinction. During the Cretaceous period, reefs were mostly built by rudists, a kind of giant bivalve mollusk, which in turn became extinct, giving way to today's hard corals. After each of these extinctions, it took hundreds of thousands or even millions of years for new reefs to be rebuilt. Traces of an exuberant past life and its high biodiversity can be seen in these ancient fossilized reefs, found on all continents.

Modern reefs, as we know them today, are present in about a hundred countries. Estimates of their surface area vary from one study to another, depending on the methods and criteria used to determine their limits. They occupy only 0.2% of the ocean surface but support the highest levels of marine biodiversity. We know of 35,000 to 60,000 coral reef associated species, but the actual figure is more likely to be between one and nine million. This discrepancy can be explained by our poor knowledge of infinitely small species (bacteria, fungi, microalgae, etc.) and of habitats that are not easily accessible (deep environments, microhabitats, etc.). This exceptional biodiversity is not evenly distributed among the world's reefs however. For example, the Indo-Pacific region is ten times more species rich than the Western Atlantic region, and it is possible to identify a gradual decline in the number of species moving away from the coral triangle, a species hotspot region between the Philippines, Indonesia and Papua New Guinea. For instance, there are about 60 coral species in the reefs of the Western Atlantic, while 500 to 600 species populate those in the Indo-Pacific. In contrast, along the western coasts of South America and Africa, coral reefs are rare or absent due to large freshwater discharge from the Amazon and Congo River basins.

The largest coral reefs are in South East Asia and Oceania. French overseas reefs and lagoons occupy 57,557 km^2 and rank fourth after Indonesia, Australia and the Philippines. The eight French overseas collectivities host nearly 10% and 20% of the world's reefs and atolls, respectively.

The lagoons and reefs of New Caledonia cover an area of about 40,000 km^2 and its 1,500 km long barrier reef is the world's longest continuous barrier reef, the second largest after the Great Barrier Reef.

These coral reefs have been used by mankind since its arrival 3,000 years ago. Evidence of this can be seen in the abundant remains of fish bones and shells found in the archaeological sites of New Caledonia. The first scientific collections date back to Captain Cook's expedition in 1774. From then on, the settlement of Europeans in New Caledonia paved the way for early naturalistic explorations and the publication of literature on the archipelago's marine life and coral reefs. Charles Darwin produced one of the first cartographic representations of New Caledonia's reefs, which was executed with remarkable precision for its time. Surprisingly, New Caledonia was not visited by the famous expeditions of the 19th and early 20th centuries that crisscrossed the oceans aboard L'Astrolabe, L'Uranie or La Zélée.

Between 1850 and 1913, Marist missionaries and amateur naturalists such as Montrouzier, Balansa or Vieillard contributed to the early naturalistic collections of New Caledonia, but it is only after the Second World War that the scientific investigation of lagoons and reefs really began. The first biological oceanography studies were signed by Mr. and Mrs. Catala, who undertook the first marine ecology survey with a comprehensive study of the Canards islet coral reef communities, published in 1950.

For 70 years, research dedicated to the reefs and lagoons of New Caledonia continuously expanded and involved many actors including researchers in various disciplines (natural sciences, human and social sciences) and NGOs and stakeholders in charge of the protection and conservation of nature and heritage. An abundant literature, including scientific papers, atlases and collective works, testifies to the attraction of researchers from all backgrounds and disciplines to the reefs and lagoons of New Caledonia. Their wide variety of habitats and exceptional biodiversity have been acknowledged by UNESCO, which in 2008 registered part of the reefs, lagoons and associated ecosystems on the World Heritage List. Since April 23rd 2014, this natural heritage of exceptional value belongs to the Natural Park of the Coral Sea, the largest French marine protected area.

In this book, you will find the contributions of more than 100 researchers and stakeholders in charge of environmental management, who have devoted part of their time to understanding the role of this extraordinary ecosystem and its interactions with human societies. Through their eyes, we wish to share our astonishment at such a diversity of forms and complex interactions, but also our doubts about the resilience of these ecosystems to global change (human activity, rising temperatures, ocean acidification, etc.). We wish to demonstrate the links that mankind has developed with this ecosystem since its arrival 3,000 years ago and we offer a number of avenues to explore past and present knowledge and practices. We also discuss the current regulations that have been developed to assist in the preservation of this outstanding natural heritage.

Readers will first learn more about the diversity of the reef and lagoon communities and their habitats, which are linked to the archipelago's geological history and maritime environment (part 1). They will then discover that the biodiversity of this ecosystem is characterized by high species richness, as well as rarity and singularity, that each species has its own niche and that each biological function counts (part 2). The book then discusses the range of threats to which reefs and lagoons are exposed, including the impact of global climate changes, and the ways in which they can be resisted (part 3). Authors of human and social sciences then lead us to take a different look at the lagoon, which, in the Kanak culture, is also an invisible world where the memory of ancestors is omnipresent and which, for 3,000 years, has offered New Caledonian men and women more than resources: a place of life and expression (part 4). Finally, with the help of some charismatic species, we outline some conservation challenges and provide an overview of the management, protection and conservation methods put in place by the provincial and government authorities of New Caledonia, who are in charge of environmental protection and management of the maritime environment (part 5).

We hope that readers will endorse the authors' conviction that managing reefs and lagoons cannot be achieved without taking into account species and spaces, as well as the different forms of knowledge, practices and uses of these environments. We believe that interplay between research and conservation issues is the only way to maintain this universal heritage, the reefs and lagoons of New Caledonia, in good condition for a long time to come.

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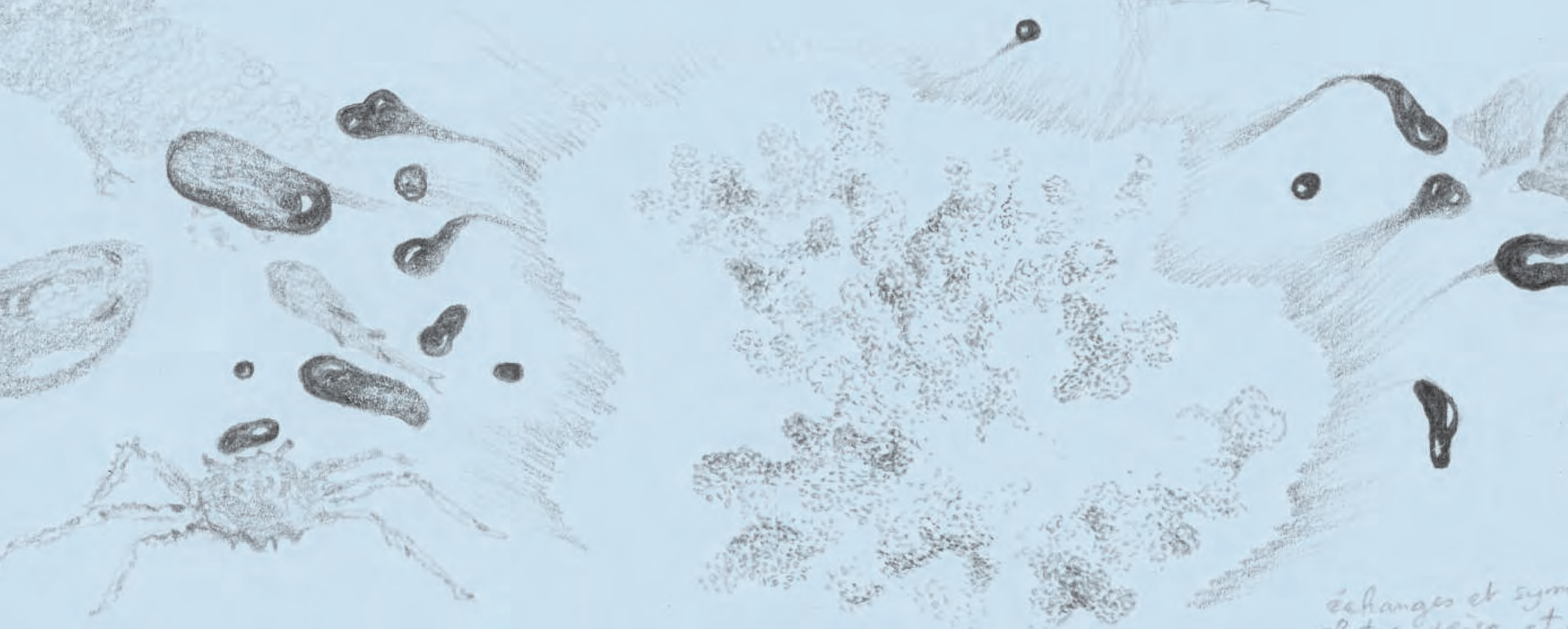
Part 1

Coral reefs: complex dynamics in a changing environment

Coordinator: Bernard Pelletier

Geological processes and environmental conditions control the development of coral reefs. Located at the interface between land and ocean in the intertropical region, coral reefs are good recorders of sea level fluctuations. Their study provides us with information on both the variation of sea level and the vertical movements of land. They are also remarkable climatic archives (water temperature and salinity). Their construction and growth depend on their exposure to the elements (wind, swell, current...), as well as the quality of the water (freshwater inputs, turdidity...). An overview of the diversity of New Caledonia's reef and lagoon systems is presented through the eyes of geologists, oceanographers, physicists and biologists.



Chapter 1

The tales narrated by coral reefs

Bernard Pelletier and Serge Andréfouët

Modern reef flat topped with an ancient reef, eroded at its base (notch) by present-day sea level, Maré. © IRD/S. Andréfouët

A large oceanic domain with numerous banks, atolls, islands and associated reefs

New Caledonia is located between Australia and Vanuatu, just north of the Tropic of Capricorn. It is known for its pristine reefs and beautiful lagoons, which are a dream destination for many. The exclusive economic zone of New Caledonia extends over 1,200 km from north to south (15°S to 26°S) and 1,800 km from west to east (157°E to 174°E), 1.4 million km^2 in total. It harbors a multitude of reefs associated with numerous banks, atolls and islands, and distributed over five ridges. These ridges are roughly parallel, mainly oriented north-south to northwest-southeast, and mostly submerged, separated by basins and deep trenches (Fig. 1).

The following reefs follow one another eastwards: (i) the large atoll-complex of Bellona-Chesterfield-Bampton that corresponds to the northern section of an alignment of seamounts on the northwest edge of the Lord Howe Ridge; (ii) the Fairway banks and reefs, and the Lansdowne Bank with its Néréus Reef at the northern extremity of the Fairway Ridge; (ii) the New Caledonia Ridge, a geographical extension of the Norfolk Ridge, along which the Antigonia and Torche banks, Isle of Pines, Grande Terre (the main island, 400 x 50 km), the Belep Archipelago, the d'Entrecasteaux Reefs, and

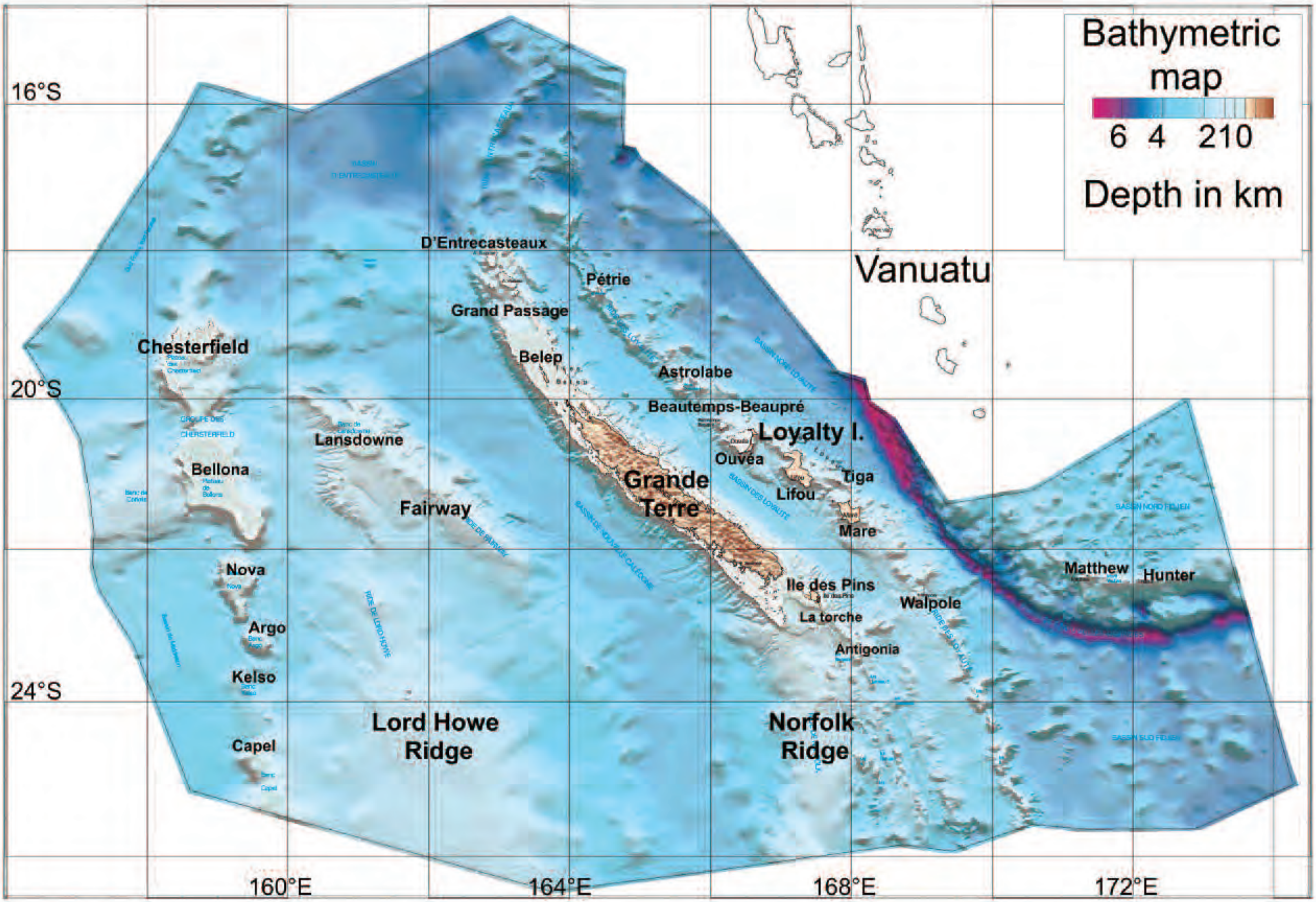


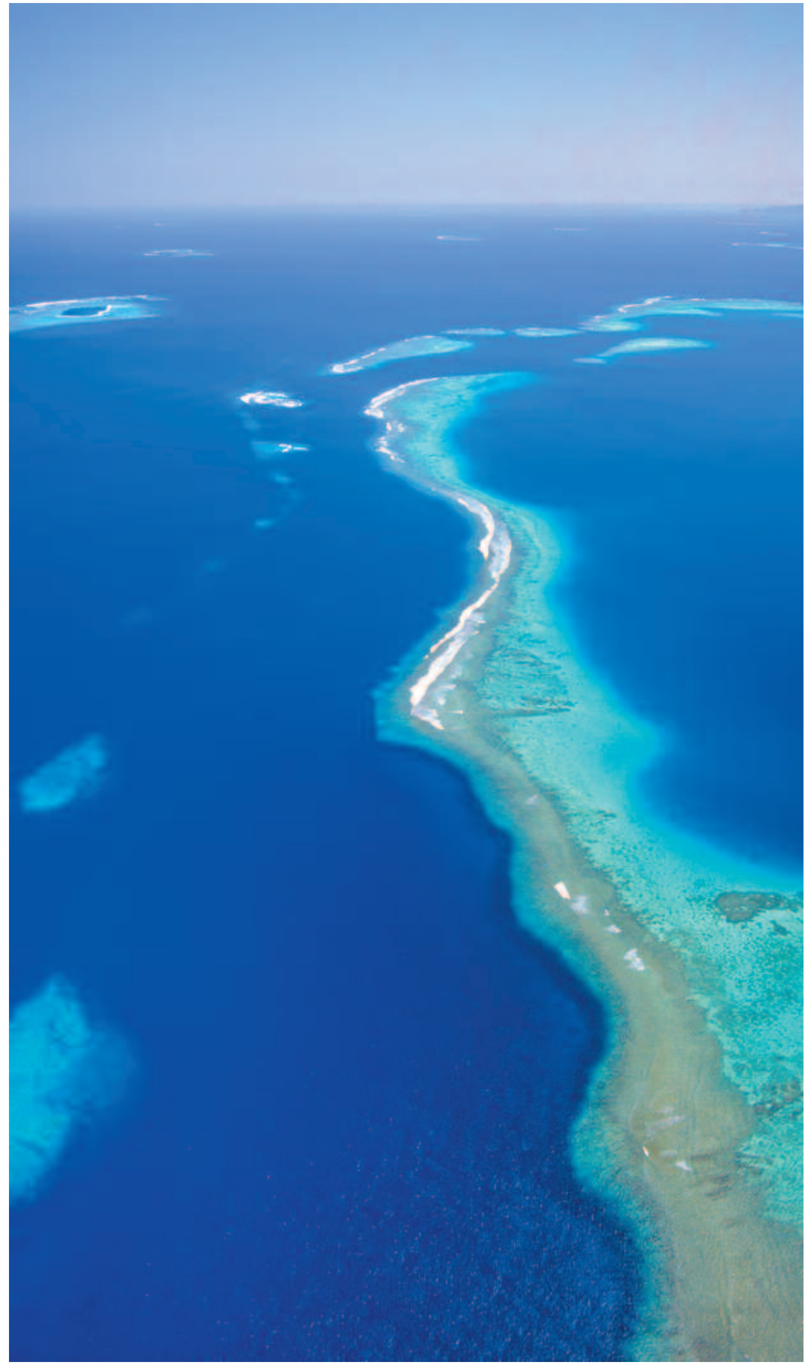
Figure 1: Exclusive Economic Zone (EEZ) of New Caledonia. Adapted from ZoNéCo program, 1998

the atolls beyond the Grand Lagon Nord (Northern Lagoon) succeed one another northward; (iv) the Loyalty Ridge, along which Walope Island, Orne Bank, Durand Reef, the Loyalty Archipelago with its main islands Maré, Tiga, Lifou, and Ouvéa, the Beautemps-Beaupré Atoll, Astrolabe Reefs, and further north Pétrie Reef succeed one another northward; (v) lastly, Matthew and Hunter Islands at the southernmost point of the Vanuatu Arc system, beyond the deep trench of the same name.

The result of a tumultuous geological evolution

The geological evolution that has shaped the New Caledonian oceanic domain into its succession of ridges (with banks and islands) and basins, can be divided into four main periods (Pelletier, 2007). From the late Cretaceous (100 Ma) to the early Eocene (50 Ma), the eastern margin of Gondwana (East Australian Margin) stretched, which led to the opening of oceanic basins and the release of continental strips eastward, such as the Lord Howe and Norfolk-New Caledonia ridges. The middle to late Eocene period (50-34 Ma) was marked by a contraction within this margin, which had previously been lacerated. This period ended with the formation, on the Norfolk-New Caledonia Ridge, of one of the largest outcrop plates of oceanic lithosphere in the world: The Peridotite Nappe of Grande Terre (large massif in the south, and klippes along the northwest coast), the Isle of Pines and the Belep Islands. The subsequent meteorite weathering of the latter led to the formation of one of the largest nickel reserves in the world. Significant vertical movements, substantial erosion, and volcanic activity characterize the period spanning from the Oligocene (34 Ma) to the late Miocene (12 Ma). The beginning of the late Miocene period was marked by the formation of the Vanuatu Subduction Zone, along which the eastern part of the domain, the Loyalty Basin, has largely disappeared.

Currently, ridges and basins surrounding New Caledonia are supported by the Australian plate, which plunges in subduction beneath the active Vanuatu Island Arc System. The relative east-northeast oriented motion of convergence is particularly fast: 12 cm/yr at the latitude of the Loyalty Islands (Dubois *et al.*, 1977; Pelletier and Louat, 1989). Closer to the subduction zone, the



Barrier-reef complex, Southern Lagoon. © P.-A. Pantz

Uplifted reef, Walpole Islet. © IRD/P. Tirard

plunging plate is deformed. It is first uplifted, and then collapses before subduction. This lithospheric bulge before its subduction, is well illustrated by the shapes and different altitudes of the Loyalty Islands, which are made of uplifted atolls and are located at different distances from the trench (Dubois *et al.*, 1974). Two atolls uplift and emerge: Beautemps-Beaupré and Ouvéa. The latter is partly exposed above sea level, has a large open lagoon, inclined westwards, and cliffs reaching 41 m high on the east coast. The ancient atolls, Lifou and Maré, are located on each side of the top of the bulge, and reach altitudes of 104 and 138 m, respectively. Walpole Island (70 m) has reached the top of the bulge and starts its subsidence. At 22°S, the Loyalty Ridge subducts and collides with the south end of the Vanuatu Arc. This collision leads to a fragmentation of the upper plate along an east-west trending left-lateral fracture zone, as well as a decrease in convergence speed south of the impact point (Pelletier et Louat, 1989). The plate, or rather the micro-plate, supporting the active volcanic islands of Matthew and Hunter, is therefore different from the plate supporting the rest of the New Caledonian Archipelago.

A high diversity of reefs

After Fiji and Papua New Guinea, New Caledonia has the world's third most diverse reef types (Fig. 2).

From the d'Entrecasteaux Reefs to those of the Isle of Pines, and from the Chesterfield-Bellona Reefs to those of the Matthew and Hunter Islands, New Caledonian reefs occupy an area of about 4,500 km^2. They form a mosaic of diverse shapes and structures, which results from the region's geological history and from the tectonic processes that still shape the terrestrial and submarine topography today (ANDREFOUËT *et al.*, 2009). The geomorphological development of the reefs is also impacted by recent environmental conditions, such as sea level change over the past hundreds of thousands of years, as well as more local and short term contemporary factors such as exposure to wind, swell, terrigenous inputs, freshwater runoff, and temperature. Besides these local and regional physical processes, reefs are also shaped by numerous short-term biological processes, such as coral growth.

Modern barrier, lagoon and fringing reefs

The reefs surrounding the main island, Grande Terre, are the most studied and also the most diverse. New Caledonia harbors the longest continuous barrier reef in the world, which extends over 1,500 km (1,300 km is intertidal reef) and covers about 1,750 km^2. It is interrupted by numerous narrow passes which are located up to 70 km off the coast and encloses Grande Terre (including the islands of Belep and Balabio) and an immense lagoon. This barrier reef displays a variety of structural configurations. For instance, the southern section of the east coast is made up of large portions of drowned reefs, and at some points a double barrier reef. In contrast, the northern section of the east and west coasts harbor relatively more typical barrier reefs. Near Bourail (on the west coast), the barrier reef is located very close to the coast and the lagoon is shallow. Besides these large groups, more unsual portions of barrier reef can be found - for example, in the north where the reef curves around Balabio Island, or at the southern end in the Corne Sud.

The lagoon surrounding Grande Terre covers 16,800 km^2 and harbors numerous shallow reefs (380 km^2). Some of these reefs are characterized by the presence of islets, built from carbonate debris that have accumulated on ancient reef reliefs. Although they can appear superficially similar, the reefs of these islets display an important diversity of shapes and structures, due to the different genesis.

Fringing reefs are contiguous to the main land mass. Around Grande Terre, they cover up to 400 km^2 and are found in places with contrasted environmental conditions: sheltered bays subject to terrigenous inputs; portions of coast exposed to trade winds but protected from the swell; and portions of coast directly exposed to the ocean, such as in the south of Grande Terre. These different environmental exposures lead to contrasted reef formations, which can be more or less developed.

Atolls

There are several atolls in New Caledonia. Chesterfield and Bellona, d'Entrecasteaux, and the Loyalty atolls have different origins. Their total reef and lagoon area (2,000 and 14,000 km^2, respectively) is almost equivalent to the reef and lagoon area surrounding Grande Terre.

The huge complex, formed by the Bellona and Chesterfield-Bampton atolls, represents a third of the lagoon and reef areas of the entire economic zone of New Caledonia. Its shape is asymmetrical with a drowned reef to the east, and a deep lagoon (40-60 m) with scattered pinnacles. These atolls rest on five seamounts, relics of ancient volcanoes - possibly dating back to the late Oligocene - which originated from the Lord Howe hotspot.

At the northern extremity of the New Caledonia Ridge, the d'Entrecasteaux Reefs are located beyond the Grand Passage to the north of the Grand Lagon Nord. They are spread out over three parallel ridges which extend the formations of Grande Terre and the Grand Lagon Nord. They include the large atolls and deep lagoons (60 m) of Huon and Surprise, and the smaller atoll of Pelotas, distributed along a central ridge. Portail Atoll and Gilbert Reef are located to the west and to the east, respectively.

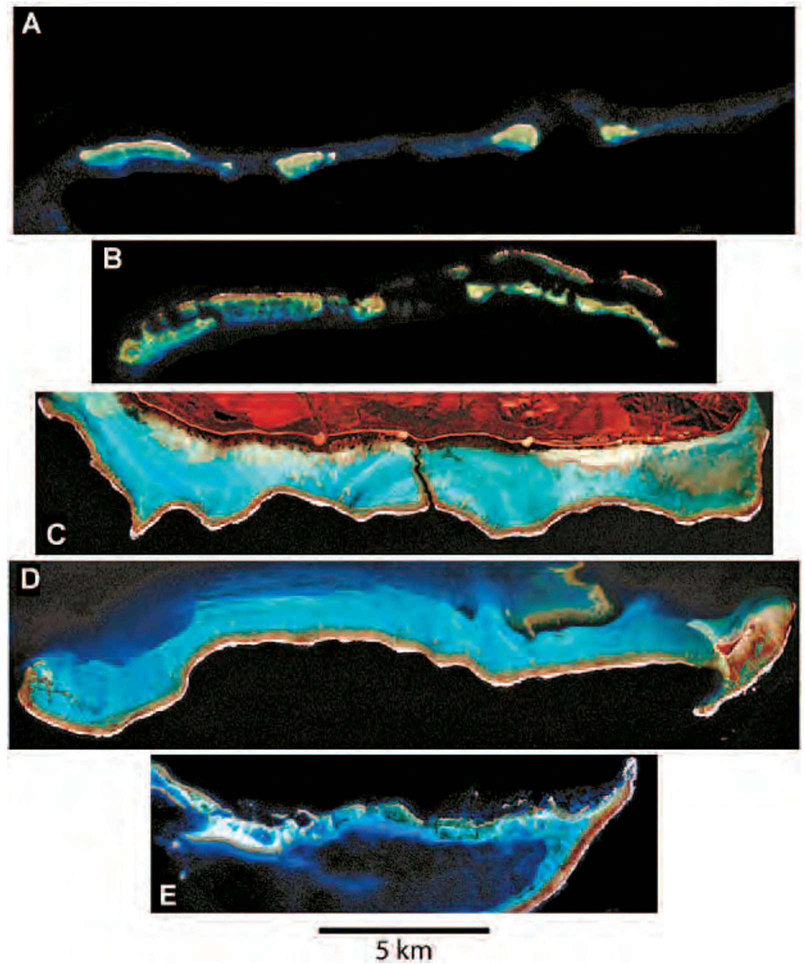


Figure 2: Diversity of New Caledonian barrier reefs. The same scale should be considered for landsat images (1999-2003), which have been rotated to simplify comparisons.
East coast:
A: Outer barrier reef, Canala; large portions of the reef are drowned;
B: Outer double barrier reef, Poindimié, Bayes Islet; West coast:
C: Coastal barrier reef, Poé;
D: Outer barrier reef, Grand Récif, Tenia Islet, Boulouparis;
E: Nested barrier reef, Corne Sud.
Adapted from ANDREFOUËT *et al.*, 2009

The atolls of Ouvéa (850 km^2) and Beautemps-Beaupré (120 km^2), supported by the Loyalty Volcanic Ridge, have shallow lagoons which open westward. The atoll of Ouvéa, bordered by the islands and reefs of the North and South Pléiades, is characterized by a lagoon floor that dips gently westward, and by the high cliffs of Ouvéa Island to the east. Unlike the other atolls, these are emerging.

When reefs inform us about vertical movements and climates

There is good knwolege of the sea level variations for the last two million years, with an alternation of warm periods with high sea level stands (interglacial periods such as present-day climate) that are favorable to coral constructions, and cold periods with low sea level stands (glacial periods). During the last interglacial period (125 ka), the sea level was 6 m higher than present. Since then, the sea level has gone down by 120 m during the last glacial maximum (20-23 ka), and then rose rapidly to remain relatively stable for the last 6 ka. Coral reefs are excellent markers of sea level variations. The past vertical movements of islands can be interpreted from sedimentological analyses, and the position and dating of ancient reefs which were built during interglacial periods and are now outcropping or buried.

Thanks to these techniques, recent vertical movements (since the late Pleistocene, 125 ka ago), and zones of uplift or subsidence have been identified and mapped. This has been done by the systematic sampling of reef formations dating back to Pleistocene and Holocene. These reef formations were either outcropping near the coast or have been reached by drilling cores into the fringing and barrier reefs, notably around Grande Terre (CABIOCH *et al.*, 1996) (Fig. 3).

Sedimentological and stratigraphic analyses of the cores also provide precious information about the resettlement processes of coral reefs during the last post-glacial sea level rise. Around Grande Terre, the age of the oldest Holocene reefs does not exceed 8.2 ka. Sea surface temperatures were probably too cold before this date (4°C lower than present) to allow the significant development of coral reefs.

Drilling of the barrier reef, Bayes Islet, east coast of Grande Terre (2002). © IRD/G. Cabioch

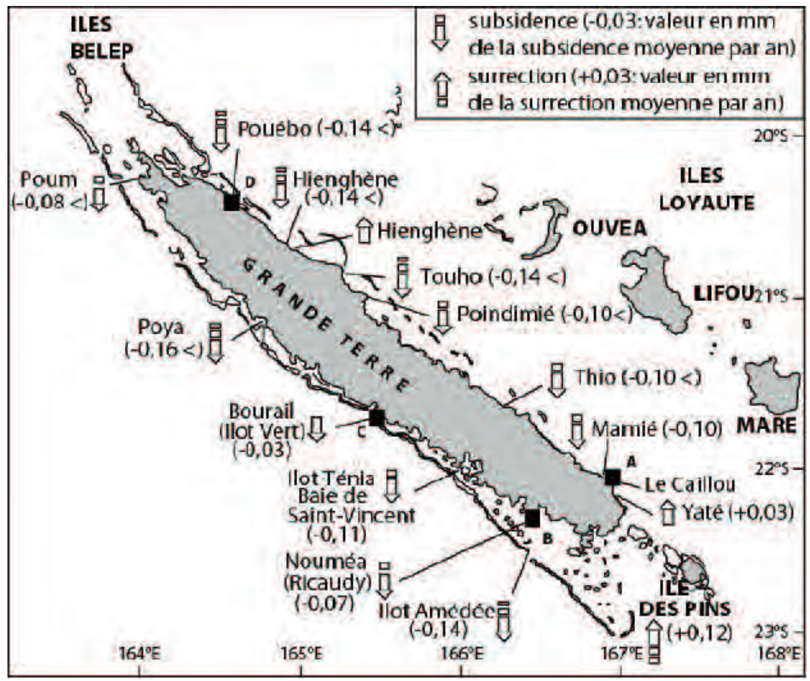


Figure 3: Vertical movements over the last 125 ka around Grande Terre. Adapted from Cabioch *et al.*, 1996

Reef limestone cliffs and modern and ancient notch, north of Lifou, Joking. © P.-A. Pantz

Surrection zones with ancient and uplifted reefs and atolls

The ancient (middle Miocene to Pleistocene) atolls of the Loyalty Islands have been substantially uplifted and now reach an altitude of between 40 and 140 m above sea level. At the Isle of Pines, the reef complex matched with the high sea level stand of the last interglacial period, has revealed an uplift of 0.12 mm/yr during the last 125 ka. In the region of Tara/Yaté, southeast of Grande Terre, the fringing reef that was built 125 ka ago also emerged. It reaches a maximum altitude of 10 m, which indicates an uplift rate of 0.03 mm/yr, while in the same region, the current barrier reef is deeply submerged at 15 to 20 m. All these surrection zones point to the lithospheric bulge of the Australian plate before its subduction.

Subsidence zones with drowned or buried ancient reefs and atolls

Relicts of the 125 ka-old fringing reef also outcrop in the region of Bourail, on the west coast of the island. However, their altitudes (about 2 m) are less than those recognized for the high sea level stand (6 m higher than present), which suggests a slight regional subsidence (-0.03 mm/yr). Everywhere else around Grande Terre, the 125 ka-old fringing reef is located below the Holocene postglacial reef or is immersed further offshore. This indicates a subsidence of 0.1 to 0.16 mm/yr, which increases northward and southwestward on each side of a relatively more stable central zone. Near the barrier reef, the 125 ka-old fringing reef is capped by a Holocene formation, whose thickness depends on subsidence. It increases substantially with distance to the coast, such as in the lagoon near Nouméa or at the barrier reef near Yaté. This points to the double warping that the New Caledonian formation has undergone during the last 125 ka. This warping has been both longitudinal and transversal, with fault-flexures that are parallel to the island, and transversal faults, which divide it into large blocks.

Comparable subsidence rates have been measured or estimated for atolls of d'Entrecasteaux (0.1 mm/yr at Huon) and Chesterfield-Bellona Reefs (0.1 to 0.15 mm/yr) over the last 125 ka.

Drillings, on the barrier reef to the west of Grande Terre have also led to the identification of reef constructions dating back to anterior high sea level stands (last 1 Ma). Detailed morphological analysis of the outer reef slopes of the barrier reef revealed the existence of five submarine terraces between 20 and 120 m deep.

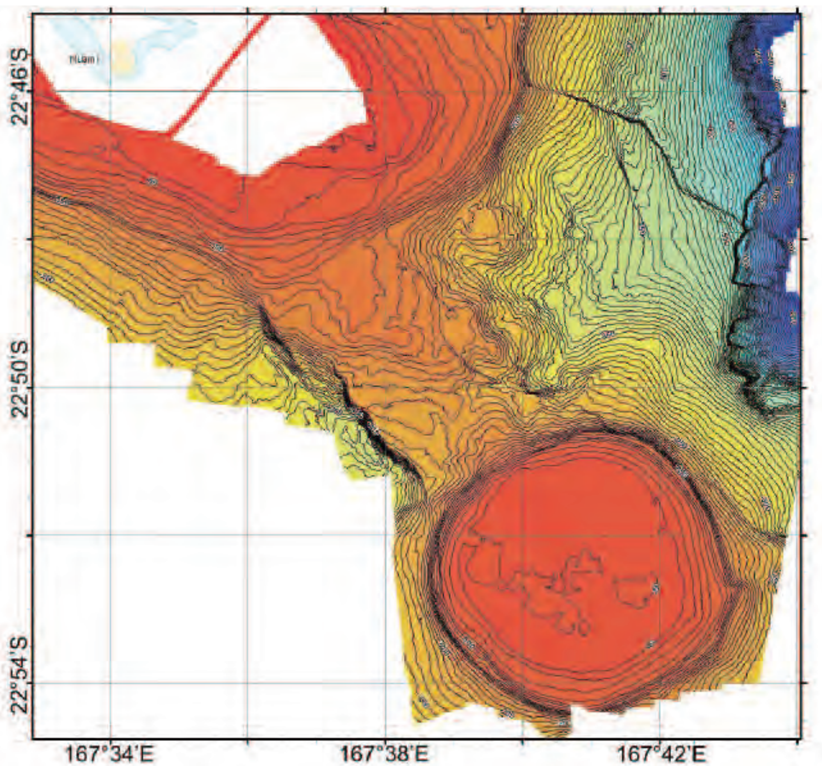


Figure 4: Map of the Torche Bank to the south of Isle of Pines. Isobaths every 10 m.
© IRD/ B. Pelletier

These have been interpreted as the morphological signature of reef units that developed during the last five high sea level stands. The largest terrace, located between 70 and 85 m deep, is thought to be the remains of a 408 ka-old high sea level stand. Its vertical distribution indicates a segmentation in displaced blocks and average subsidence rates of 0.13 and 0.20 mm/yr, which are in the same range as those of the last 125 ka.

Lastly, subsidence is also indicated by the presence of drowned atolls (such as those of the Torche Bank (Fig. 4) and Antigonia to the south of Isle of Pines), as well as seamounts on the Norfolk Ridge to the south of Grande Terre, on the Loyalty Ridge, and to the south of the Bellona-Chesterfield complex (Capel, Kelso, Argo and Nova banks, Fig. 1).

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Chapter 2

New Caledonia reef and lagoon habitats

Serge Andréfouët

Aboré reef extending north from Dumbéa Pass, Southwestern Lagoon. © P.-A. Pantz

Why do we need to know habitats?

Knowledge of habitat types and their spatial distribution (habitat mapping) is necessary for management at any geographical scales, from islets, to reefs, or groups of reefs. This knowledge allows for the estimation of a site's vulnerability and provides a better understanding of the effects of disturbances on a reef. Habitat characterization is also a method to identify the outstanding feature of a site. In addition, the distribution of resources is often linked to the distribution of habitats

Habitat typology

New Caledonia has a wide diversity of reef and lagoon habitats. To understand and describe this diversity, a reference habitat typology is required. Traditionally, a habitat typology requires several levels of hierarchical descriptions including geomorphology, architecture, benthic cover, and taxonomic groups.

The geomorphological description provides a preliminary indication on the reef physical environment and properties such as:

Examples of New Caledonia reefs and lagoons habitats. A-D: four coral habitats.

A: Islet reef crest dominated by large tabular Acropora (Southern Lagoon).

B: Infratidal reef flat with mixed coral assemblage (d'Entrecasteaux).

C: Reef flat of islet reef under terrigenous influence with massive micro-atoll Porites (Petit-Borendy).

D: Intertidal reef flat of barrier reef dominated by small tabular Acropora (Southern Lagoon).

E: Mixed seagrass bed associated with a Sargassopsis algal bed on a sandy terrace of fringing reef (Canala).

F: Infratidal reef flat with soft corals Sarcophyton (Thio).

G: Sandy atoll lagoon, here during a hermit crab aggregation (d'Entrecasteaux).

H: Atoll lagoon with sandy bottom and wreck (d'Entrecasteaux).


Micro-atolls made of massive corals on the modern reef flat, southeast of Maré. Wrinkles surrounding the micro-atolls result from sea-level fluctuation. © IRD/S. Andréfouët

reef genesis, influence of terrigenous inputs, distance to the shore, swell exposition, wind-waves exposition, depth, etc. For instance, a bay-exposed reef implies an enclosed area of low hydrodynamic energy that is protected, turbid, and exposed to terrigenous and freshwater inputs. A geomorphological description can have several levels. The first level can include, for example, the following classes: barrier reef, lagoon patch reef, island reef, fringing reef, oceanic patch reef, bay-exposed reef, atoll, or bank. Each of these categories is mutually exclusive; for instance, the "fringing reef" of an "atoll" is not possible.

A second level is described using the following classes: reef flat, forereef, crest, pass, terrace, lagoon, enclosed lagoon, escarpment, and channel. These categories allow for a detailed description of the first level units. For example, this is done by breaking down a "barrier reef" into all of its different sub-units from the ocean to the lagoon. The first or second level classes mentioned here are far from exhaustive. Out of the hundreds that have been described, many are rare and we listed here only those likely to be commonly observed by the public (e.g., "reef flat").

The third level of habitat description is the “biocenosis” level. This is the level that is commonly associated with the concept of “habitat”. This third level is benthic and described here in a generic manner by the following classes: hard coral habitat, soft coral, dead coral, algal bed, seagrass bed, sand, detritic, and others. The label of a class thus depends on the dominant communities, organisms and substratum of the biocenosis (e.g., coral, macroalgae, or sand). The class “others” includes habitats where sponges, gorgons or other organisms are well represented. These organisms are seldom responsible for the physical structuration of a biocenosis in comparison with corals and macroalgae, at least in New Caledonia. The class “others” also includes mixed biocenoses which are assemblages of multiple elements with no particular dominance. It also includes artificial habitats, accidental or planned, such as wrecks or mine slag accumulations.

Each biocenosis has its own characteristics. Benthic cover, architecture (growth forms, rugosity, and organisms size), as well as dominant and associate organisms, are seascape structuring factors. They correspond to what scuba or free divers would see first. For example, in the case of a coral biocenosis, the visible characteristics would be: substratum, living (or dead) cover, growth forms, the size of coral colonies, and dominant genera. For a seagrass bed, characteristics that would be perceived first are: seagrass density, canopy height, species diversity (mono or multi-species assemblages), and presence of associate organisms (corals, macroalgae, sponges, or burrowing organisms). For a detritic zone, a diver would notice the origin of rubbles, their size, their degree of cementation, and the presence of associate organisms.

Finally, the taxonomic information is the lowest level of the hierarchy of habitat information and the most difficult to describe given the required expertise. In the absence of an experienced taxonomist, the information can be simplified by working at taxonomic levels higher than species, such as families, genera, or morphotypes (e.g., branching corals, massive corals, etc.).

Habitats examples

In conclusion, habitats are defined by three main key elements. In theory, each different combination of these variables describes a different habitat. A biocenosis “algal bed” of “reef flat” of “fringing reef” is not the same habitat than a biocenosis “algal bed” of “terrace” of “island reef”. But it can be the same biocenosis and can be perceived as similar by a scuba or free diver. Indeed, the geomorphological context is part of the habitat concept, but is not necessarily directly perceived by the diver in his visual field.

Eight habitats are illustrated here, but these are far from an exhaustive representation of the New Caledonian diversity. A first set of 150 habitats have been described in an initial compilation (ANDRÉFOUËT, 2014) based on observation data acquired during several research campaigns conducted between 2009 and 2013. These included, notably, the Northern Lagoon (Grand Lagon Nord), the south, south-east and north-west lagoons, the east coast, Isle of Pines, Cook and d’Entrecasteaux reefs. However, considering all of the areas that have not yet been explored, we have estimated that these 150 habitats may only represent half of the possible existing configurations in the New Caledonian reefs and lagoons.

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Chapter3

A satellite view of lagoons

Cécile Dupouy, Jérôme Lefèvre, Guillaume Wattelez, Chloé Martias, Rémi Andreoli and Didier Lille

Northern New Caledonia. Récif des Français (left), Balade Reef (top-right). Fringing reefs to the north and around Balabio Island are visible (Landsat 7 image).

We use satellite imagery to answer various questions related to oceanic systems. New Caledonia is known for its rich biodiversity, particularly in its marine environment. This aquatic diversity is threatened by many anthropic activities and extreme climatic events, which are important to study in order to better understand and manage the resulting ecological impacts. For this purpose, scientists use several biochemical indicators which provide information about sedimentary and terrestrial elements, compounds that are dissolved in the water, and microscopic organisms containing chlorophyll.

The development of coral reefs relies on several favorable environmental conditions, including temperature, salinity, oxygen, and the availability of food. Symbiotic corals require very clear water for their zooxanthellae to perform photosynthesis. Although some corals can flourish in very turbid conditions, such as in bays, it is known that too much sedimentation can negatively impact their growth. Coral polyps feed on other living organisms, which also have to find food.

Offshore waters, where barrier reefs develop, are generally clear and nutrient poor. However, some episodic enrichments can happen, such as nutrient inputs or upwelling, and this can trigger phytoplankton blooms. Hence, the construction of barrier reefs requires healthy corals, which, in turn, depend on the balanced alchemy of different sea-water components.

Satellite images show that the ocean is not always blue. Although a human eye would not be able to see it, the sensitivity of satellite sensors is such that even the slightest color variation is rapidly detected. Non-stationary satellites can scan and "see", in one go, a substantial breadth of field that spans hundreds or thousands of kilometers with a resolution of 10 to 250 m (camera with a sweep system image sensor at a distance of 700 km).

Because each of the water components (chlorophyll, turbidity, and dissolved organic matter) has a specific color, the concentration of each of them can be estimated. Using this method, it is possible to distinguish between the different inputs of minerals originating from different catchment areas (large particles with high sedimentary rate such as sand grains, or in contrast, thin laterites), and the green and chlorophyll-rich phytoplankton, or the part that is dissolved. The latter, which strongly absorbs UV light, acts as a solar umbrella for tropical corals. Its presence can also be associated with pollutants (such as pesticides) or metals, which are present at a low concentration in the lagoon. Ocean-color satellite data therefore allow for the description and understanding of the environmental dynamics of lagoons and coral reefs (i.e., the levels of turbidity, dissolved matter, and chlorophyll).

The impact of rain on chlorophyll and turbidity

During heavy tropical storms or after prolonged rainfall, the chlorophyll observed by satellites (i.e., the quantity of phytoplankton) is three-fold in lagoons (DUPOUY *et al.*, 2010). This effect is visible up to 50 km offshore (Fig. 1, A and B) and the increase correlates with oceanographic data. With a 3D coupled hydrodynamic-biogeochemical model which integrates the lagoon-ocean interface, it is possible to model the chlorophyll increase inside reef passes and the model can then be validated using MODIS satellite images of chlorophyll in the lagoons (FUCHS *et al.*, 2013).

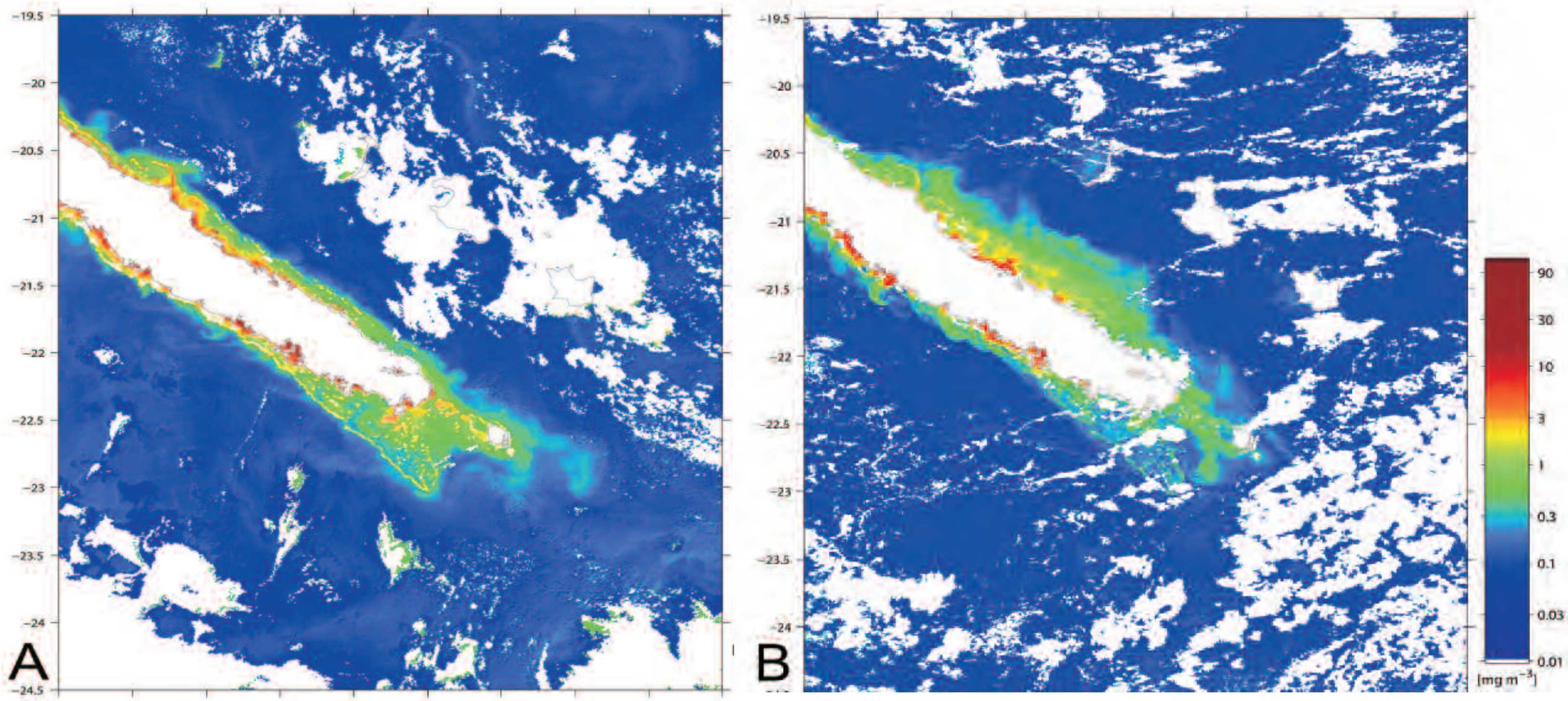

Figure 1: A and B: MODIS images of chlorophyll (mg.m-3) before and after heavy rainfall in March 2008. © H. Murakami

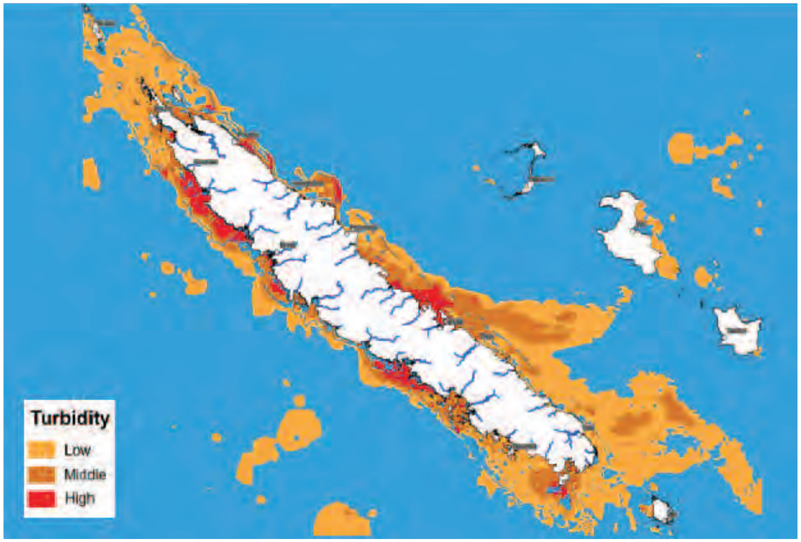

Figure 2: Turbidity (modelled) after the tropical storm Finna in December 2011. © Bluecham SAS

When the lagoon is deeper than 20 m, the water turbidity can be measured using remote sensing and the results are validated using *in situ* measurements. The turbidity plumes that are detected on MODIS images allow the impacts of catchment areas to be estimated. These plumes develop according to the local oceanographic circulation. The east coast is the most often impacted because of the frequency and intensity of rainfall, and the presence of a large ultrabasic and lateritic massif in the south (Fig. 2).

In the Southwestern Lagoon, satellite images indicate a lower chlorophyll concentration in waters surrounding barrier reefs than along the coast demonstrating that the water is clearer around coral reefs. Figure 3 shows the evolution of chlorophyll over time at three sites: an oceanic site offshore from the Dumbéa Pass (OC1), a site in the middle of the lagoon (M33), and one in a bay (Dumbéa Bay, GD10) (Fig. 3A). During spring, the chlorophyll peak appears later outside of the barrier reef (OC1) than in the middle of the lagoon (MD33) or in the bay (GD10) (Fig. 3B). However, in cases of upwelling, offshore waters can sometimes be richer than those inside the lagoon (NEVEUX *et al.*, 2010).

When water is shallow, the color of the bottom substantially influences the satellite signal. The objective is then to detect which part of the effect is due to bathymetry, and which part is due to the color of the bottom (MINGHELLI-ROMAN and DUPOUY, 2014). In these cases, the sea water components are only accessible using more complex calculations (MURAKAMI and DUPOUY, 2013; WATTELEZ *et al.*, 2016, 2017) such as in the Southwestern Lagoon near Nouméa, or near backreefs and shoals (Fig. 3A).

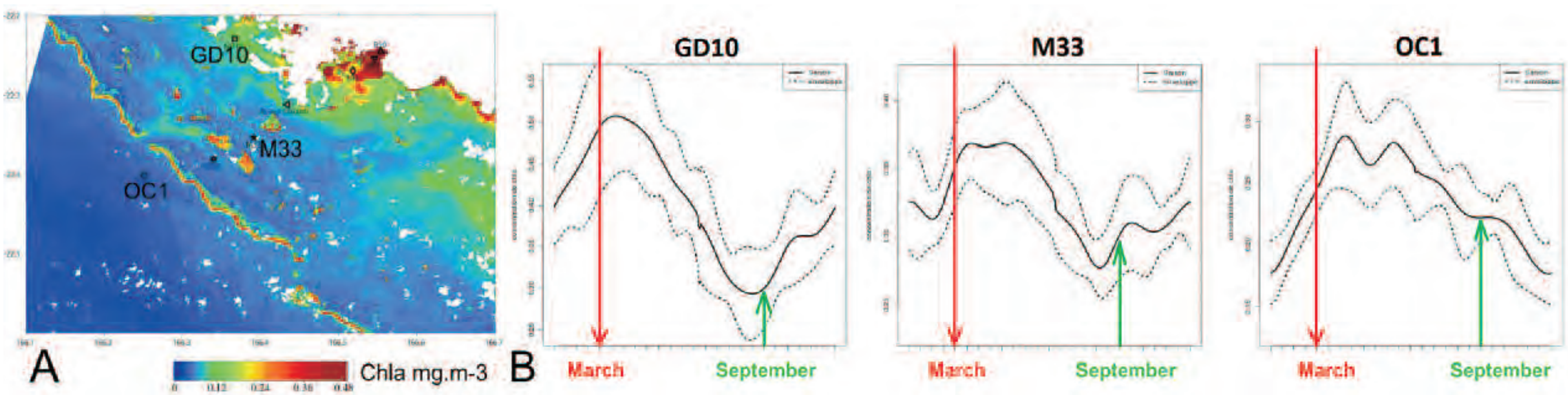

Figure 3: Chlorophyll in the lagoon of Nouméa. A: Chlorophyll estimated from a high-resolution AVNIR image (20 m), after bottom reflexion has been corrected. Adapted from MURAKAMI and DUPOUY, 2013. B: Chlorophyll seasonnal cycle at various sites (oceanic OC1, lagoon M33 and coastal GD10). Adapted from DUPOUY *et al.*, 2011.

Trichodesmium cyanobacterial blooms

The filamentous *Trichodesmium* cyanobacteria accounts for a large part of the chlorophyll offshore and inside lagoons (DUPOUY *et al.*, 2011). These blooms can be observed for over thousands of kilometers off New Caledonia and can drift into the lagoons through the reef passes. Very often, they are visible on satellite images and they aggregate in lines parallel to the barrier reef (Fig. 4). Superficial rafts can be detected using a near infra-red signal and anomalies in reflectance (DUPOUY *et al.*, 2011).

Colored dissolved organic matter

In the lagoons, the quantity of colored dissolved organic matter (CDOM), that protects corals from high UV, is often linked to river inputs, which are abundant on the east coast of New Caledonia. This terrestrial organic matter is transported over long distances to the lagoon, depending on river discharge. CDOM can be combined with metal elements and is therefore a very useful indicator when monitoring coral reef ecosystems as it can be detected using satellite images. Tryptophan, which is also part of the dissolved matter, is produced by coral reefs (MARTIAS *et al.*, 2018), but can only be measured using spectro-fluorescence, an optical analysis.

Chlorophyll and turbidity maps, which are compiled from satellite data, can be produced continuously and, in the future, will be produced in almost real-time. They provide information on sea-water composition, allowing for the detailed and relatively inexpensive characterization of water quality around coral reefs and they show the extension of chlorophyll and turbidity plumes. The analysis of satellite image series since 1998 has traced and quantified the impact of climatic events (seasonal, El Niño, etc.) on lagoon and reef environments.

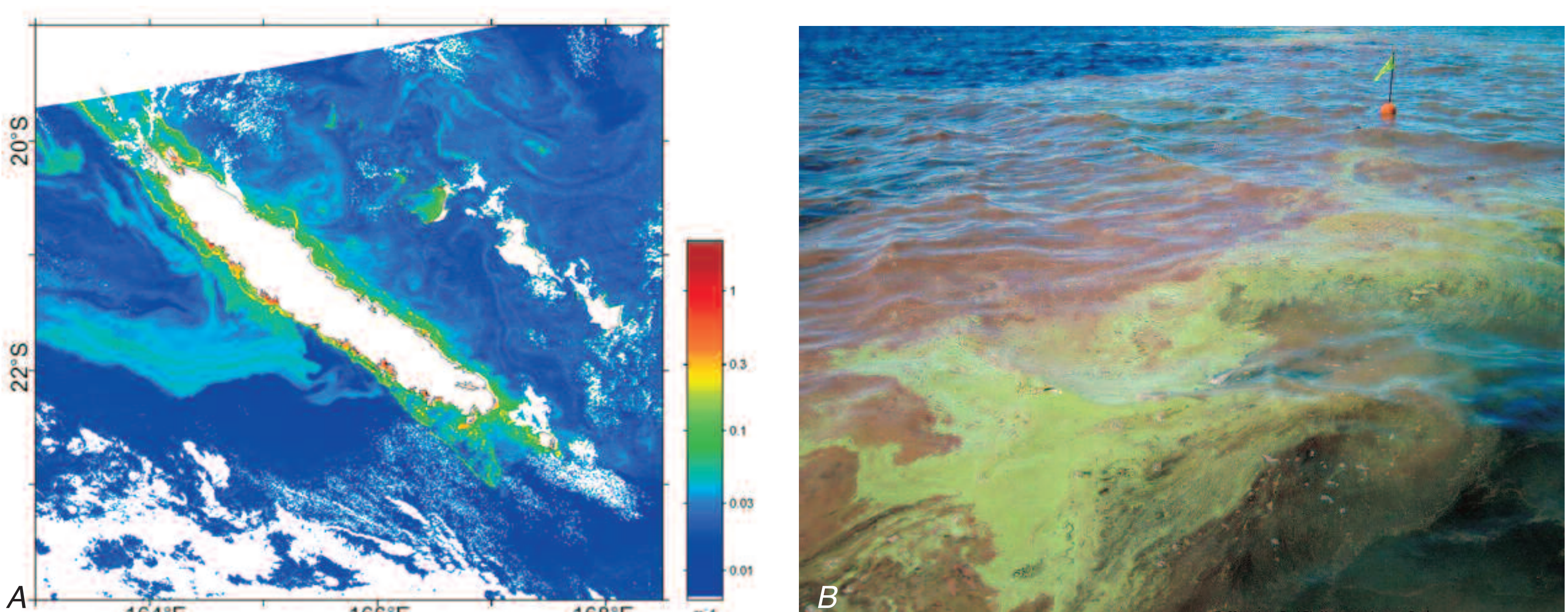

Figure 4: Blooms of the cyanobacteria *Trichodesmium*. A: Blooms around New Caledonia in summer with calm weather (February 2010, MODIS image).
B: A pink coloration of the water is frequently observed near barrier reefs (Prony Bay). © A. E. L. /B. Moreton

Atolls of Ouvéa (center) and Beautemps-Beaupré (top). © (2000, Landsat 7 image)

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Chapter 4

The waltz of the water masses in the New Caledonian lagoon

Pascal Douillet, Jérôme Aucan, Jérôme Lefèvre, Romain Le Gendre, Térence Desclaux and Marion Drouzy

Waves breaking on a coastal reef flat, Isle of Pines. © P.-A. Pantz

The hydrodynamic circulation in the lagoon is the result of movements of the water masses which constrained by the complex geomorphology of the lagoon. The major oceanic (CRAVATTE *et al.*, 2015) and coastal (MARCHESIELLO *et al.*, 2010) currents and eddies, tides (OUILLON *et al.*, 2010), local winds (LEFÈVRE *et al.*, 2010) and waves (AUCAN, com. pers.) are the main triggers of these movements (box. 1). Although most of us are familiar with the oscillation of tidal cycles, the properties of water masses and currents are the result of non-linear and complex interactions. Numerical models have demonstrated the critical effect of tides and wind on the lagoon rhythm. For example, they control the renewal of water masses, the properties and forms of organic matter, and larval transport.

The impact of oceanic swell combined with wind-waves (waves generated by local winds in the lagoon), whose energy propagation is in turn modulated by tides, is only starting to be studied using numerical models. The calibration and validation of our numerical models is achieved using precise and valuable observations collected over the past 20 years by scientists working at the IRD center in Nouméa. These observations are acquired using *in situ* devices (tidal or sea level gauges, current meters, drifting buoys, wave buoys, temperature and salinity sensors), automated weather stations and scientific field surveys for the measure of the water's physicochemical properties. These observations are supplemented with data collected by Météo-France and IFREMER as well as satellite data (on wind, swell, temperature, turbidity and phytoplankton surface distribution).

Box 1

New Caledonian reefs are surrounded by currents

Christophe Menkès

In the southern Pacific region, the main trigger of oceanic circulation is the South Equatorial Current (SEC), which flows westward and redistributes subtropical waters towards the Equator and the Southern Ocean. Like every archipelago, New Caledonia is an obstacle to water transport and this generates coastal currents. When it reaches the Loyalty and New Caledonia ridges, the South Equatorial Current splits into two branches (MARCHESIELLO *et al.*, 2010; CRAVATTE *et al.*, 2015). One branch flows westward around the south of New Caledonia and forms the South Caledonian Jet (SCJ). A weak and variable current, the Vauban Current, generally flows southeastward along the east coast of Grande Terre. To the east of New Caledonia, the main branch of the SEC (the East Caledonian Current - ECC) passes north, around the New Caledonia Ridge, and contributes to the North Caledonian Jet (NCJ) in the Grand Passage and to the north of the d'Entrecasteaux Reefs. This current continues westward, passes north of the Chesterfield Islands and, when it reaches the east coast of Australia, splits into a northern and a southern branch. The East Australian Current (EAC) also splits and forms the subtropical countercurrent (STCC), which flows eastward, south of New Caledonia. This countercurrent partly feeds the Alis Current (ACNC, Alis Current New Caledonia), which flows southeastward along the western margin of Grande Terre. In addition, during the warm season (November to April), trade winds, blowing from the southeast, induce an upwelling along the west coast of Grande Terre (HÉNIN and CRESSWELL, 2005; MARCHESIELLO *et al.*, 2010).

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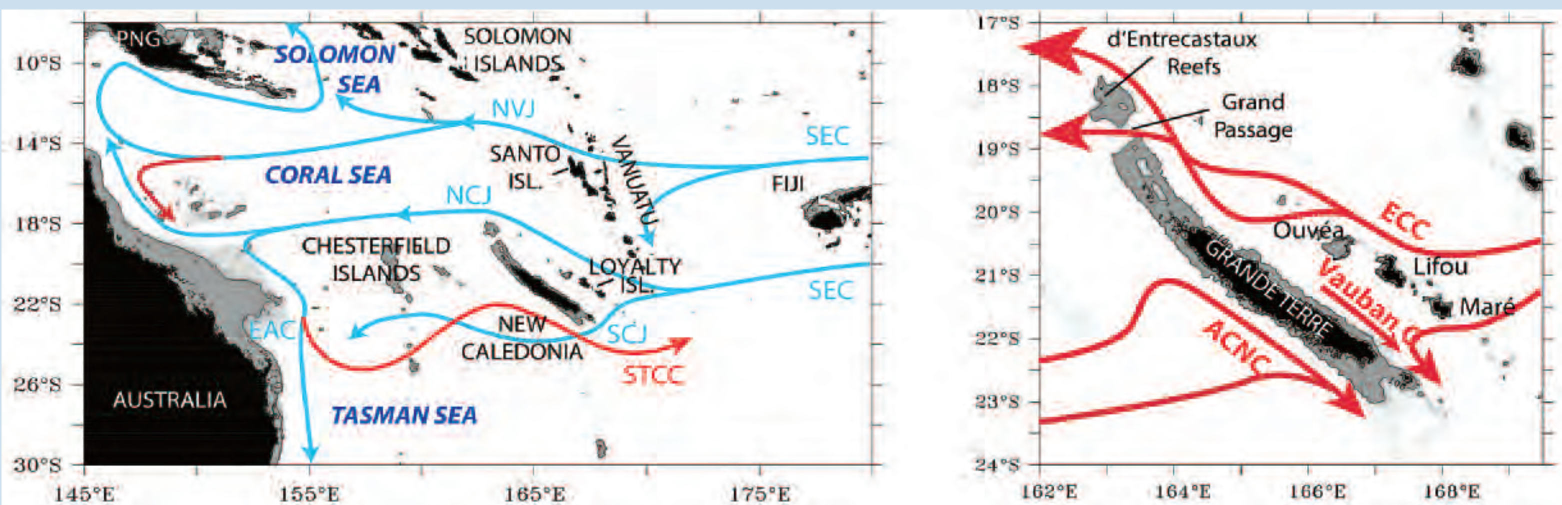


Oceanic circulation around New Caledonia. Adapted from CRAVATTE *et al.*, 2015

The influence of the planets

Tides in the lagoons are the result of a combination of tidal waves produced by the gravitational attraction of celestial bodies (moon, sun and planets) located close to Earth. Tidal currents are mainly generated by the lunar semidiurnal wave, which is the result of lunar forces (M2 waves), and, to a lesser extent, by the solar semidiurnal wave, which is the result of solar forces (S2 wave), and the solar-lunar diurnal wave, which results from the joint forces of the sun and the moon (K1 wave). Currents generated by the M2 wave (about 20 cm/s) are three-times faster than those generated by the S2 wave. Currents due to the K1 wave are ten-times slower (about 1 cm/s), except in passes where they can reach 5 cm/s (OUILLON *et al.*, 2010).

The amplitude and phase of M2 and S2, which respectively represent the sea-level and the direction of current propagation, are illustrated on Fig.2-3. The M2 wave propagates westward, perpendicularly to Grande Terre with a faster propagation in the center of the island. It propagates around the northern and the southern ends of the island and mainly enters the Southwestern Lagoon through the Havannah Channel.

The amplitude of the M2 wave increases from north to south on both sides of Grande Terre but is higher along the west coast. In the Southwestern Lagoon, the tidal amplitude decreases at the Havannah Channel, and increases inside the lagoon. The S2 wave propagation is different on the east and west coasts. Grande Terre acts as a boundary, particularly along the line "Grande Terre - Isle of Pines" and it has the same effect on the amplitude of the S2 wave as on the M2 wave. In the Southwestern Lagoon, the waves expand from the Corne Sud and the Havannah Channel into the lagoon. The currents generated by these waves flow at the same speed throughout the entire water column. An example of current fields in the Havannah Channel in the south of Grande Terre is shown for various tidal periods (box. 2).

Waves can play too

Due to its geographical position in the middle of the southwest Pacific and the intertropical zone, New Caledonia is exposed to waves of multiple origins. In both hemispheres, winter storms generate long swell that can cross the ocean and reach the archipelago. As a result, the barrier reefs to the west of Grande Terre are impacted by

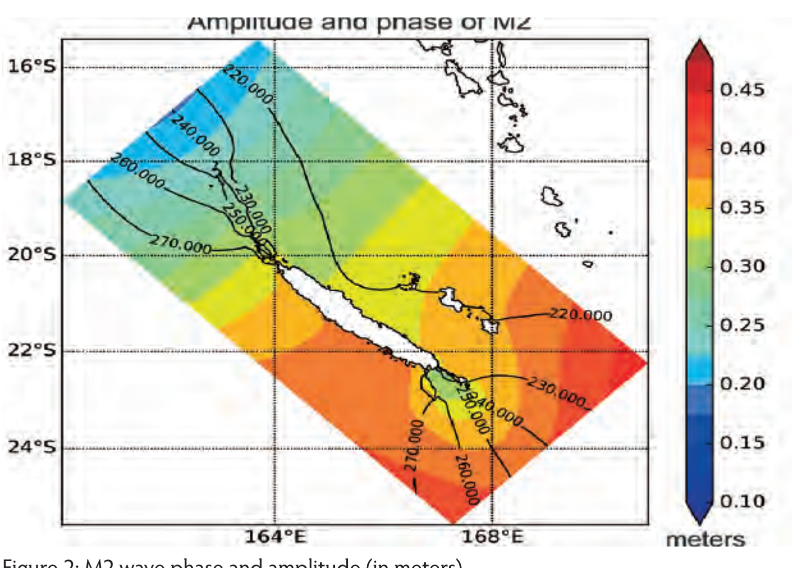


Figure 2: M2 wave phase and amplitude (in meters).

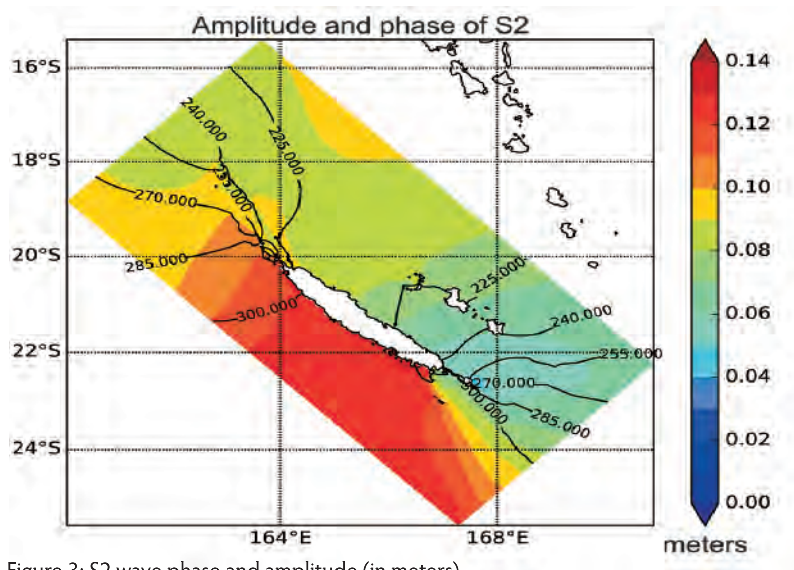
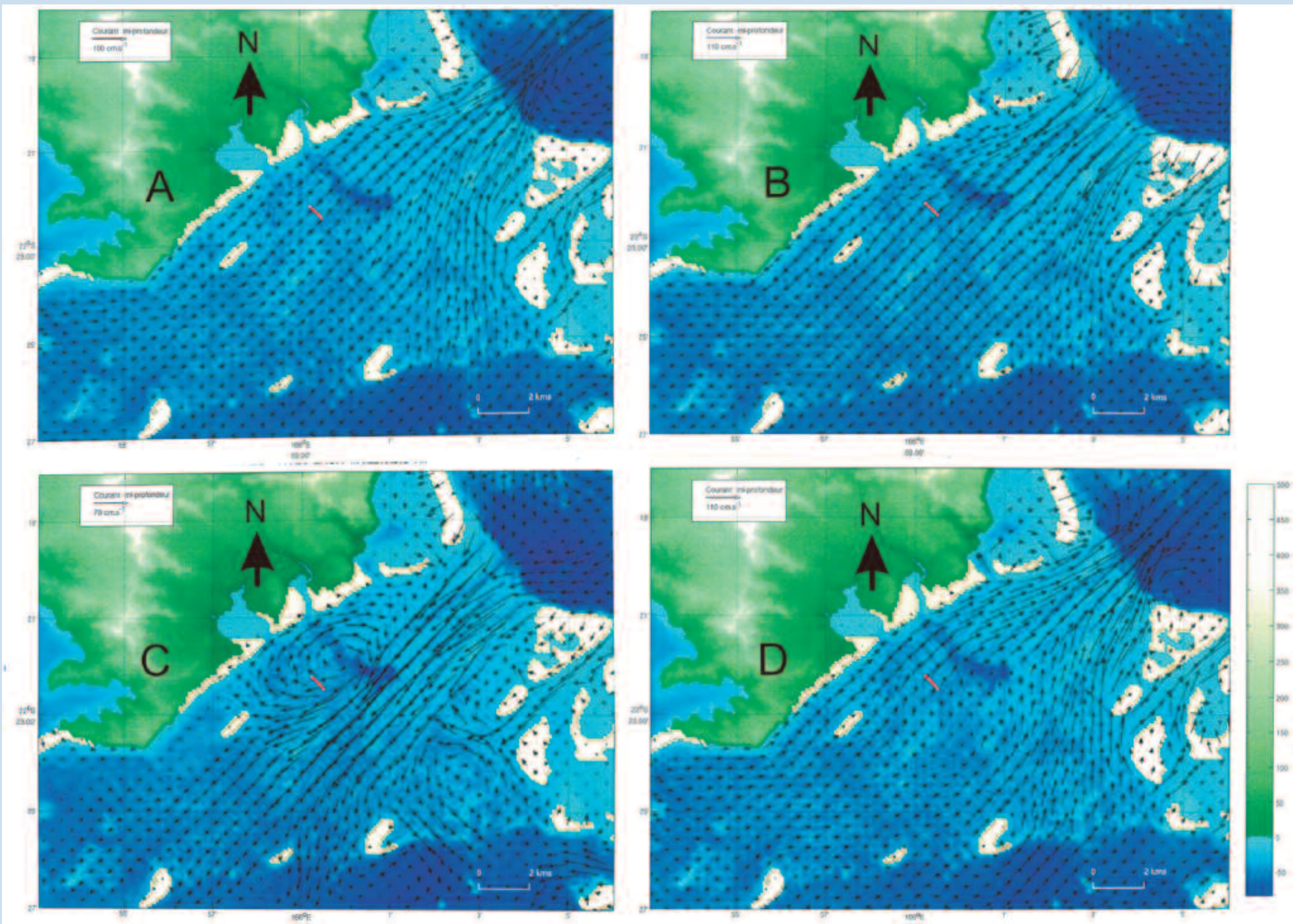


Figure 3: S2 wave phase and amplitude (in meters).

Box 2

Back and forth in the Havannah channel

In the Havannah Channel, tidal currents are very strong and follow a specific rhythm linked to the height of the tide. During low tide, currents are outgoing with increasing strength towards the pass (about 1 m/s). Four hours after low tide, currents in the channel are strongly incoming, exceeding 1.5 m/s and transporting important water masses southward, into the Merlet Reserve. One hour after high tide, currents are still incoming in the center of the channel, and two eddies develop on the north and south sides of the channel. Finally, tides create a global residual current flowing southwestward into the lagoon with a strength of about a few centimeters per second.



Tidal currents in the Havannah Channel. A: Low tide. B: Low tide + 4 hrs. C: High tide + 1 hr. D: High tide + 4 hrs. © IRD/P. Douillet southwesterly swell generated by storms off the coasts of Australia and New Zealand, and which can be over 4 m high. The island of Ouvéa, in the Loyalty Archipelago, receives smaller northwesterly swell, which is generated by storms off the coast of Japan. Around New Caledonia, trade winds, which are the dominant winds, generate waves locally. In the Southwestern Lagoon, these wind-waves can reach 2 m high and, tropical cyclones can generate extreme waves, which can be higher than 10 m. The effect of waves is therefore diverse. They can impact the water circulation in the lagoons (box. 3) and shape the evolution of beaches and islets. In addition to currents induced by tides and storm winds, the action of waves breaking on reefs and beaches induces the formation of a wave setup with strong currents, particularly during tropical cyclones.

The impact of tropical cyclones

Located at the southern edge of the South Pacific convection zone, New Caledonian lagoons are exposed to tropical cyclones. Reef obstacles (barrier and fringing reefs) and mangroves provide natural protection against erosion and coastal flooding. However, the ecosystems resilience to sea-level rise is little understood.

The simulation of waves generated by the tropical cyclone Cook upon its arrival on Kouaoua, shows how coral reefs absorb waves (Fig. 4, A). Coastlines with a double protection (barrier and intermediate reefs, such as at La Monéo River mouth) are relatively sheltered from waves induced by tropical cyclones (wave height is 3 m at the coast

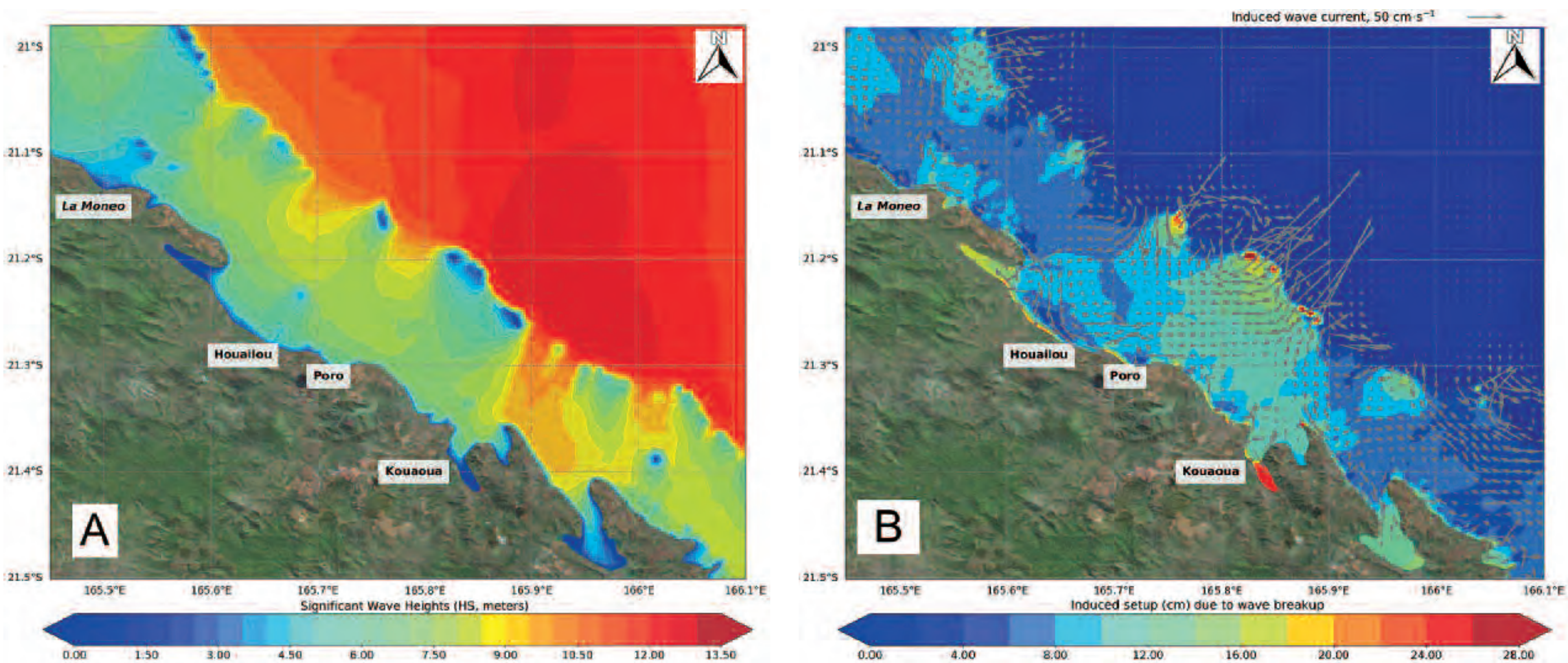


Figure 4: Cyclone Cook at its peak, upon arrival on Kouaoua, April 9th 2017.
A: Maximum significant wave heights (in meters) simulated using the SWAN wave model at 300 m resolution.
B: Wave setup (in centimeters) and current induced by wave breaking, simulated with a wave-current coupled model using SWAN and FVCOM. Wind data during tropical cyclone events are from Météo-France, bathymetry is from the New Caledonian government (DTSI). Model validation was carried out using wave observations recorded at the Fourmi pass in Poindimié. © IRD/ J. Lefèvre

vs. 13 m offshore), while shores located across the Kouaoua and Canala passes are more severely exposed (9 m at the coast vs. 13 m offshore). This example demonstrates how the diversity of reef configurations results in a diversity of exposure to flooding hazards over short distances. Water movements generated by cyclone waves also trigger a spectacular redistribution of sands and coral debris.

The wave-currents coupled model allows the reproduction of wave breaking impact (predicted by the wave model) on the momentum balance. Setups and currents that are associated with the wave breaking process during tropical cyclone Cook are shown on Fig. 4, B: a water bulge forms on the barrier reef and causes a wave setup of 25 cm, which is compensated by strong rip currents (1 to 2 m/s) flowing offshore.

In the wave breaking zones (surf zones) that are close to beaches, currents form streams parallel to the shore, which are able to carry eroded sediments. In bays sheltered from waves induced by cyclones (e.g., the narrow Kouaoua bay), waves breaking at the entrance of the bay act against outgoing currents. This phenomenon leads to an additional elevation of the mean water level by 20 to 30 cm.

Wind direction and dispersion of terrigenous inputs

Besides its role in wave formation, the wind also impacts the transport and dispersion of terrigenous discharge in the lagoon. Coral reef ecosystems are exposed to inputs of terrestrial nutrients, sediments and pollutants which have a negative impact on corals. Any anthropic alteration of the terrestrial biotope (fertilizers, increase in soil erodibility, pesticides, and contaminants) causes major stress to corals, including smothering by sediments. New Caledonian lagoons are no exception. The hydrological functioning of New Caledonian rivers is characteristic of high tropical islands, including quick and intense increases in flow.

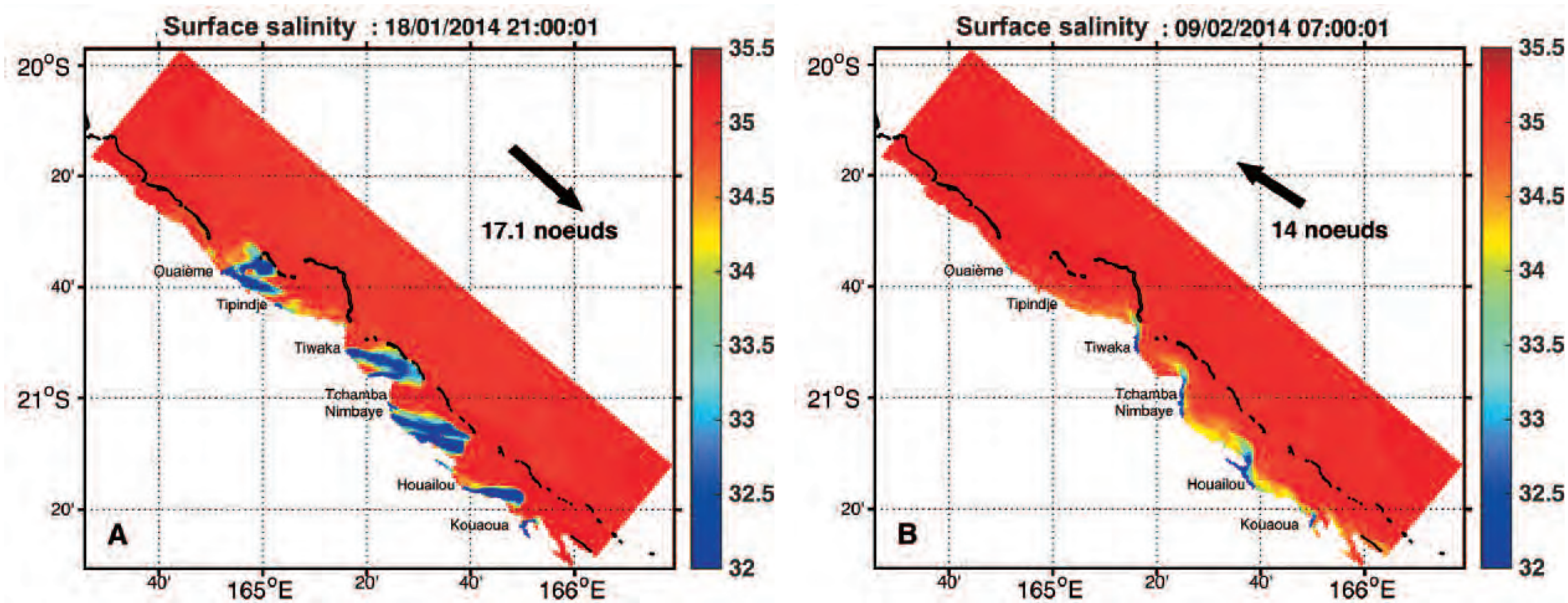
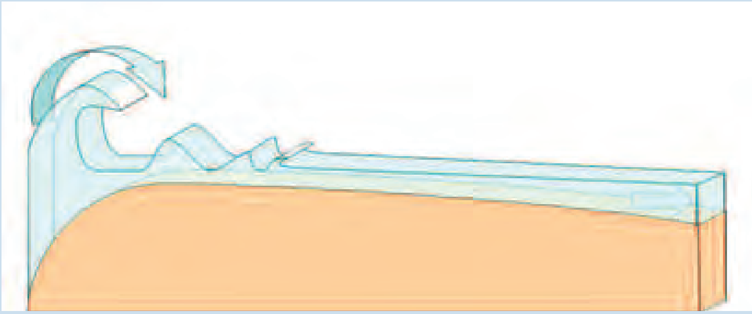


Figure 5: Snapshot of the surface salinity distribution simulated by the MARS3D model (http://wwz.ifremer.fr/mars3d/), in PSU.
A: during the moderate tropical storm, June (January 2014), with northwesterly winds.
B: following a river flood in early February 2014 with trade winds. Only the major rivers have been considered in the model. © IFREMER/R. Legendre

Waves on Grand Récif, Bourail. © P.-A. Pantz

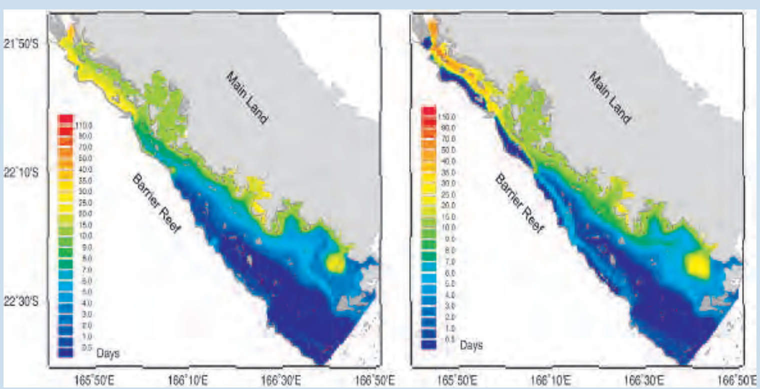
Box 3

Lagoon flushing is forced by waves



Schematic view of waves breaking over the barrier reef.

The barrier reef is higher on the west coast than on the east coast. On the west coast, the reef emerges at low tide and offshore waves breaking on the reef act as a physical barrier, preventing lagoon waters from flowing out, over the barrier reef and instead, offshore waters enter the lagoon. For average waves, this flux is about 0.25 m/s per linear meter of barrier reef (BONNETON *et al.*, 2007). It influences the residence time of lagoon waters, and this is particularly visible in the northern section of the Southwestern Lagoon. With waves, residence time decreases from 25 days to less than a day along the barrier reef, while it increases by the same amount of days at the coast.



Residence time in the Southwest Lagoon. A: Without wave breaking. B: With wave breaking.

The interactions of atmospheric conditions with local topography lead to a significant disparity between the east (wetter) and the west (drier) coast of Grande Terre (LEFÈVRE *et al.*, 2010). According to OUILLON *et al.* (2010), the low-frequency variability of salinity inside the lagoons is mainly driven by the seasons (dry and wet) and, to a lesser extent, by the consequences of ENSO (El Nino-Southern Oscillation). The major processes that more frequently structure the salinity distribution within the lagoons, are winds and river discharges. Hydrodynamic models help in understanding the spatio-temporal distribution of plumes coming out of Grande Terre's many rivers.

Figure 5 shows the spatial extent of those plumes on the east coast, as simulated after two major rainfall episodes. On the east coast, with southeasterly trade winds, the plumes are pushed northward along the coast, whereas, with a northwesterly wind, the plumes propagate eastward and southward towards the ocean.

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Part 2

Coral reefs, a reservoir of life

Coordinator: Claude E. Payri

The current coral reefs of New Caledonia are at most 8,000 years old and yet most of the biological groups are abundant. They are among the richest and most diverse in Oceania with nearly 9,000 species described and undoubtedly much more to discover. The Natural Park of the Coral Sea is an area of almost 1.3 million square kilometers, not far from the coral triangle, in a region of the Pacific where oceanic waters are oligotrophic, but yet a hotspot of nitrogen fixation. Much more than a collection of species, the New Caledonian biodiversity encompasses multiple functions and complex biological interactions. From phytoplankton to seabirds, biologists and ecologists from here and elsewhere invite you to discover the implications of this natural heritage.

Chapter 5

Reef corals of New Caledonia: a diverse and valuable heritage

Francesca Benzoni

Between mountains of corals: a diver swims in a groove between two reef formations covered in the same corals from which they are built, Chesterfield Reefs. © IRD/F. Benzoni

Reef corals may not look like animals at all, but they are in fact very ancient and complex invertebrates. They belong to a group of exclusively aquatic animals called cnidarians, which are believed to have colonized the oceans as early as 600 million years ago. Cnidarians take very different forms, including free-living medusa, suspended or drifting in the water column, or polyps, attached to the bottom of the reef. They can even alternate between these two forms during their life cycle. Whatever the form, the body organization is very simple: a sac-like structure with one opening, surrounded by a crown of tentacles, soft and mostly made of water.

Hard corals spend their whole life, generation after generation, in the form of a polyp, looking much like an anemone. However, although they are close relatives of the colorful sea anemones, their body parts are organized differently and they can build a solid skeleton made of white calcium carbonate (similar in composition to limestone). Leaving a skeleton behind means leaving easily detected evidence in the fossil record.

The earliest known hard coral fossils date back to approximately 240 million years ago, but the study of living species DNA provided strong evidence that hard corals are even more ancient, dating back to the Palaeozoic period about 425 million years ago. This is approximately when the first plants started to colonize the dry part of Earth.

Box 4

The first overseas observation of coral spawning

Pascale Joannot

In 1986, Australian scientists observed coral spawning between the 3rd and 6th nights after the first summer full moon in tropical latitudes. However, this phenomenon had never been observed in French overseas territories before.

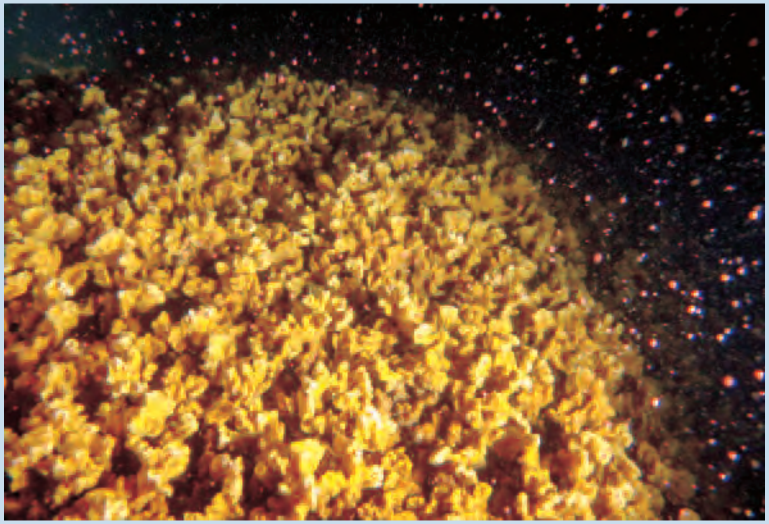
In New Caledonia, on Monday the 13th of November 1989, the day after the full moon, I had mobilized a full team of scientists, divers and journalists, some of whom were observing at sea and the others at the aquarium of Nouméa (Aquarium des Lagons). The latter turned into a nocturnal hive where our flashlights swept the tanks with the hope of finally seeing the famous "night of coral love".

By the end of the fourth night, most of team had given up and on the Saturday evening, the whole team had deserted the aquarium. However, on this same evening (November 18th), the trade winds, well established at that time of the year, weakened and I had the intuition that the corals were about to spawn. I went to the aquarium and in the beam of my torch I finally saw the signal!

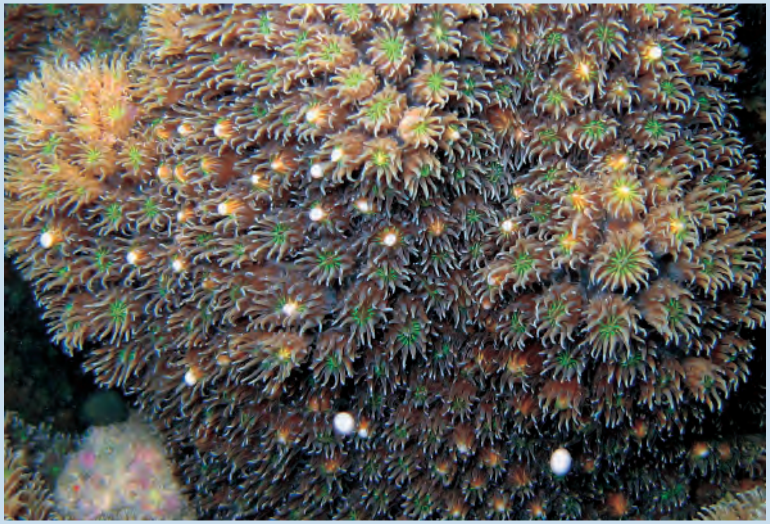
Thousands of small pink pearls appeared shyly on the surface of the corals, ready to randomly venture into the waves. Amazed, I took some pictures and called my colleagues to share this wonderful show.

Alain Gerbault†, then working as a diver for the aquarium, dived in the bay close to the aquarium (Baie des citrons) and confirmed that the spawning also took place at sea and Claude Bretegnier, journalist at RFO, filmed the cloud of eggs of a solitary coral!

With this event, New Caledonia became the first French overseas country where mass coral spawning was observed.



Spawning of the coral *Merulina scabricula* occurred on December 1st 2015 in the lagoon of Nouméa. Gametes are released into the water column and rise to the surface due to their high fatty content. © Biocénose/G. Lasne



Spawning of the coral *Galaxea fascicularis* occurred on September 9th 2009 in the lagoon of Nouméa. The small white balls that escape through the mouth of polyps are the female gametes. They will disperse in the water column where they will be fertilized to produce larvae. © Biocénose/G. Lasne


Zooxanthellate coral species in well-lit conditions form healthy and high cover communities on an outer reef of the west coast of Grande Terre. © IRD/F. Benzoni

On the evolution of hard corals

The first hard corals were nothing like the ones we can observe on a coral reef today: they lived in deep, dark and cold waters and were relatively small. Over time, some of the hard corals have moved up from the depths and adapted to live in shallower waters where they have become increasingly more colonial (i.e., having multiple identical polyps) and have reached larger sizes. At some point, once established in the well-lit shallow waters, hard corals started a symbiotic relationship with unicellular algae living within their tissues. These microalgae associated with marine animals are called zooxanthellae. The association between a marine animal and unicellular algae has been found several times in our oceans because it is an effective win-win situation for both parties. The alga gains physical protection within the animal host while the host has the advantage of living in intimate contact with a primary producer that traps the energy of sun light into sugars through photosynthesis. To put it simply, zooxanthellae provide hard corals with an additional energy supply and conditions that allow it to produce its hard skeleton more efficiently: symbiotic corals are better skeleton producers. However, because zooxanthellae need light, the coral host is forced to live in shallow and well-lit conditions. Today, there are approximately 1,400 living hard coral species. Approximately half of them are devoid of zooxanthellae and live in deeper waters reaching 6,000 m deep. The other half is symbiotic and lives in shallow waters. The latter are mostly, though not exclusively, found in the tropical belt and they are major reef builders, forming and sustaining one of the most diverse, productive and economically important ecosystems: coral reefs. Although comparably less diverse in terms of species, deep water coral reefs, formed by non-symbiotic species of corals, support an important and productive ecosystem which is still relatively poorly known. Both deep and shallow reef systems are valuable and economically important, and they are currently facing a number of local and global threats such as demographic development and the increasing use of resources. In addition, the warming of the ocean has a direct impact of the coral's vitality (coral bleaching, chap. 25) and ocean acidification. This situation has led scientists to define and declare a global coral reef crisis.

Coral hotspots

Shallow water coral species which form coral reefs are not equally distributed throughout the tropics: the Atlantic and the Indo-Pacific coral fauna are very different from each other, the latter being more rich and diversified. Within the Indo-Pacific region the highest concentration of hard coral species occurs in an area called the "coral triangle", a coral hotspot which roughly includes the Philippines, Papua New Guinea, Indonesia, and Malaysia, and where up to 500 hard coral species can be encountered. This diversity does not only hold for corals, but also for several other invertebrates and fish as well as for marine macrophytes. Several concurrent factors have contributed through time to the formation of this marine hotspot of diversity. Outside this coral triangle, diversity slowly decreases to reach its lowest values in the East Pacific.

New Caledonia is not very far south of the limits of the coral triangle, at the eastern end of the Coral Sea. Its proximity to this world's hotspot of shallow-water marine diversity partially explains the richness and variety of the territory's marine ecosystems and coral reefs. New Caledonian marine and coral reef ecosystems are currently part of the largest French marine protected area to date: the Natural Park of the Coral Sea. They have also been listed as UNESCO World Heritage sites (box. 5).

A geomorphology highly favorable to reef habitats

Another important factor, which can explain the diversity of New Caledonian coral reefs and reef corals is the remarkable heterogeneity of the area's geomorphology. This heterogeneity creates a large diversity of reef habitats sheltering a multitude of marine species (fauna and flora). These include bay and lagoon habitats, where benthic reef species are exposed to important sediment discharges of terrigenous origin, leading to unusual species assemblages, distributions and morphologies (e.g., Prony Bay and Gail Bank) (box. 6).

Hovering on a fragile garden of branching *Acropora* in the inner lagoon of d'Entrecasteaux Reefs, a breeding ground for fish (low hard coral species diversity and high ecological function). © IRD/F. Benzoni

Box 5

Natural Park of the Coral Sea: an abundance of species

Marie-Hélène Merlini and Julie-Anne Kerandel

The scientists are unanimous: what they see when diving on the reefs of remote islands during biodiversity surveys is astonishing! In front of their eyes: bigger and less apprehensive fish, and many predators such as jackfish and groupers with surprisingly curious behaviors. Laurent Wantiez, a lecturer in marine ecology at the University of New Caledonia, is definitive: "Almost every time you dive, you can see between one and ten sharks, schools of humphead parrotfish, big jackfish, dogtooth tuna [...]. All these species are abundant in these reefs (Bioreef campaign 2016)".

Lethrinus miniatus (sweetlip emperor) is not fearful and can be aggressive by biting anything that moves. © M. Juncker

To keep on increasing knowledge

Since 2006, dedicated scientific campaigns have been organized to accurately assess the biological richness of the coral reefs in the natural park. The objective: to carry out a species census based on a previously defined route. The current state of knowledge available for many groups of species in the study areas (Chesterfield, d'Entrecasteaux, Astrolabe) indicates that there is a particularly rich fish community on the d'Entrecasteaux and Astrolabe reefs, including healthy sharks. The Chesterfield Reefs are home to remarkable resources of algae, corals, echinoderms (marine animals such as sea urchins, starfish, holothurians), reef fish (parrotfish, groupers, butterflyfish, etc.), sharks, sea-snakes, etc.

Coral reefs, or reef and lagoon ecosystems, are home to 25% of the marine species known to mankind (MC ALLISTER, 1995; BURKE *et al.*, 2012). As a result of their isolation, the coral reefs in the Natural Park of the Coral Sea can be quite special. For example, because some organisms do not disperse very much or even at all, it is likely that new, and therefore relatively unknown, species may appear. Connectivity between the park's reefs and neighboring countries, which is essential for the proper functioning of ecosystems, is also of interest to scientists. The biodiversity of the natural park is far from having revealed all its secrets.

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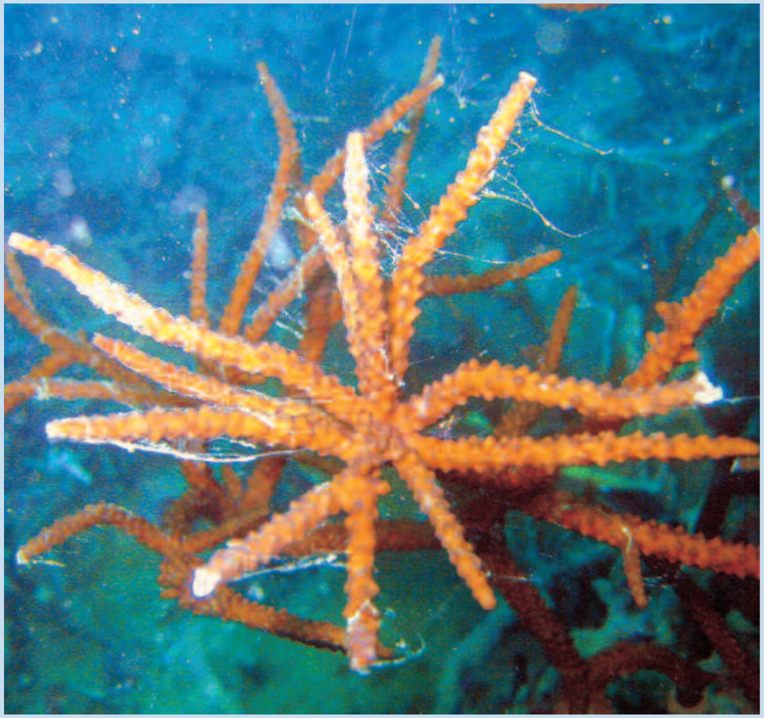
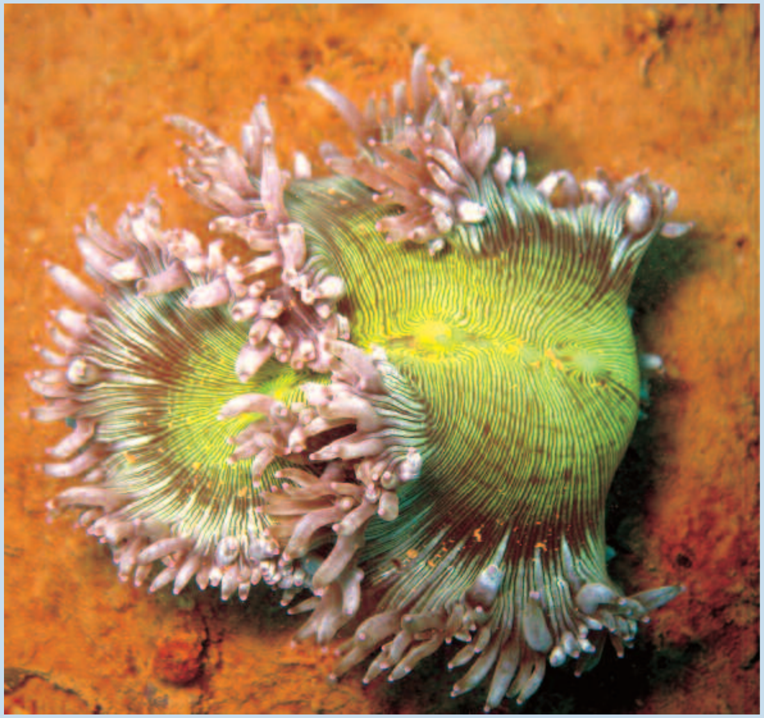
Box 6

Best in the mud



Acropora tortuosa producing a mucus that traps sediments (banc des Japonais). © IRD/F.Benzoni

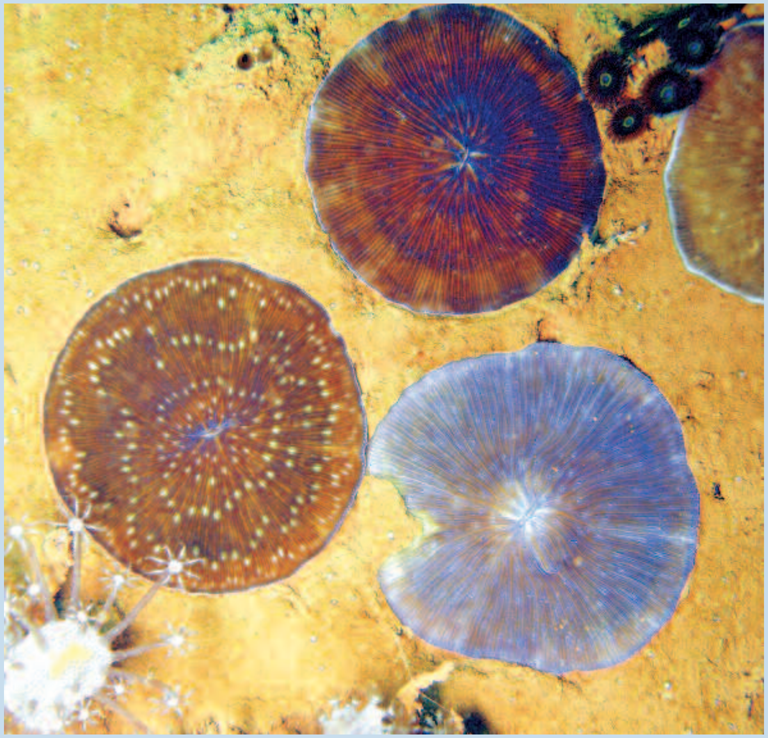


Catalaphyllia jardinei, spreading its soft and colored polyps, which can reach up to 2/3 of the skeleton volume (Gail Bank). © IRD/F.Benzoni

Reef corals usually live and grow in clear and well-lit waters. Experiments have demonstrated that an excess of sediments can deposit on coral polyps and smother them to death. However, clearing off the sediment is not an easy task for an organism which lives attached to the substratum. Consequently, one would expect turbid environments to be a less appealing habitat for corals.

The coastline of Grande Terre offers a number of bays protected from wave-action, where the bottom is covered in fine sediment, or even mud. Some of these bays are naturally charged with red soil, washed off the land, others are affected by discharges due to direct or indirect human activities. A very special community of corals lives in such habitats including species almost exclusively found there, such as the New Caledonian endemic coral *Cantharellus noumeae*.

How do these corals do it? They master two effective strategies which, skillfully combined, allow them to flourish in the mud. The first requires the production of mucus: highly efficient, the slimy mucus abundantly produced by these corals is a precious ally. Once the sediment is trapped in the mucus, the coral clears it off by moving its tentacles. The second strategy involves expanding parts of the polyps so that the sediment accumulates on parts of



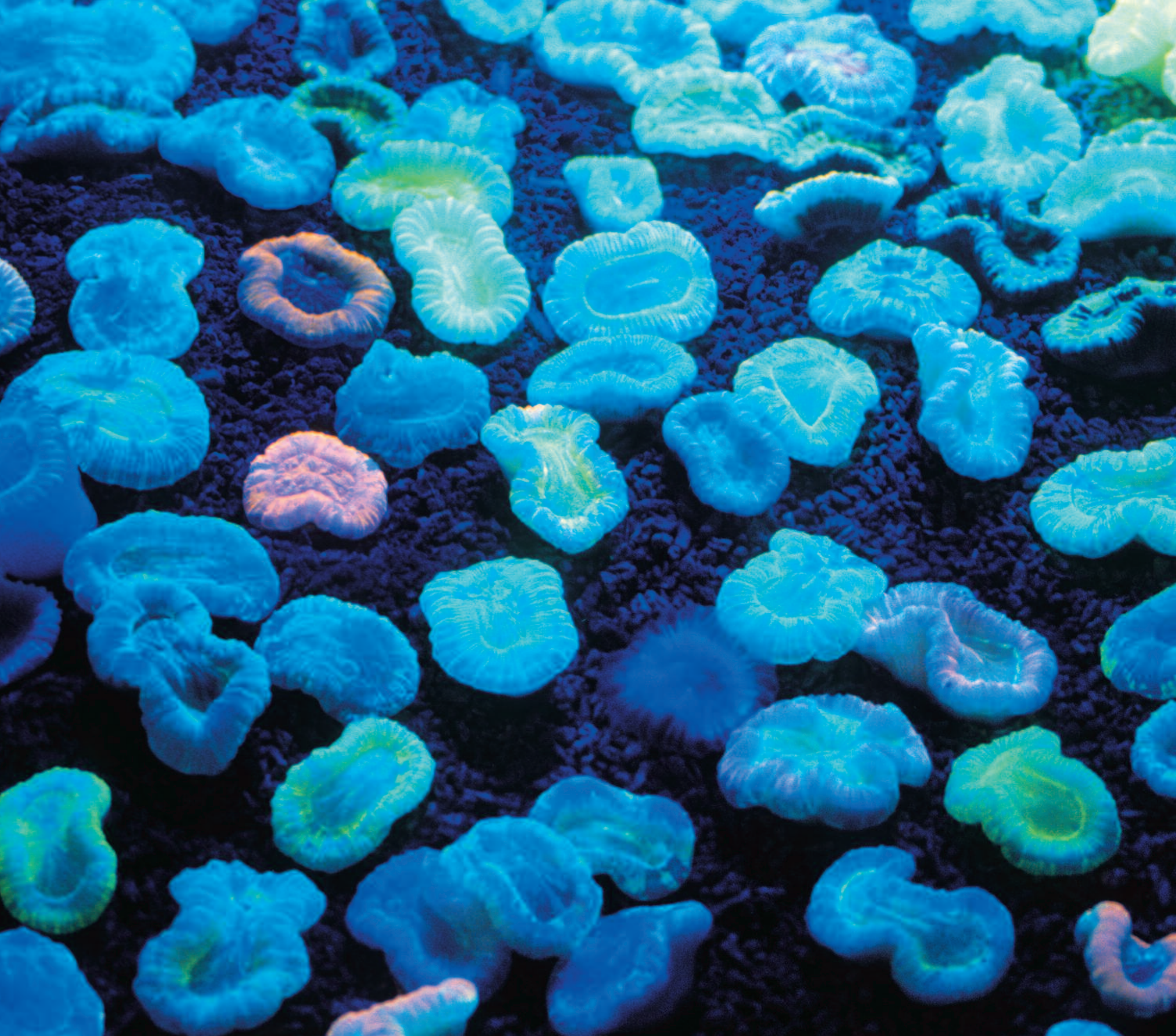
At 35 m, the deep, calm and dark waters of Prony bay hide a colorful community of corals, which are adapted to sediments and life in extreme environments. © IRD/F.Benzoni

The endemic coral *Cantharellus noumeae* is found exclusively in muddy environments around Grande Terre (Port-Boisé). © IRD/F.Benzoni

the body that the animal is able to move or that will be exposed to water movement. Many of these look like colorful flowers blooming over the sediment.

The presence of corals on the soft bottoms of lagoons provides a habitat for a large number of coral-associated animals which otherwise would not thrive in these environments: they sustain an unexpected highly diverse community. The Grande Terre soft bottom coral aggregations, like those in Prony bay or at the Gail Bank, are rarely observed elsewhere in the world and are listed among the singularities of New Caledonia.

Moving from the shallows to the deep, New Caledonia is also currently considered the world's hotspot for deep water coral diversity. The study of New Caledonian hard corals started in the early 1900s but followed very different trajectories for shallow and deep-water species. Deep water corals were sampled using dredging and trawling between 80 and 1,434 m deep during a number of oceanographic campaigns in the 1970s and 1980s (Bathus 3-4, MUSORSTOM 5, 7-9). The study of these impressive collections, hosted at the MNHN (Muséum national d'histoire naturelle, Paris), was only recently finalized by specialists. Results revealed an unprecedented concentration of species diversity in the deep-water ecosystems of New Caledonia, with about 170 species identified, including some species entirely new to science (M. Kitahara pers. comm.) - a diversity much higher than that currently known for the Philippines.



Box 7

Wonderful fluorescent corals

Pascale Joannot

It is in New Caledonia that the first fluorescent corals were collected in 1958 by divers Michel Laubreaux and René Gail (who has since disappeared while diving). They were found on a remarkable, but difficult to access, 35 m deep mud-flat on the Gail Bank, near the Pirogues River.

Dr. Catala, founder of Nouméa's first aquarium, exposed them to ultraviolet light and discovered the fluorescence of these corals, ranging from dark green to bright yellow and a whole series of reds and oranges.

Fluorescent corals are also found near the surface where the same species may have an entirely different fluorescence. The granulations that support the pigments responsible for fluorescent properties are located in the animal's flesh. These pigments belong to the flavin, urobilin and pterin groups (PELOUX, 1960) and in contrast, the calcareous skeleton of the animal does not produce any fluorescence.

I was able to see that repeatedly exposing corals to UV light causes them to bleach. They can recover in a month's time when they are returned to natural light.

In 1996, very calm waters, high temperatures and sun exposure in the New Caledonian lagoons and at the Nouméa aquarium caused significant bleaching of corals, with a rapid or gradual change (depending on colonies) from their natural colors to pastel fluorescent colors including white, pink, yellow or blue. At the aquarium, as the corals bleached, some of them resisted and turned brown. Although each previous summer it had bleached and regained its brown colors as soon as the water cooled down, a colony of *Echinopora* displayed an even more intense pigmentation.

These observations raise questions about the role of the pigments (flavoproteins) responsible for the production of fluorescent colors and the possible "UV screen" role of symbiotic zooxanthellae.

Reference

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Mat of *Trachyphyllia geoffroyi* with various pastel fluorescent colors in a tank of the *Aquarium des Lagons.* © P.A. Pantz

Box 8

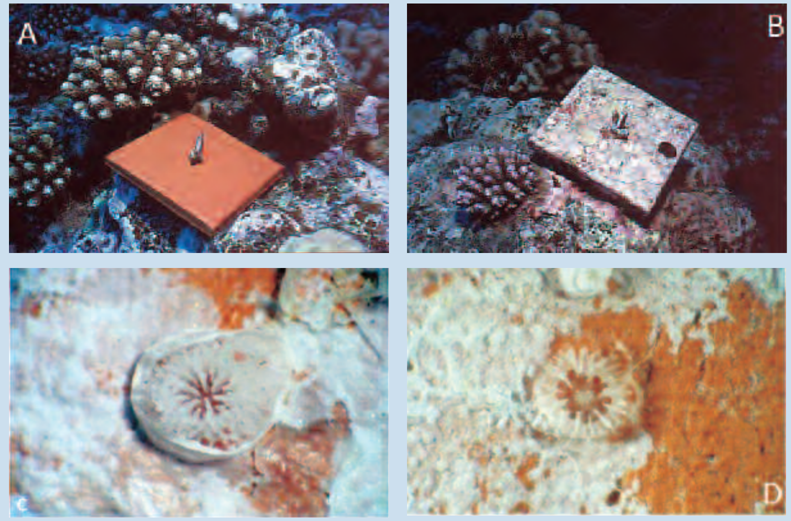
New generations: strong coral recruitment in the southwestern lagoon of New Caledonia

Mehdi Adjeroud and Christophe Peignon

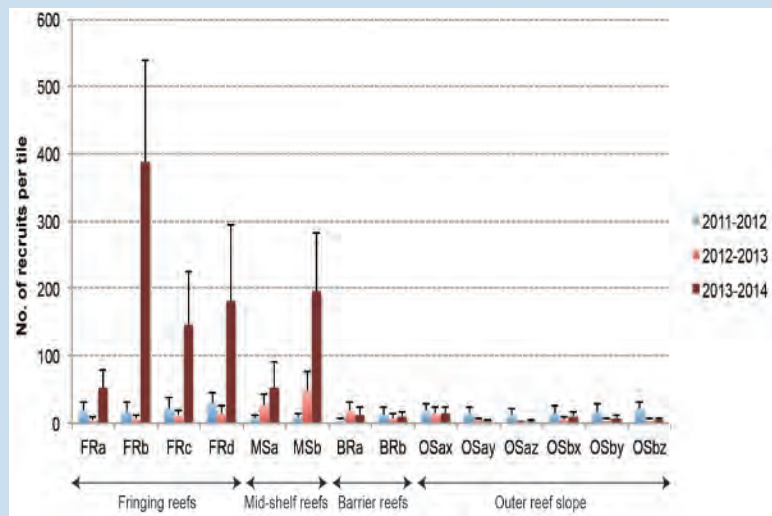
Recruitment, defined as the integration of young individuals into adult populations, is a crucial stage in the life of corals. It influences both the spatial distribution of adult populations and their temporal variability. After major disturbances, such as tropical cyclones, coral bleaching events or outbreaks of predators (e.g., acanthasters), which cause severe mortality in adults, recovery occurs mainly through recruitment. In their first year, recruits are only a few millimeters in diameter. These recruits grow up rapidly but only become adults and able to reproduce sexually, after 4 years, on average.

In order to better understand how New Caledonian corals are structured and maintained, a recruitment study was launched in 2011. Terracotta tiles were placed at 14 sites, representing the main habitats of the southwestern lagoon. These tiles were left on the bottom of the reefs and lagoons for 5 months (October to March) to allow for the settlement of recruits. The tiles were then returned to the laboratory for microscopic examination. At this stage, the morphological characteristics on which species identification is based, are not sufficiently developed and only a few families of recruits can be distinguished.

The results of the first three years of research show that coral recruitment is highly variable in space and time. Compared to other reefs in the Pacific, recruit abundance is often relatively high with a significant peak at some of the sites on fringing reefs and mid-shelf reefs in 2013-14. These rates of recruitment are even higher than those recorded on the Great Barrier Reef in Australia. These results suggest that New Caledonia's reefs have a high capacity for recovery and resilience.



Terracotta tiles used for the recruitment study of corals.
A: Newly deployed tiles.
B: After 5 months on the reef, tiles have been colonized by crustose calcareous algae and corals invisible to the naked-eye. Microscopic photographs of recruits from the two most abundant families in New Caledonia.
C: *Acropodiae*.
D: Pocilloporidae.© IRD/M. Adjeroud



Spatial and temporal variability in the abundance of coral recruits (all families combined) recorded at 14 sites in the four main reef habitats of the southwestern lagoon of New Caledonia. © IRD/M. Adjeroud

In the case of shallow reef corals, although specialists have made remarkable efforts to identify species, and to understand their distribution and ecological role, exploration of the territory's vast reef areas remained relatively scarce until the last decade and, for logistical reasons, studies were mostly limited to the south of Grande Terre. Since 2005, the IRD research center in Nouméa has led a number of scientific cruises onboard the research vessel Alis. The main objective of these cruises is to explore and document the diversity of New Caledonian coral reefs, with a special focus on two main reef organisms: macroalgae and hard corals, which are fundamental for the construction and the functioning of these ecosystems. The occurrence and distribution of these organisms is sampled by specialists during scuba dives down to the limit of the mesophotic zone. The material that has been collected is being studied using both traditional approaches based on the morphological examination of the organisms (shapes, sizes, etc.) as well as modern genetic approaches.

Today, thanks to these scientific campaigns and the unprecedented effort of the scientists involved (over 350 hours of underwater observations by several specialists), we have a better understanding of the diversity and distribution of hard corals throughout the territory, including remote reef areas such as Chesterfield and Bellona in the middle of the Coral Sea, d'Entrecasteaux Reefs, the Loyalty Islands and Isle of Pines. Although reference collections are still being studied, the results already provided a more realistic estimate of the hard-coral diversity as well as a description of previously unknown species. Taking into account the considerable changes that have occurred over the last decade in the way coral species are identified and classified, the current species diversity estimate (based on existing specimens and/or *in situ* illustrations) reaches a total of 390 species. Overall, taking into account both shallow and deep-water corals, New Caledonia harbors an impressive third of the world's living hard coral species.

Taking a step beyond the simple total number of species, and based on the exploration of these different zones, today we can say that each region and group of islands within the New Caledonia EEZ is characterized by unique assemblages of corals and coral habitats. Some are characterized by large high-cover communities structured by a few dominant species (e.g., lagoon sites in the remote Chesterfield or d'Entrecasteaux reefs), while others are made of small, cave-dwelling species which are hidden at the limit of the mesophotic zone. Clearly the unique diversity of New Caledonia's coral reef fauna does not simply lie in the number of species present, but also in the diversity of their associations to create strikingly different reefscapes supporting different associated organisms and productive ecosystems. This is a highly valuable heritage that needs and deserves, not only the conservation management currently in place, but also a continuous monitoring of its state.

Chapter 6

Are reefs fertilized by seabirds?

Anne Lorrain, Fanny Houlbrèque, Francesca Benzoni, Laura Tremblay-Boyer, Christophe Menkès, Claude E. Payri and Éric Vidal

Chesterfield Islands: sooty terns nest in large colonies. © IRD/E. Vidal

Reef building corals create thriving ecosystems in the middle of vast oceanic deserts. They structure habitats for tens of thousands of species of fish, crustaceans, mollusks and other marine species. Some species of seabird may travel long distances across oceans to forage, but they all meet on coral reef islets to breed. Recent research has found unexpected interactions between these seabirds and reef building corals, showing that corals partly use the nitrogen released by seabird excrement (LORRAIN *et al.*, 2017).

Seabirds nest on coral reef islets during a few months each year, which leads to the accumulation of large quantities of fecal material, known as guano. Guano is recognized as a significant source of nitrogen and phosphate and has been used since ancient times as a natural fertilizer. Accumulations of guano from seabirds nesting on the shore fertilize terrestrial ecosystems and could also impact coral reef ecosystems locally.

Using stable nitrogen isotopic markers it is possible to trace the nitrogen derived from guano up the marine food web. The analysis of water and coral samples has demonstrated the presence of guano-derived nitrogen in both the lagoon waters and the living tissues of corals collected in the proximity of islets. The local nitrogen enrichment of lagoon waters can occur by direct surface run-off of the guano accumulated on islets, percolation into the sediments (with

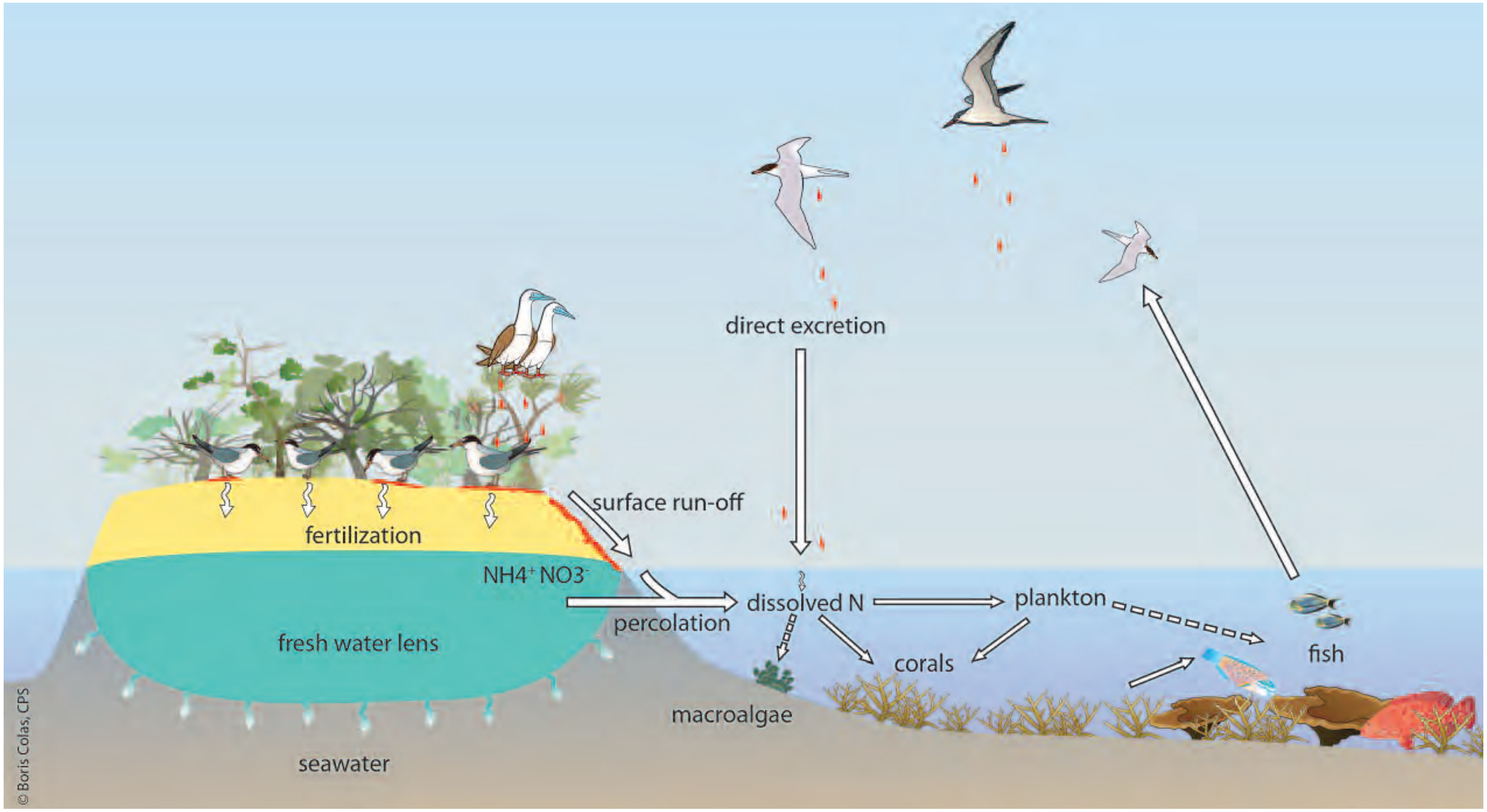


Figure 1: Schematic diagram of the guano-derived nitrogen inputs into a coral reef ecosystem. Adapted from LORRAIN *and al.*, 2017

precipitations) and resurgence at sea, or the direct excretion of feces into the water during seabirds' foraging trips (Fig. 1). Several hypotheses exist, or coexist, regarding the mechanisms behind the corals uptake of guano-derived nitrogen. One theory is that nitrogen can be used by plankton which in turn is ingested by corals. Alternatively, a dissolved form of nitrogen could be directly assimilated by corals and zooxanthellae (coral symbiotic microalgae).

Breeding black noddis providing huge amounts of guano, Chesterfield Reefs © E Vidal/IRD

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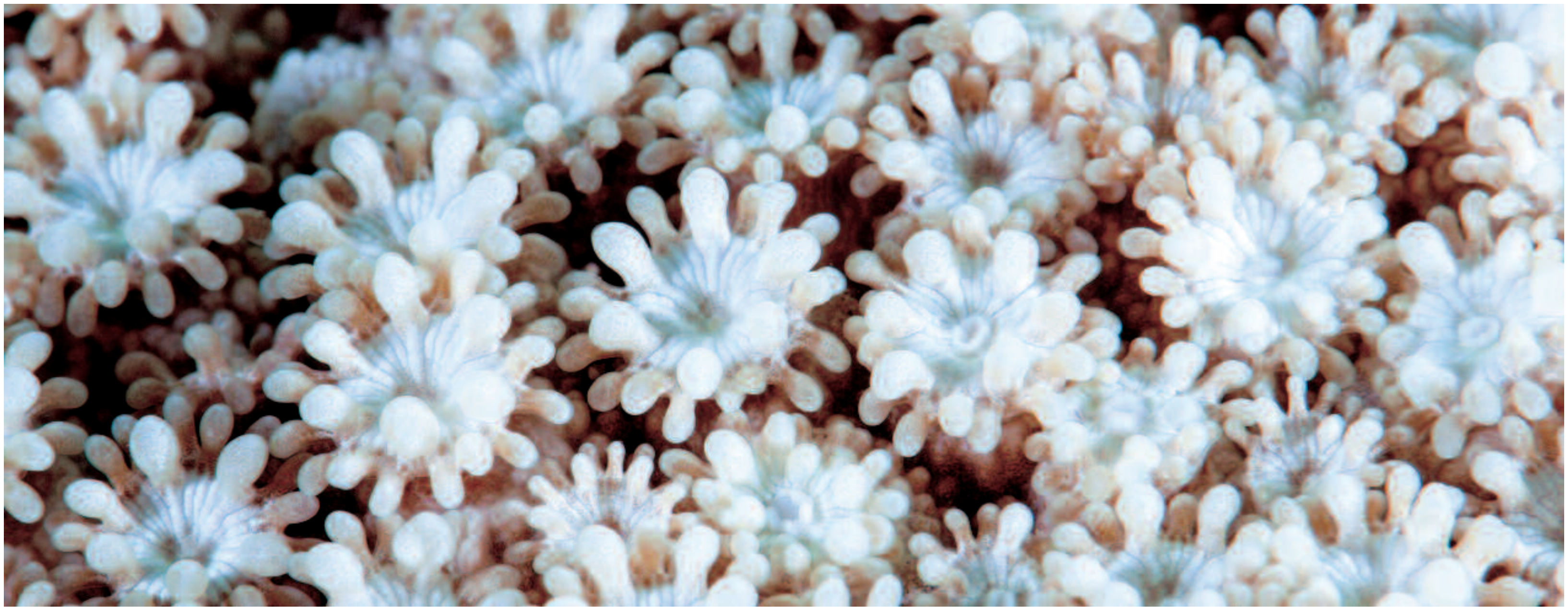
Chapter 7

The reefs' quest for diazotrophs

Valentine Meunier, Sophie Bonnet, Anne Lorrain, Mar Benavides, Mercedes Camps, Olivier Grosso and Fanny Houlbrèque



Deployed coral polyps searching for food. © G. Boussarie

Corals are voracious predators

Coral reefs are important diversity hotspots and major ecological reserves. Although corals develop in oligotrophic waters (poor in nutrients), they are recognized as the most productive ecosystems on our planet. Such a successful evolution is mainly due to their symbiotic relationship with microalgae. The symbiotic microalgae (*Symbiodinium*) present in the coral tissues provide their coral host with most of the carbon that they produce by photosynthesis.

However, in order to fulfill all their nutrient and energy needs, corals are also able to use a different nutrition mode: they are voracious predators that can feed on a wide range of preys (heterotrophic nutrition) (HOULBRÈQUE et FERRIER-PAGÈS, 2009). Their diet includes sediment particles, dissolved organic matter and plankton, which is present in the water column. Corals catch their prey in different ways. They can, for example, discharge stinging filaments (nematocysts) that contain toxic and paralyzing substances, produce mucus to which very small prey adhere, or use their tentacles to grab their prey and bring them to the buccal cavity.

Nitrogen at any price!

Nitrogen is essential to the development of corals. It is particularly important for the synthesis of proteins, molecules which are present in all living organisms. To meet their daily nitrogen requirement, corals use various mechanisms (Fig. 1): they host bacteria and cyanobacteria in their tissues that can fix atmospheric dinitrogen (N_2); with the help of their *Symbiodinium*, they can uptake dissolved inorganic nitrogen (DIN: nitrate NO_3^- and ammonium NH_4^+) and dissolved organic nitrogen (DON: urea and amino acids) in the surrounding seawater and nitrogen is also supplied by ingested prey and particles.

The Western Tropical South Pacific Ocean is known as a hotspot for atmospheric dinitrogen fixation. Around Melanesian archipelagos, and particularly in New Caledonia, the rates of dinitrogen fixation are some of the highest in the world (BONNET *et al.*, 2017). This is mainly due to abundant quantities of planktonic nitrogen-fixing bacteria and cyanobacteria. These "diazotrophic" organisms are able to fix N_2 dissolved in the surface layer of the ocean, and to transform it into ammonium to satisfy their nitrogen requirements. Part of this nitrogen is released in the surrounding environment and transferred to other planktonic organisms that do not have the same ability (BONNET *et al.*, 2016). During summer, nitrogen fixation supports most of the new planktonic production in the New Caledonian lagoon (BERTHELOT *et al.*, 2015). Furthermore, it has also been shown that an important part of this plankton is rapidly exported to the bottom of the reef, which potentially benefits benthic organisms such as corals.

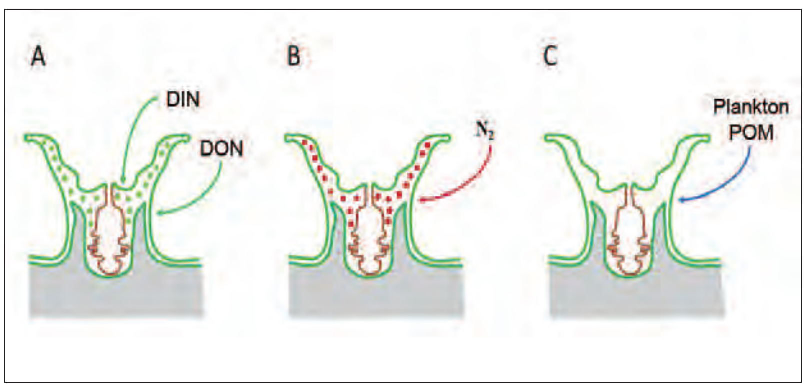


Figure 1: Major nitrogen uptake strategies of corals.
A: In dissolved organic or inorganic forms (DON or DIN), by coral tissues and *Symbiodinium* (green dots).
B: In the form of N_2 by bacteria and cyanobacteria inside coral tissues (red dots).
C: In the form of particulate organic matter (POM) and plankton, by corals.

Diazotrophs for corals

Corals are very important predators of plankton so dinitrogen-fixing organisms or plankton which have benefited from dinitrogen fixation could constitute food sources for corals, through heterotrophic nutrition. However, to date, the role of planktonic dinitrogen fixation in the nutrition of corals has been little investigated. A team from the IRD research center in Nouméa, traced nitrogen from the atmosphere, through plankton and all the way to its ingestion by corals.

Natural N_2 in the Earth's atmosphere is a mixture of two stable isotopes: ^{14}N and ^{15}N. The latter is widely used as an isotopic tracer to monitor the flow of matter in the environment. In order to follow the transfer of nitrogen resulting from diazotrophy, ^{15}N plankton isotopic labelling has been carried out. Small colonies of the coral species *Stylophora pistillata*, which is very common and abundant in the New Caledonian lagoon, were incubated for 12 hours in seawater containing ^{15}N-prelabelled plankton. The concentration of plankton was measured before and after the incubation in order to quantify the ingestion rates by corals.

Analyses were carried out to assess the exact isotopic composition of coral tissues and their symbionts and the results highlighted a significant ^{15}N enrichment in *Symbiodinium*, meaning that diazotroph-derived nitrogen is assimilated by these symbionts and directly allocated and stored into these cells. The ingestion of planktonic diazotrophs or plankton derived from diazotrophy would provide six times more nitrogen than the daily ingestion of small plankton. The abundance and activity of diazotrophs in the New Caledonian lagoon suggest that these organisms are an important nitrogen source for tropical corals (BENAVIDES *et al.*, 2016).

Branching *Acropora* massif, Larégnère Reef, damaged during the massive bleaching event in February 2016. © IRD/F. Houlbrèque

However, further research is needed to understand how the diazotrophic nitrogen is transferred into corals, and in order to investigate its preferential use by symbionts.

Nitrogen to the rescue!

For the last 30 years, repeated beaching events have struck the world's coral reefs with increasing frequency. Although they had been previously spared, the New Caledonian fringing and intermediate reefs were heavily damaged in February 2016 by a massive beaching event which also hit most of the world's coral reefs (chap. 25). When corals are bleached, they lose their *Symbiodinium*. Their colors fade and they lack their main source of energy. Several studies have shown that, during environmental stress such as seawater warming events, corals were capable of increasing their feeding rates on plankton and dead organic matter (PALARDY *et al.*, 2008). This raises the hypothesis that corals could benefit from the presence of diazotrophic plankton to fulfill their nitrogen demand during bleaching events. Preliminary experiments have demonstrated the capacity of *Stylophora pistillata* to increase its feeding rates on diazotrophic plankton or to incorporate more diazotrophic compounds in its diet, during a bleaching event. Hence, bleached corals could compensate for the lack of energy and nitrogen linked to the loss of their symbionts. However, it is not known if this nitrogen intake can, over the long term, increase the resilience of corals after a bleaching event.

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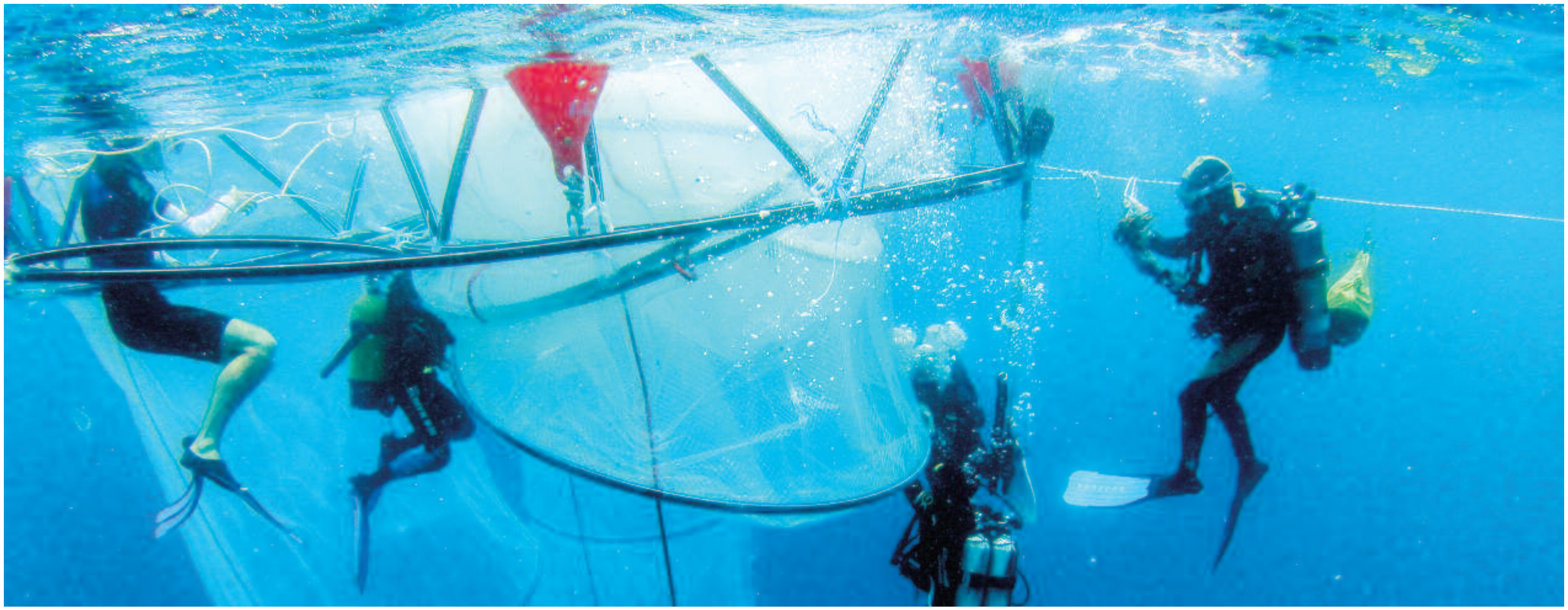
Chapter 8

Crystal clear waters filled with microscopic organisms

Sophie Bonnet, Renaud Fichez, Cécile Dupouy and Martine Rodier



Mesocosms set up for the VAHINE project in New Caledonia. © IRD/J.-M. Boré and IRD/E. Folcher

Most of the water surrounding the coral reefs and lagoons of New Caledonia is crystal clear. The water clarity, or oligotrophy (poor in nutrients, from the Greek "*oligo*": few, and "*trophein*": feeding), is due to the very low nutrient concentration of the oceanic waters that flow into the lagoon with tidal currents or wave-breaking over the reef. Research programs carried out in the lagoon have identified two major factors which explain most of the spatial variability of the waters' characteristics (FICHEZ *et al.*, 2010): a trophic enrichment gradient and a salinity gradient. These two factors testify to the perpetual battle between terrestrial and oceanic influence in the lagoon. While the trophic enrichment at the coast can be due to natural factors, such as long water-renewal time in the most sheltered zones, some sites are markedly different. For instance, near urban zones, abnormal enrichments can be linked to wastewater discharge. Seasonal and interannual temperature and salinity variations are also amplified at the coast. As a result, bays amplify the physical functioning of the lagoon, with implications for the distribution of species and environmental vulnerability.

Although, waters surrounding the coral reefs and lagoons of New Caledonia are mostly crystal clear, each of the water drops that fill the lagoon is packed with millions of microscopic organisms called plankton (from the Greek *"planktos"* meaning "errant" or "drifter"). These organisms are remarkably adapted to their very specific environment, where they live suspended, and drift with currents.

Barely known, because they are invisible to the naked eye, they are mostly made of bacteria, microalgae (or "phytoplankton"), and microscopic animals (or "zooplankton"). Like terrestrial plants, phytoplankton is made of photosynthetic organisms that contain chlorophyll, with which they can absorb solar energy. Sunlight, carbon dioxide (CO_2) and minerals dissolved in seawater (nitrogen, phosphorus, and micronutrients) are sufficient for phytoplankton to grow and develop. Phytoplankton plays a key role for several reasons. Firstly, it is at the base of the marine food chain and it also produces large quantities of oxygen through photosynthesis. At the global scale, it is estimated that phytoplankton generates over half the oxygen of our planet, while it represents only 1% of the biomass of all photosynthetic organisms (most being terrestrial plants). Lastly, it plays a role in climate regulation, as it uptakes atmospheric CO_2 through photosynthesis. When it dies, part of the phytoplankton sinks to the bottom of the oceans, allowing for the durable sequestration of CO_2 through a process known as the "biological carbon pump". In the lagoons, the planktonic organisms that sink to the bottom contribute to feeding benthic organisms such as corals (chap. 7).

The Western Tropical South Pacific Ocean, including New Caledonia and archipelagos between Australia and Tonga, are unique because they harbor the largest biomass of nitrogen-fixing microalgae in the world (BONNET *et al.*, 2017) (Fig. 1). These microalgae, also called "diazotrophs" are very competitive organisms in these oceanic deserts. They are capable of living in waters that are very poor in mineral nitrogen elements because they can use atmospheric dinitrogen (an unlimited resource) and fix nitrogen themselves. This process fertilizes surface waters with nitrogen, acting like a natural fertilizer, and sustains other organisms that, otherwise, would not have been able to live in these deserts.

The filamentous cyanobacteria *Trichodesmium* are found throughout the year in tropical waters. Aggregated in fusiform colonies, they accumulate at the surface to look like gold dust (or sawdust). They are often observed by ships that navigate in the region and recorded as "colored waters" on the most ancient nautical charts. Samples collected by the national navy, stretching all the way to Vanuatu, Fiji and Tonga, revealed an important species diversity,

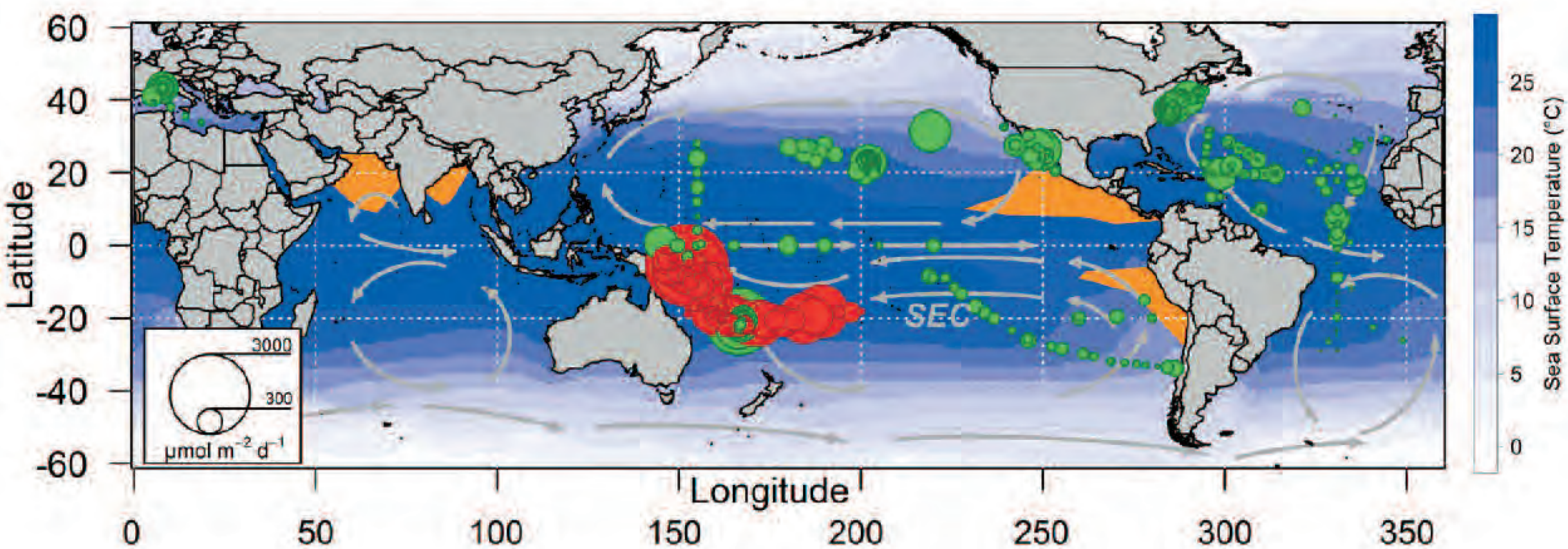


Figure 1: Nitrogen fixation rate (µmol N m^{-2} j^{-1}) in the Southwest Pacific (in red) and in the rest of the world (in green). Adapted from BONNET *et al.*, 2017

which is similar to what is found in New Caledonia. These 98 surface water samples have been used for the calibration of an automated detection algorithm (DUPOUY *et al.*, 2011). Algal blooms seen on satellite images can cover thousands of square kilometers. Assuming a homogeneous distribution of *Trichodesmium* across the areas where it is detected (90,000 km^2), and an average nitrogen fixation rate, it has been estimated that a bloom of diazotrophs can fix between 0.02 and 1.17 x 109 g of nitrogen over a period of 10 days (DUPOUY *et al.*, 1988).

In the lagoons of New Caledonia, the growth of *Trichodesmium* increases during summer. Blooms approximately a week-long are triggered by the combination of weak winds and nutrient enrichment on the west coast in the Sainte-Marie Bay (*T. erythraeum*), and on the east coast in the Ouinné Bay (*T. thiebautii*, oceanic species) (RODIER and LE BORGNE, 2010).

In order to study the role of these organisms on the functioning of the New Caledonian lagoon ecosystem in detail, a team from the IRD research center has led experiments in the lagoon over a month. They used mesocosms, giant 50,000 L test tubes, for the study of organisms that form the base of the marine food chain. The objective was to answer the question: Who benefits from the fertilization provided by diazotroph microalgae? The main results of this project highlighted that most of the new biological production in the water column in the New Caledonian lagoon, is supported by the activity of diazotroph microalgae during the summer. Within the mesocosms, blooms increased the system's productivity by two-fold, and its carbon export by five-fold (BERTHELOT *et al.*, 2015). The fate of nitrogen produced by fixation in the ecosystem appeared to be dependent on the organisms that were present.

When the dominant organisms in the community were diazotrophs living in symbiosis with microalgae that are incapable of fixing dinitrogen (diatoms), the nitrogen derived from diazotrophy (NDD) was exported (directly) (BERTHELOT *et al.*, 2015). In this case there was no transfer to the organisms at the base of the planktonic food chain (phytoplankton/bacteria), but instead the NDD was transferred to zooplankton through direct grazing (HUNT *et al.*, 2016).

When free and unicellular diazotrophs (UCYN, *Cyanobacterium*) were dominant, about 20% of the NDD was rapidly (in 24 hrs) transferred to non-diazotrophic plankton (BONNET *et al.*, 2016), and to zooplankton. For the latter, nitrogen demand was sustained at 35 % by nitrogen fixation (HUNT *et al.*, 2016), either directly by grazing on diazotrophs, or indirectly by grazing on plankton that developed on NDD. The efficiency of the system in exporting carbon, relative to the fixation of carbon by phytoplankton (primary production) (e-ratio), was higher when UCYN were dominant. This export was both direct, with the high sedimentation rate of UCYN small cells (5.7 ± 0.8 µm) aggregated in large particles (100-500 µm), or indirect, through the sedimentation of non-diazotrophic plankton that developed on NDD (BONNET *et al.*, 2016). In total, 60% of the exported production was supported by diazotrophy.

Results obtained during the VAHINE (Variability of Vertical and Trophic Transfer of Diazotroph-derived Nitrogen in the Southwest Pacific) project provided the first quantitative data on the fate of nitrogen fixation in the marine ecosystem, as well as a classification of the dominant types of organisms involved. These were integrated into a model that enables numerical simulations to predict the evolution of productivity in the lagoon and the surrounding waters (GIMENEZ *et al.*, 2016). Numerous studies show that diazotrophy should increase in the warmer, more acidic and stratified oceans predicted to exist in the future, reinforcing the relevance of these simulations.

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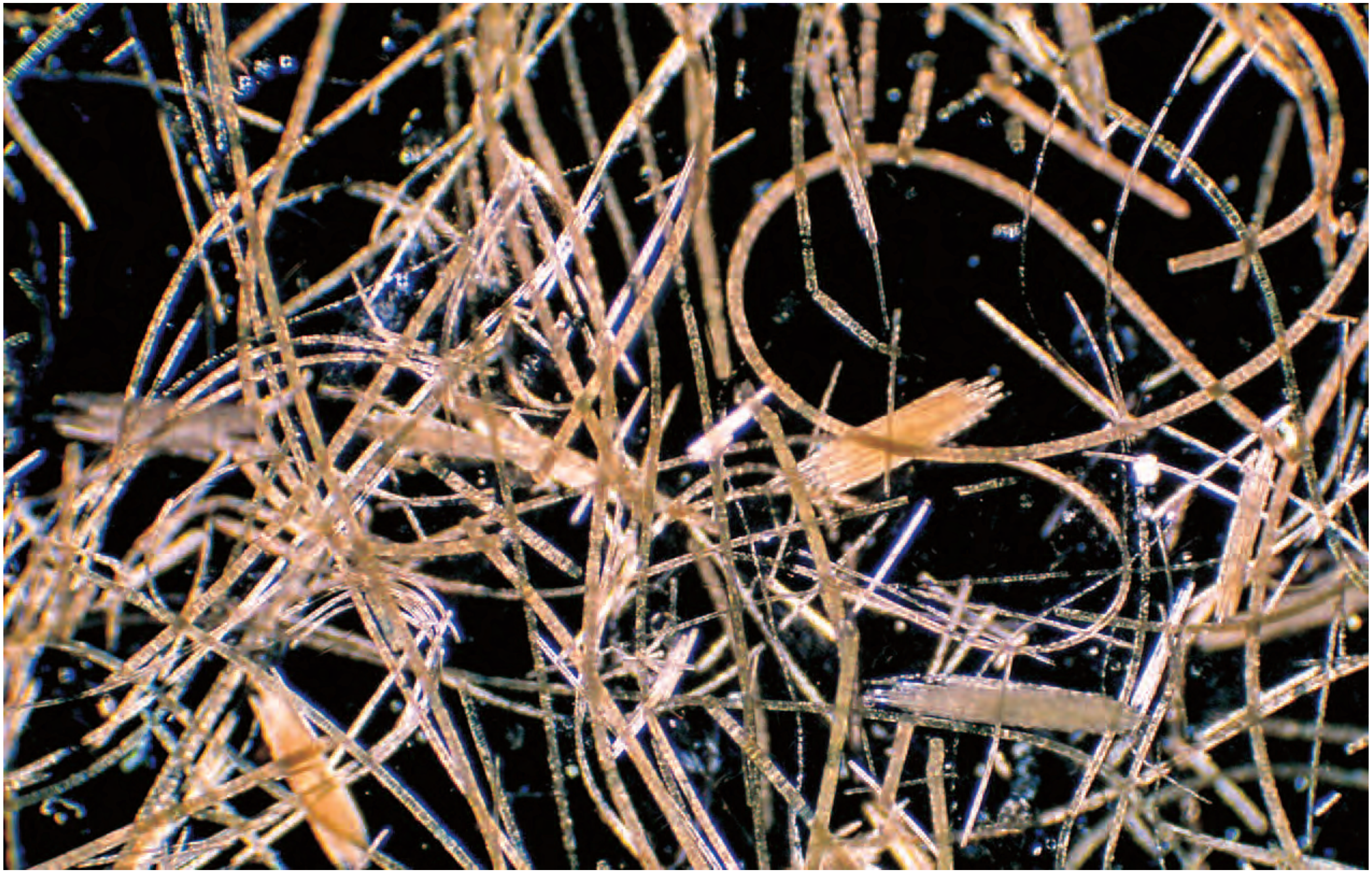

Trichodesmium seen through a microscope. © IRD/G.Dirberg and C. Dupouy

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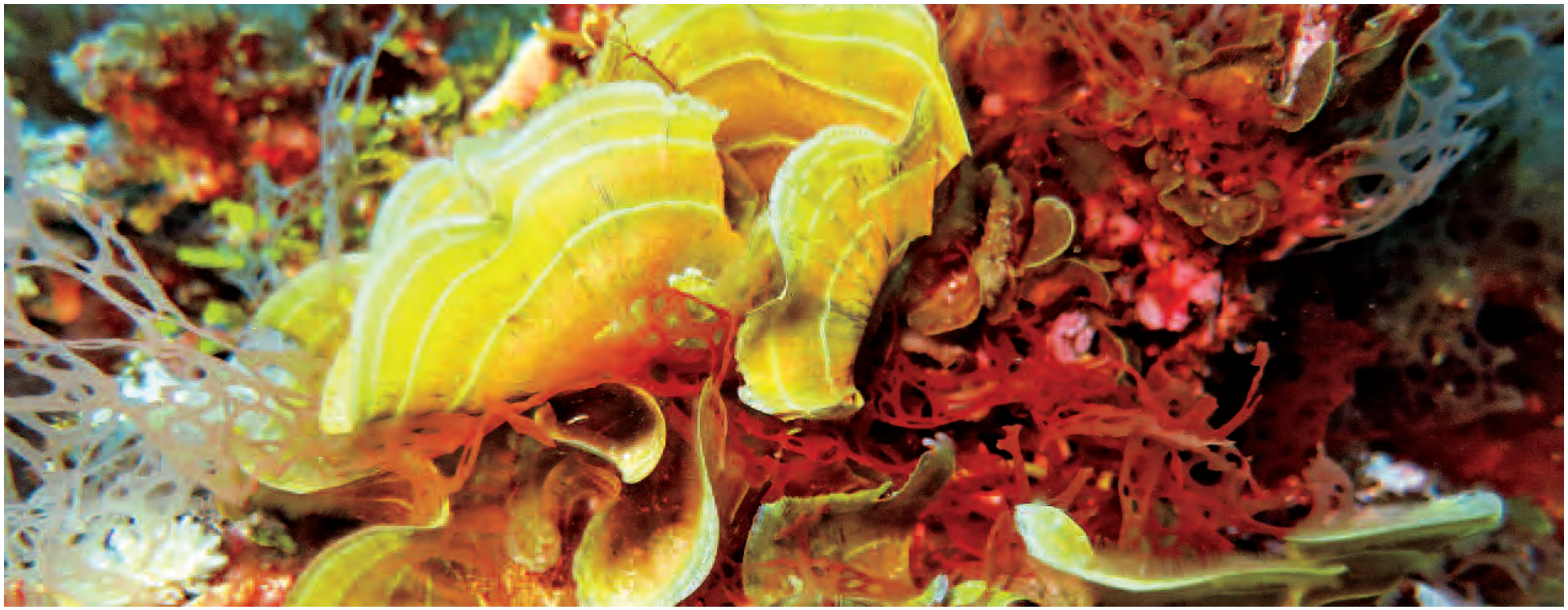
Chapter 9

Tales of algae

Claude E. Payri, Laura Lagourgue, Lydiane Mattio, Julie Gaubert and Christophe Vieira



Macroalgal community typical of the Southern Lagoon. Woodin Channel, 2015. A golden brown and iridescent *Stypopodium* blade (center) mixes with the delicate red lace-like *Kallymenia*. © IRD/ C.E Payri

Algae, these funny organisms

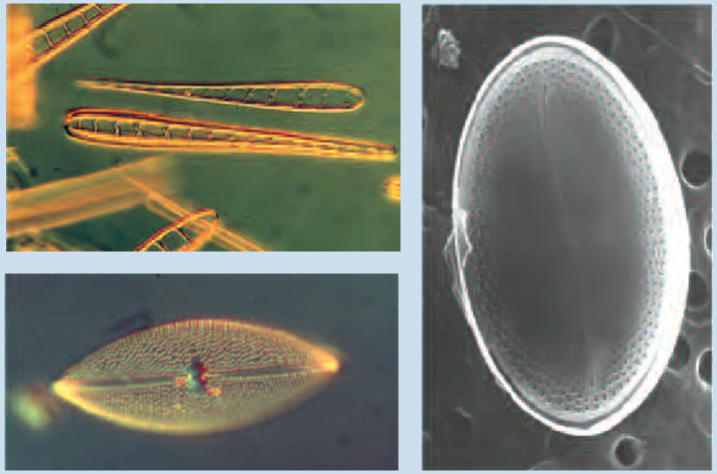
Coral reef algae are a heterogeneous group of organisms, all capable of photosynthesis, but which have diverged during evolutionary history into several large and independent lineages. Although it has no taxonomic meaning, the term "algae" is generally used for convenience to refer to marine plants of various shapes and colors. They include unicellular microalgae of a few microns, or macroalgae, generally pluricellular, which can be several tens of centimeters in length (box. 9)·

Nourishing seaweeds, protective algae

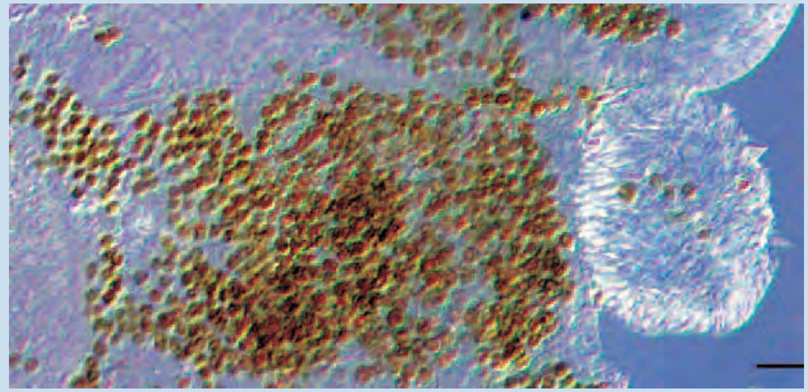
Macroalgae, also known as seaweeds, play an important role in the ecology of coral reefs. Like all photosynthetic organisms, they actively contribute to primary production. They are the main food source for a wide variety of herbivores living in reefs and lagoons (e.g., fish, crustaceans, mollusks) and are the very basis of the food web in coral ecosystems. The most consumed are the filamentous forms that cover dead corals and create an algal turf, which itself shelters a small and very rich mobile fauna loved by herbivorous fish. More coriaceous

Box 9

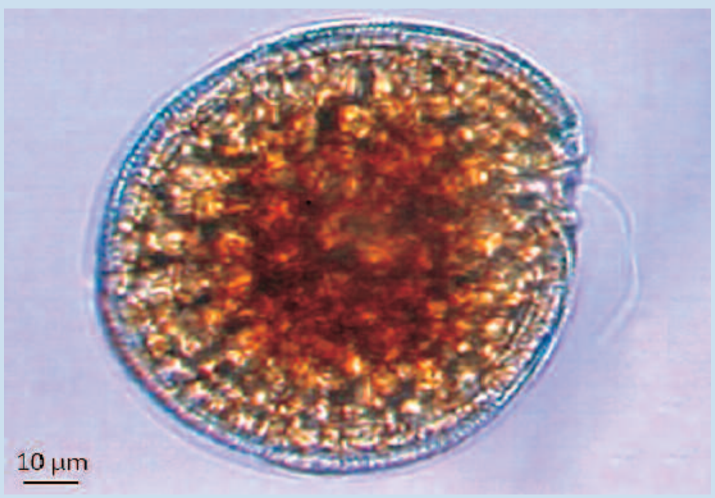
Microalgae



Benthic diatoms. A: *Climacosphenia moniligera* (250 µm).
B: *Navicula granulata* (90 µm). C: *Cocconeis* sp. (40-50 µm).
A, B: © M. Ricard; C: © CRIOBE/B.Delesalle



Microscopic view of zooxanthellae (*Symbiodinium*) in the polyp of the branching coral *Pocillopora damicornis*. Scale: 40 µm. © CNRS/V. Berteaux-Lecellier

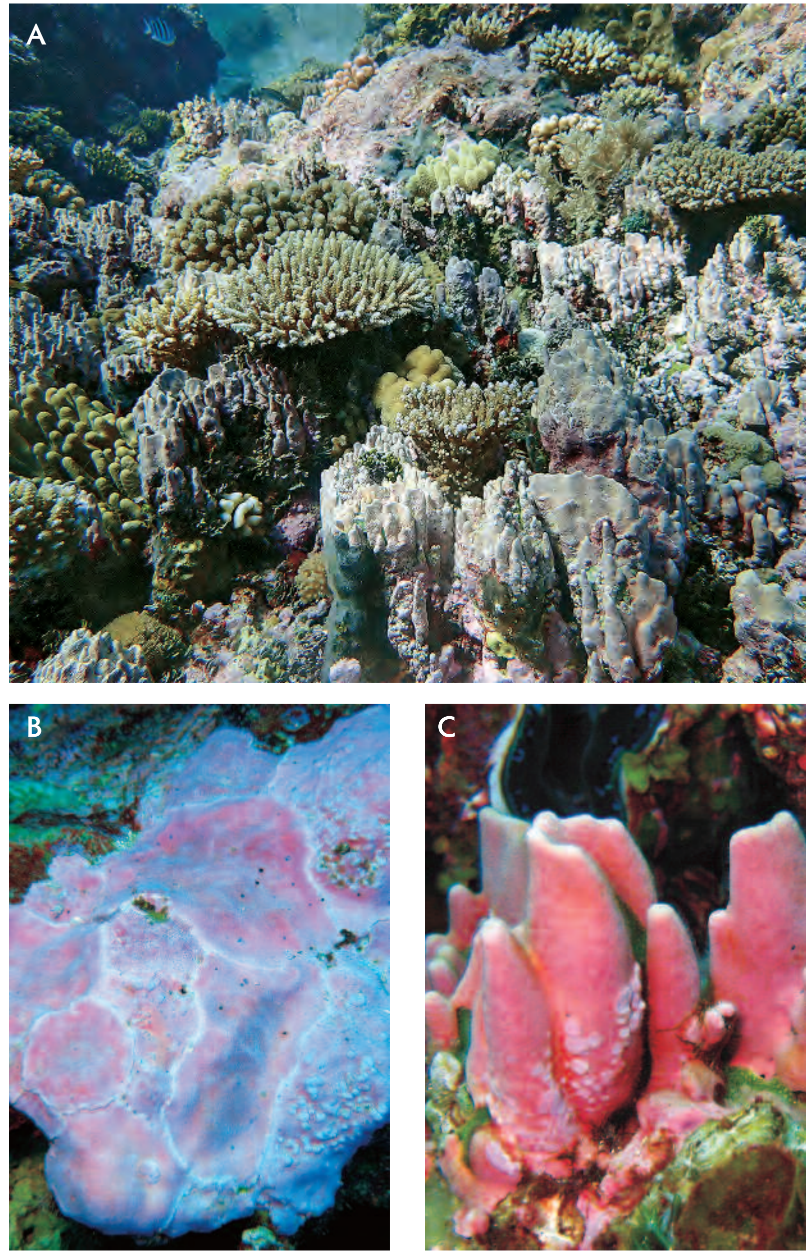


Gambiersdiscus cultivated cell. These microalgae develop on other substrata, including macroalgae. When they graze on maroalgae, herbivorous fish also consume *Gambierdiscus*. These microalgae have toxins (ciguatoxins) which accumulate up the food chain and trigger an fooodborne sickness called ciguatera.
© Louis Malardé Institute/M. Chinain

Microscopic unicellular forms of algae, or microalgae, generally live free in the water column and form the phytoplankton. However, several of them, such as some diatoms, have to be attached to a substratum in order to develop and form the first stages of "fouling". Others have forged a symbiotic partnership with animals; the most famous are zooxanthellae. They are found in the polyps of reef-building corals or in the mantle of giant clams. Zooxanthellae, or *Symbiodinium*, are dinoflagellates, such as *Gambierdiscus*. The latter is another microalga well known in coral reefs because it causes ciguatera, a food poisoning due to the consumption of certain reef fish species and large predators (e.g., barracudas and sharks). While *Symbiodinium* shelters in the tissues of its animal host, *Gambierdiscus* develops on the surface of dead corals or large macroalgae forms are rarely grazed. This is, for example, the leathery species of the brown macroalgae genus *Turbinaria*, or the calcareous algae that only parrotfish species or some mollusks are able to scrape with their powerful teeth, leaving very specific marks. The largest of them, such as the large brown algae *Sargassum*, form a canopy under which many species of invertebrate and fish escape predation, reproduce or live (box. 10).

In addition, massive and calcareous red algae play an essential role in the construction and consolidation of the reef structure. They cement the reef into a sturdy structure; the coral matrix alone would not be strong enough to withstand wave action and major events such as cyclones and tsunamis. On the most exposed sites of the barrier reef and the outer reef slope, they replace corals, which are less adapted to strong hydrodynamics. They form a compact pinkish-beige glaze, or rounded brain-shaped clusters or candles, such as in the Chesterfield or d'Entrecasteaux reefs.

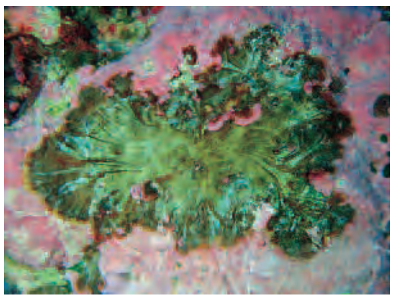
Parrotfish grazing on turf and coralline algae. © M Juncker

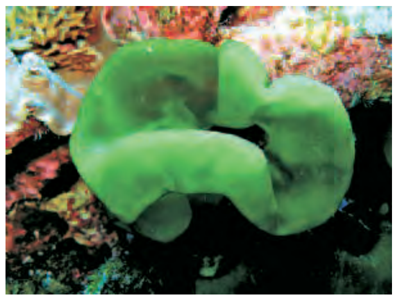


A: Calcareous red algae (corallinales) are dominant in exposed sections of the external reef slopes where they build massive constructions, for example in the Chesterfield Islands. © IRD/G. Lasne
B: Massive encrusting forms that cement the substratum. © IRD/C.E. Payri
C: Candle-like forms of *Porolithon*. © IRD/C.E. Payri

Macroalgae, a cabinet of curiosities

Between soft forms or stone-like masses, the architecture and colors of these organisms is astonishing. Red, green or brown, the macroalgae of tropical reefs and lagoons can take unbelievable shapes. They range from leaf-like appendages to branched, feathery, filiform, and articulated forms or to barely recognizable shapes when they adhere to the substratum. These adherent, or even encrusting species, whether brown like *Lobophora obscura*, green like *Codium lucasii* or red like Neogoniolithon or Peyssonnelia, appear like a lively and colorful painting on these otherwise dead coral debris and inert substratum. The khaki beret forms of *Codium saccatum* are as strange as the beads of its sister species *Codium globosum*, or the young specimens of *Halimeda cylindracea*, which spread out their segments like an outstretched hand. These three species are all made of a single giant tubular cell containing multiple nuclei, which is branched to form the body of the algae (box. 11). Even more unusual are these gelatinous and fluffy red algae, sometimes globular like *Gibsmithia*, sometimes branched like *Dudresnaya* or *Trichogloea*, which resist to strong currents, but dislocate when you try to pick them up.

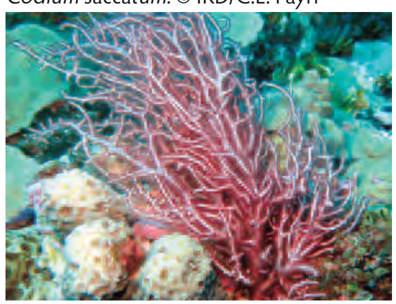

Lobophora obscura. © IRD/C.E. Payri

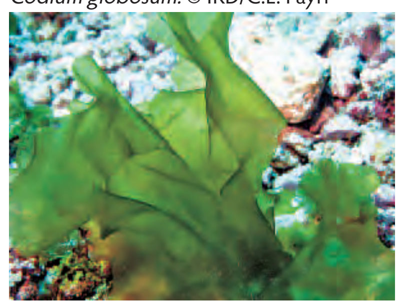

Codium saccatum. © IRD/C.E. Payri


Codium globosum. © IRD/C.E. Payri

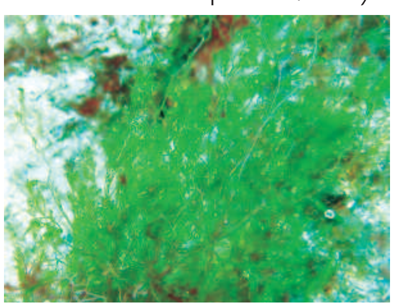

Halimeda cylindracea. © IRD/C.E. Payri

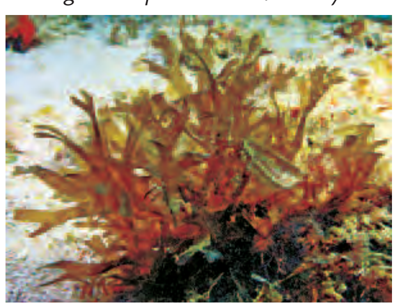

Gibsmithia hawaiensis complex. © IRD/C.E. Payri


Trichogloea requinerii © IRD/C.E. Payri

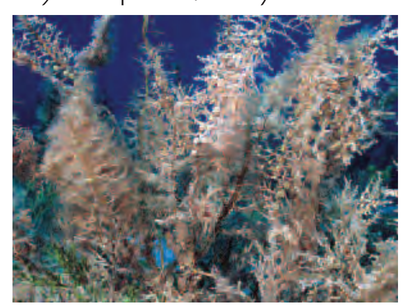

Umbraulva sp. © IRD/C. Geoffray


Halymenia sp. © IRD/C.E. Payri


Cladophora sp. © IRD/C.E. Payri

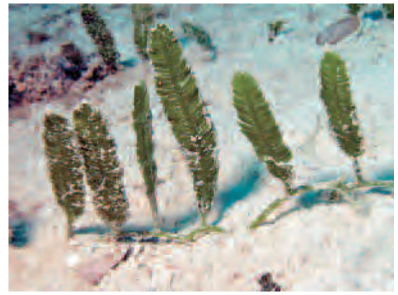

Dictyota sp. © IRD/J.-L. Menou


Caulerpa cactoides. © IRD/C. Geoffray


Sargassopsis decurrens. © IRD/J.-L. Menou

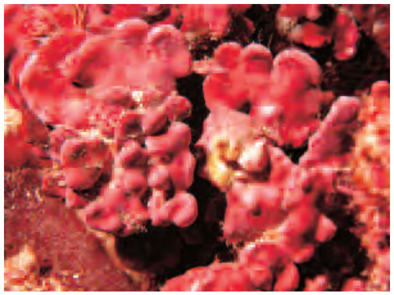
Halimeda minima complex. © IRD/C.E. Payri

Udotea geppiorum. © IRD/J.-L.Menou



Caulerpa taxifolia. © IRD/C.E. Payri

Avrainvillea sp. © IRD/C.E. Payri



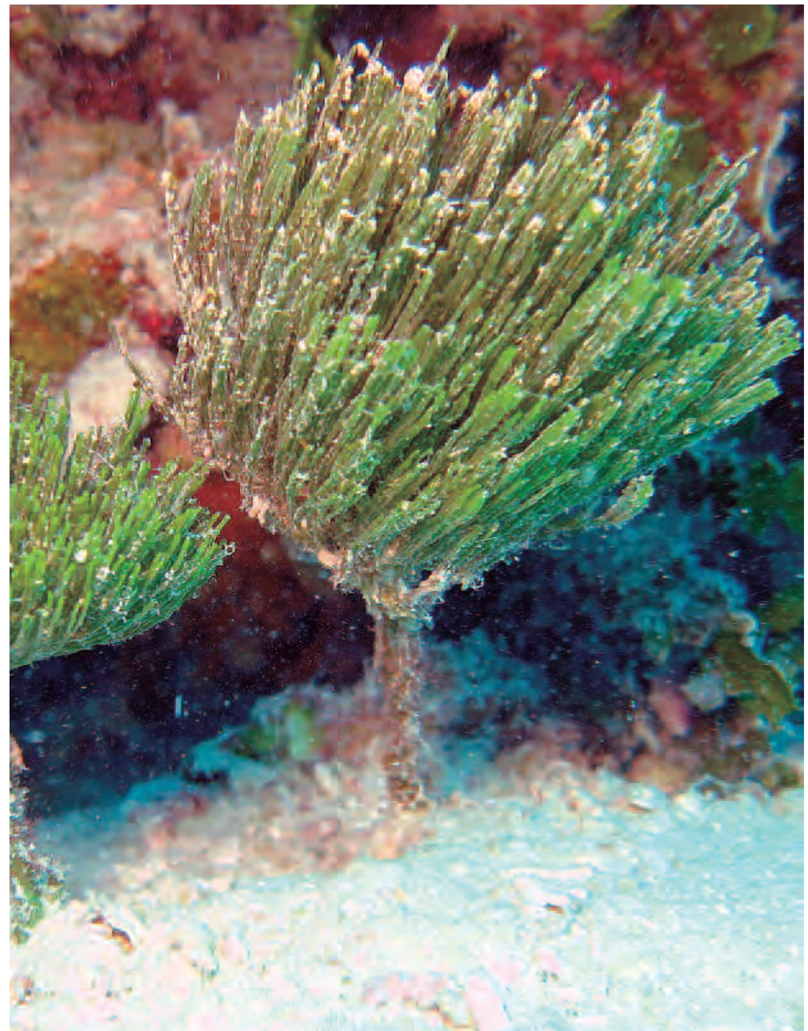
Lithophyllum proliferum. © IRD/C.E. Payri

Padina melemele complex. © IRD/C. Geoffray

More classical, the fronds of some species can be thin foliaceous blades (*Umbraulva*), thick and digitate (*Halymenia*), or filamentous (*Cladophora*) forms, with simple branched (*Dictyota*) to more complex *(Caulerpa)* structures. The shapes of some species are even more complex and mimic the leaves and stems of terrestrial plants, like the brown macroalgae *Sargassum*.

While most macroalgae are fleshy and soft without a rigid structure, several groups can build a calcified skeleton by precipitating calcium carbonate from seawater into the inner walls of their cells. This is the case for the red coralline algae (over 100 different genera) or some green algae (about 20 genera) such as *Halimeda, Udotea*, or *Neomeris*. Only two genera of brown algae, *Newhousia* and *Padina*, precipitates a thin calcified layer in the fronds or on their surface, respectively.

Rhodoliths are even more singular. These free-living stony nodules that can be round or branched, are built by calcareous red algae. The algae develop in concentric layers, around a piece of coral debris (nucleus), as it rolls on the bottom under the action of a moderate current. They are purple-red to pink in color, and line parts of reef flats or form maerl fields at the bottom of lagoons swept by moderate currents.

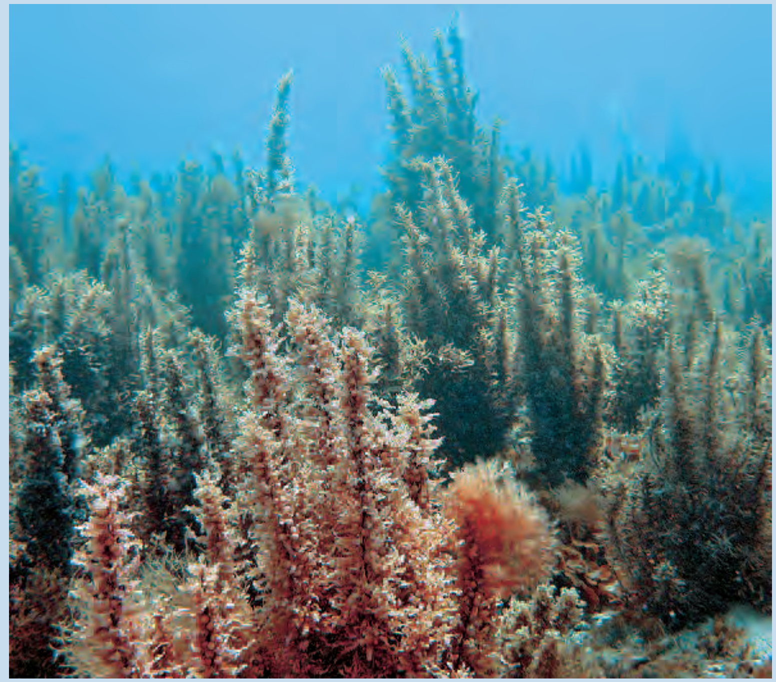


Penicillus sp nov. © IRD/C.E. Payri

Box 10

Sargassum, the bush of the lagoon

Sargassopsis decurrens belongs to the Sargassaceae family. This species is easily recognized by its singular morphology in "fish bone" or Christmas tree. Vesicles (the "Christmas baubles") provide Sargassaceae species with a way of standing upright when attached to the bottom or to float at the surface when they detach (storms, senescence).
© IRD/C. Geoffray



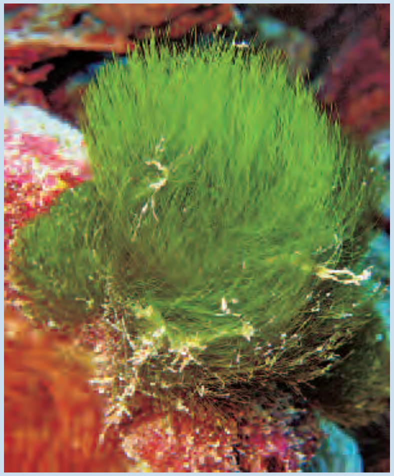
Sargassum bed in the Southern Lagoon. *Sargassum spinuligerum* is the most abundant species and can reach 1.5 to 2 m high. This underwater "bush" is an essential habitat for numerous species of other macroalgae, fish, invertebrates and mollusks.
© IRD/C. Geoffray

Like the temperate kelp forests (Fucales and Laminariales), species of the Sargassaceae family structure one of the major benthic habitats of the lagoons of New Caledonia. Their canopy can reach a height of 1 to 2 m, forming an underwater bush, which plays an essential role in the life cycle of many species of animals by providing substratum, food and refuge against predators or harsh environmental conditions. In the lagoon, *Sargassum* beds are home to a great diversity of invertebrates (amphipods, polychaetes, mollusks...) and play an essential role as nurseries for many species of fish. *Sargassum* species are very diverse morphologically. Some look like brown mistletoe (e.g., *Sargassum ilicifolium*), while others resemble a flattened Christmas tree or even a fish bone (e.g., S*argassopsis decurrens*)! They are found in a wide variety of habitats from coastal intertidal zones to barrier reefs. They form dense or scattered populations on coastal reef flats, on fringing reefs of islets, on lagoon bottoms to a depth of 30 m, and on the barrier reef to a depth exceeding 50 m (-56 m for *S. turbinarioides* at the Isle of Pines). They develop on all types of hard substrata, including more or less silted rocky bottoms (e.g., *S. polyphyllum*), coral debris (e.g., *S. polycycstum*), reef crevices or artificial riprap (e.g., *S. aquifolium*).

Box 11
Amazing siphonous algae!

Avrainvillea sp nov. © IRD/C.E. Payri

Rhipilia sp nov. © IRD/C.E. Payri



Chlorodesmis sp. © IRD/C.E. Payri

Rhipilia penicilloides. © IRD/C.E. Payri

Who would have thought that these algae are one single cell? This is characteristic of species belonging to the order Bryopsidales. Despite this simple structure, their morphological diversity is unbelievable. Specimens can reach over 10 cm in height, and are capable of forming very different body shapes depending on the family to which they belong. Some are so complex (rhizoids, stipe and blades comparable to the roots, stem and leaves of terrestrial plants) that it is difficult to believe they are unicellular organisms. However, these algae are made up of a single, plurinucleate and tubular cell called a siphon, which divides into several branches that share the same cytoplasm. The arrangement and organization of these siphons (which can intertwine, be perfectly aligned, even coalesce, or remain free) is very different from one species to another and creates an important morphological diversity, which is visible to the naked eye.

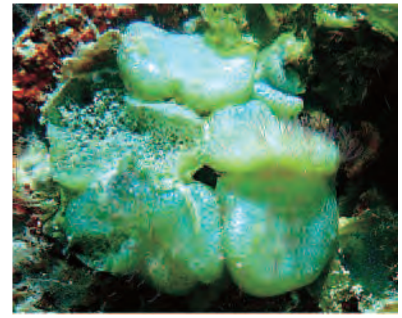
In New Caledonia, all macroalgae are benthic organisms. It means that they attach to a support, which can be as tiny as a grain of sand. To date, only two macrophyte species are known to develop without ever being fixed. They are two species of the brown algae *Sargassum*, found in the Sargasso Sea, in the North Atlantic. These pelagic algae can form very large rafts, which are very important ecologically. For a few years now, the Caribbean islands and the coasts of Brazil and West Africa have been experiencing massive stranding of these pelagic *Sargassum*, but no one has yet been able to identify their origin or explain this recent phenomenon.

In the lagoon of New Caledonia, it is common to see *Sargassum*, which after having been detached from their substratum, float (thanks to small air vesicles) and drift according to currents before stranding on beaches or disappearing into the depths, marking the end of their life.

A world of colors

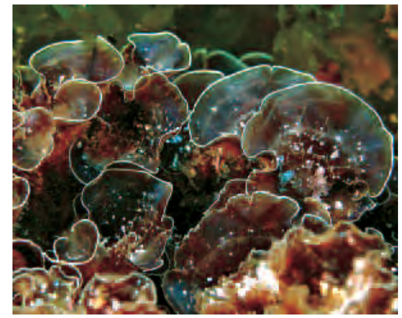
Macroalgae are commonly referred to as red, green and brown algae – here, we do not consider the so-called "blue-green algae", which are bacteria (cyanobacteria), or seagrasses which belong to a completely different evolutionary lineage: the phanerogams. For macroalgae, the three broad categories of colors refer to three main taxonomic divisions, rhodophytes (red algae) and chlorophytes (green algae), which form two evolutionary divergent lineages but belong to the same "green lineage", and the phaeophytes (brown algae), the "brown lineage", which is evolutionarily distinct from the previous one. Three types of pigments, chlorophylls (green pigments), carotenoids (orange and yellow pigments) and phycobilins (red and blue pigments) are sufficient to create a whole range of colors depending on their concentration, sometimes causing confusion. Red algae can appear brown, while brown algae can take on greenish colors... But the different combinations of pigments are not the only criteria on which taxonomy and phylogeny are based. The various products of photosynthesis, cell walls, the shape and number of flagella in unicellular cells or reproductive organs in pluricellular organisms, and cellular organelles, such as plasts, are also taken into account.

Caulerpa chemnitzia. © IRD/C.E. Payri

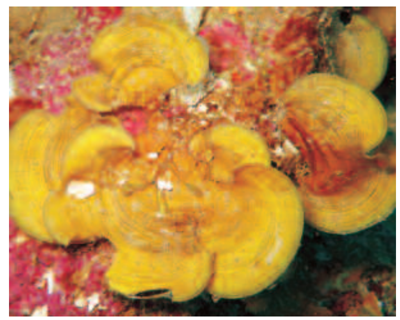


Dictyosphaeria cavernosa. © IRD/G. Lasne

Codium taylorii. © IRD/C.E. Payri

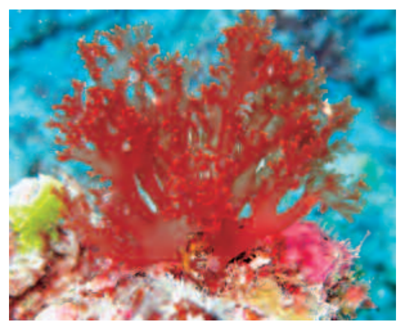


Distromium didymotrix. © IRD/C.E. Payri



Padina melemele. © IRD/C.E. Payri

Melanthalia vieillardii. © IRD/C.E. Payri



Platoma sp. © IRD/C.E. Payri

Callophycus serratus. © IRD/C.E. Payri

They are everywhere...

Macroalgae are everywhere: from mangrove forests, where the small red algae *Bostrychia* nests on mangrove roots, to coastal meadows, where grow many species of brown algae such as *Padina*, red algae such as *Dichotomaria*, and green algae such as *Caulerpa*. The latter has fronds that can be digitate (e.g., *Caulerpa cupressoides*), feather-like (e.g., *Caulerpa sertularioides* or *C. taxifolia*), or like a bunch of grapes (e.g., *Caulerpa racemosa* and *C. chemintzia*).

On the bottom of the lagoon, several species of green algae are anchored in grey sand with their compact rhizoidal bundle: *Halimeda*, recognizable for its small calcified segments, the tender green and fan-shaped *Udotea*, and the dark green *Avrainvillea*, whose frond, devoid of calcified structures, has a velvet touch.

Rocky bottoms are generally covered by *Sargassum* meadows. Their small floats pull their long fronds towards the surface. They shelter under their canopy other species of brown algae *(Lobophora, Dyctyopteris, Hormophysa...)*, which together form a particularly productive ecosystem. On intermediate reefs and barrier reefs, soft macroalgae are more modest, although they are still many. It is the realm of the green algae *Rhipilia* and *Chlorodesmis*, which form small pompon balls, of an intense green, at the top of coral colonies. Next to them, *Halimeda* spreads out in long curtains along the walls of massive corals, or hide in coral interstices with other strange species, such as *Valonia ventricosa* (large green marbles) or *Dictyosphaeria cavernosa* (compact cupules). In these areas, the slightest hard substrata are cemented by crustose coralline algae which consolidate the reef.

On the outer reef slope, algae are distributed according to depth and water movements, forming communities down below 100 m deep. Regardless of their color, they are strongly attached to hard substrata. Species with erect fronds sway in the endless movement of water; this is most red algae, such as *Gibsmithia, Dudresnaya, Predaea, Platoma* and species of Liagorales. Others spread out over the substratum, like the thin, golden-brown and rounded blades of the brown algae Dictyotales (e.g., *Distromium, Lobophora, Homeostrichus*). Green algae are mainly represented by *Halimeda* and *Codium*, the latter is sometimes branched and erect, sometimes strongly adhering to corals. Many species live under overhangs or line the walls of caves: they are the numerous *Peyssonnelia* species, some encrusting, others forming large rounded blades of a very dark red. They are easily distinguishable from calcareous coralline algae, which form crusts over any available surfaces, creating artistic mosaics of warm colors in this relatively dark universe.

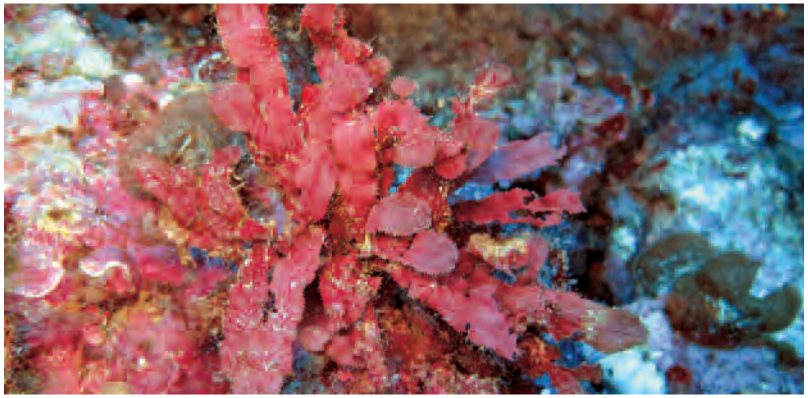
Contrasting with the large red algae are the tiny and delicate green species, of only a few millimeters high, whose diversity is inversely proportional to their size. This is the world of the *Rhipidosiphon* (calcified), *Rhipiliopsis* and *Rhipiliella* (uncalcified) species, many of which are still to be described. Macroalgae are everywhere, they even live inside coral skeletons or other carbonate substrata, they are called "endoliths". Through their perforating action, along with other perforating organisms such as bivalves, sponges and worms, these algae cause a superficial decay in the rock which affects the morphology of the reef.

Although they are dependent on light, macroalgae also colonize the mesophotic zone, this section of the reef between 70 and 125 m deep, which some experienced divers have explored equipped with recyclers powered by suitable gas mixes. Algae in this area are not very well know and each new dive brings back new species, including some of the brown *Distromium*, the red *Delisea*, and the green *Phacelocarpus* and *Halimeda*.

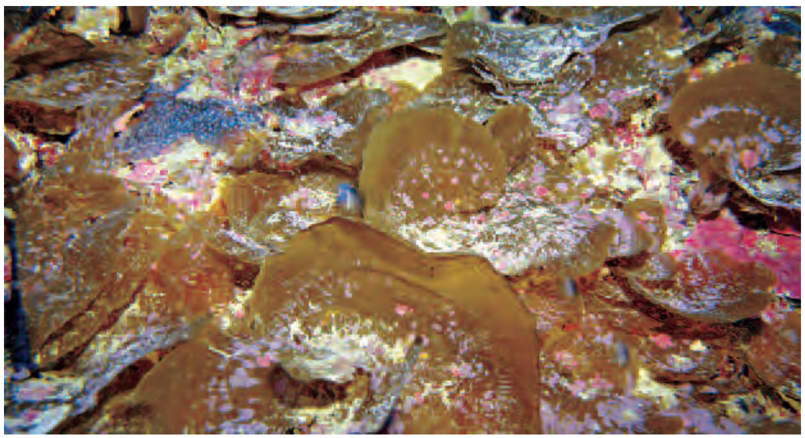
How many algae species in New Caledonia?

The total number of macroalgae species in world has been estimated to be between 7,000 and 15,000. In New Caledonia, the first estimate, published in a compendium in 2007, totalized 443 species. However, this is a very preliminary estimate, because it is based on relatively limited collections and mainly morphological observations. This number keeps growing with additional collection campaigns, repeated surveys between 40 and 60 m deep, and

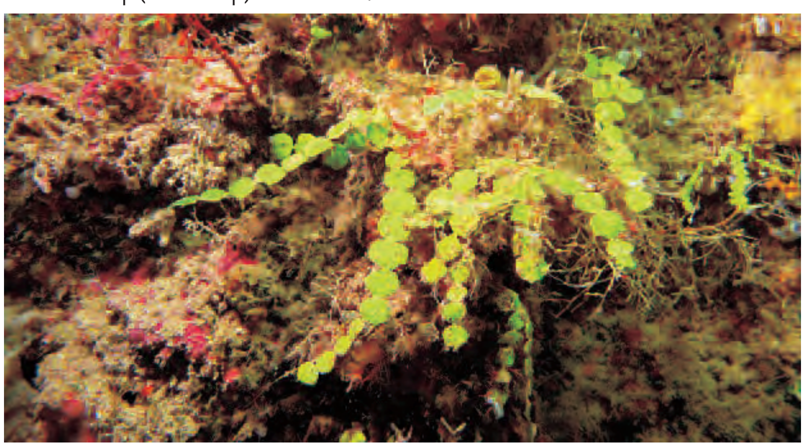
Macroalgae from the mesophotic zone



Phacelocarpus neurymenioides (80 m deep) © IRDJ.-L. Menou



Distromium sp.(85 m deep) © Biocénose/G. Lasne



Halimeda minima complex (100 m deep) © IRD/J.-L. Menou

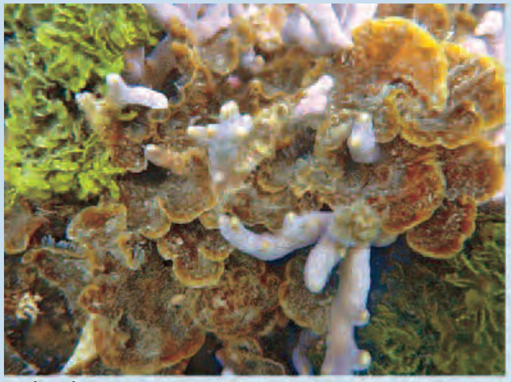
genetic analyses. It is likely to reach or even exceed 1,000 species. It would be pretentious to think that the inventory of New Caledonia's macroalgae has been completed. This is because despite the prospecting effort developed throughout the archipelago over the last 15 years, sites have not been prospected in a comparable manner and, as a matter of fact, the large Southwestern Lagoon region remains the best known to date.

While marine macrophytes are increasingly being studied, a large number of species are still waiting to be named according to the code of botanical nomenclature (i.e., a genus name followed by a species name). As DNA and genetic barcoding analyses become more common, the discovery of new species has increased at a rate much higher than the time required to formally describe these species. For example, only two species of the genus *Lobophora* (brown algae) were recorded in New Caledonia until 2007, but it now has nearly 30 species, 10 of which are new to science. Globally, this genus accounts for more than 100 species, but only about 30 have been described and named; the others are indexed by DNA sequences linked to reference specimens. The situation is similar for most groups, supporting the idea that the total number of species will never be known!

Species communities can be described according to large habitat types or their biogeographic affinities. As an indication, the few hundred species that have been recorded to date represent 63 families and 185 genera unevenly distributed among the three major divisions. Red algae account for more than half of the species, followed by green algae, with a very strong dominance of Bryopsidales, and brown algae, which account for less than one-fifth of the species, but represent the largest biomass. Nine families account for more than half of the species, while many others have a small number of representatives. In addition, many species are relatively rare. The biological and ecological scarcity that have been reported for fish, mollusks and other invertebrates appears to be a rule. Similarly, endemism in algae is less than 3%, which is similar to most other biological groups.

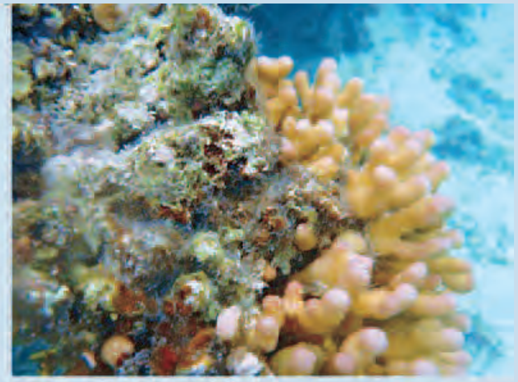
Box 12

Similar… but different!

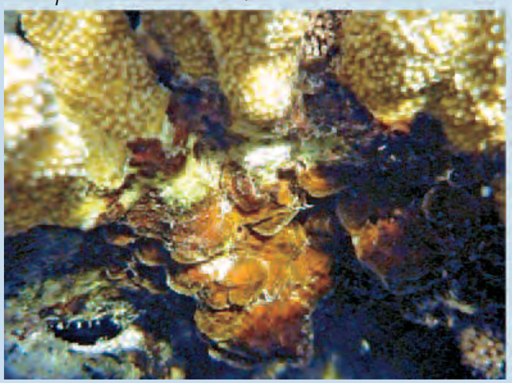


Lobophora rosacea. © IRD/C. Vieira

L. hederacea. © IRD/C. Vieira



L. hederacea. © IRD/C. Vieira



L. hederacea. © IRD/C. Vieira

L. hederacea. © IRD/C. Vieira

L. obscura. © IRD/C. Vieira

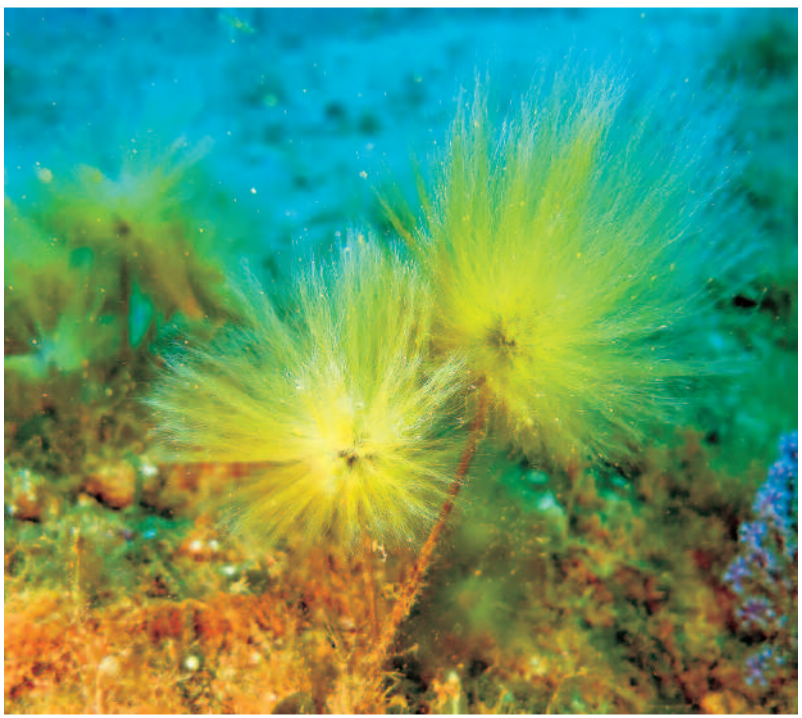
The identification of biological diversity units is essential in fundamental ecology, for the quantification of biodiversity, but also for conservation biology. However, this identification is made difficult by the presence of cryptic species, which are species that are genetically distinct but morphologically similar.

The development of molecular biology has led to the discovery of a particularly important cryptic diversity in the marine environment. This cryptic diversity is only starting to be explored in marine algae. For example, more than a hundred species were hiding under the name *Lobophora variegata*, a small brown alga growing in coral reefs and assumed to be present in all warm seas.

The situation is similar for the red algae *Portieria hornemannii,* which in fact includes over 90 distinct genetic entities. The recent discovery of this cryptic flora calls for a re-evaluation of the algal biodiversity, particularly in tropical regions where this interspecific biodiversity reaches its maximum.

When geological history and geography govern diversity

Mediterranean Sea, yet for a much smaller area. There are several reasons for this. First is the proximity of the coral triangle (Philippines, Indonesia, and Papua New Guinea), an area that concentrates the world's highest marine biodiversity. Second is an exceptional diversity of habitats with more than 150 geomorphological units. Last is the oceanographic and climatic context, with a gradient ranging from tropical to subtemperate, or even temperate, from north to south. Although the southwest region is influenced by cold-water upwelling, the water temperature at the coast is a few degrees higher. As a consequence of this geographical and climatic setting, the Loyalty Islands share less than 25% of their macroalgae species with the rest of the archipelago, but have a very strong affinity with the flora of Vanuatu, the Solomon Islands and Papua New Guinea. In contrast, the Southern Lagoon, which includes Isle of Pines and Corne Sud, harbors species, characteristic of subtemperate coral reefs, which are also recorded from Lord Howe Island and the west coast of Australia. Some genera, such as *Melanthalia*, a large red macroalgae, have a distribution restricted to the south of New Caledonia, the south of Australia, and the north of New Zealand. This sub-regional endemism has been interpreted as a vestige of Gondwana.



Bellotia simplex described from the bay of Saint Vincent, west coast of Grande Terre. Woodin Channel, 2015. © IRD/J.-L. Menou

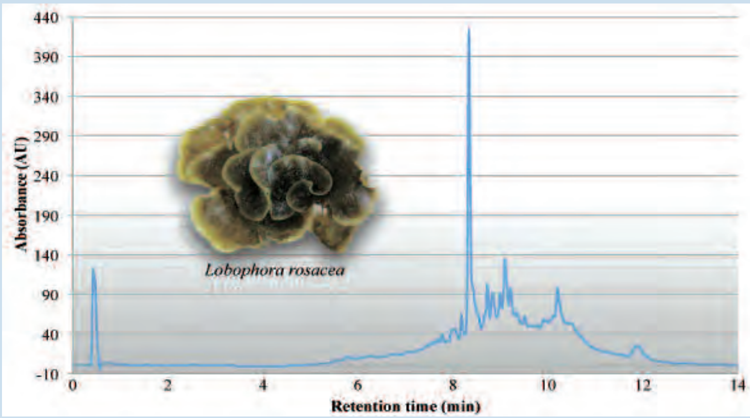
Each region of the New Caledonian archipelago has a few characteristic taxa that are only found there. The genus *Penicillus*, a brush-like green algae, has only been observed on the sandy bottoms of the Chesterfield atolls; whereas *Apjonhia*, a fir-shaped green alga, is only found at the Isle of Pines. The order Sporochnales (e.g., *Bellotia, Nereia*) testifies for the similarity of the New Caledonian and Australian marine flora. They are very elegant brown algae with small pompon-like tips and a slimy touch, very diverse in genera and species, and which are found in bays rich in terrigenous sediments. There is also a whole selection of species in common with the Ryukyu archipelago in southern Japan. Most of these species, which prefer shallower habitats in Japan, develop in deeper habitats (30 m) in New Caledonia, where they find a matching water temperature. The best example is *Padina stipitata*, which grows at the Gail Bank south of Grande Terre, and whose DNA sequences are strictly the same than those of specimens from the type locality in Japan.

The taxonomic data available for the Pacific is too fragmented to draw conclusions about the exact limits of the geographic range of algal species. However, results of molecular phylogenetic studies, carried out for some groups, show that the New Caledonian marine flora belongs to a Southwest Pacific biogeographic region, which includes the Coral Sea to the west and, the Melanesian arc to the east, stretching from the Solomon Islands to Fiji. New Caledonia also shares part of its biodiversity with other regions in the Pacific Basin.

In order to explain its exceptional biodiversity, one must go back in time to periods when sea level was lower. At that time, it is likely that the New Caledonian archipelago was a biodiversity refuge, similar to the coral triangle, where numerous coral reef species accumulated over time.

Box 13

A complex chemistry, a fragile equilibrium



Metabolomic profile of the brown macroalgae *Lobophora rosacea*, a common species in the lagoon of New Caledonia, often associated with branching corals. @ IRD/C. Vieira

Within coral ecosystems, interactions are widely mediated by chemicals, especially between benthic organisms. Marine animals use chemical signals, for example in the regulation of social and reproductive behaviors, or for the recognition of food. In order to avoid, minimize or tolerate the damages caused by herbivores, macroalgae have adapted to reduce their attractiveness, and chemical defenses are one of the most common strategies used by tropical algae. With their arsenal of chemical substances, macroalgae can create a chemical barrier against aggressors (herbivores, bacteria, epiphytes, and pathogens), but they can also use them as a “weapon” while competing for space with other benthic organisms such as corals, particularly when the ecosystem is weakened by disturbances. Like in corals, chemical interactions play an important role in the reproduction and recruitment of algae. However, this is only the visible part of the iceberg, and further research is needed to understand the biological and ecological functions of chemical compounds in macroalgae.

Good or bad algae?

Macroalgae are often wrongly associated with environmental degradation. As mentioned above, they are so essential to the system that it would be more accurate to call these ecosystems “algo-coral” reefs. However, ecological imbalance sometimes leads to the abnormal proliferation of some algal communities, which can, in some instances, take over living corals. Are algae the cause or the result of coral disappearance? This is a major question in the context of global change, and as the international community is warning about the regression of coral reefs. The community changes that have been described in many parts of the world seem to have spared the New Caledonian coral reef ecosystem, but for how long? Human populations and their activities at the coast are increasing.

While the coral reefs of New Caledonia still are in a good (even excellent) health for the majority of them, near peri-urban areas, reefs show some stigmas of degradation. In some instances, these stigmas are biological interactions between algae and corals to the detriment of the latter. Algae have much higher growth and reproductive capacities than corals. When for various reasons coral colonies die, a new substratum is available for algae to colonize. Coral bleaching, coral diseases, and smothering of coral polyps by terrigenous particles are all causing coral death. If environmental conditions have changed to a point that algal growth is promoted, the coral recruitment will be affected, and then, algal blooms may be associated with reef degradation (box. 13).

However, there are no good or bad algae; they all have a role and function in coral reef ecosystems. Like all other organisms, they have, during their own evolutionary history, developed functional biological traits that allow them to live in their specific environment. Algae are an invaluable reservoir of bioactive substances. The way they interact with their environment is not easy to comprehend, but chemical ecologists have shown that these substances are pathways of communication for biological interactions. Many Dictyotales produce polyphenols that keep predators at bay, others cause the death of coral polyps, such as *Lobophora hederacea* in New Caledonia.

While some red calcareous algae are known to kill the corals with which they compete for space occupation (e.g., *Pneophyllum conicum*), others from the same group (*Titanoderma*) play an important role in the fixation of coral larvae. The mechanisms that are involved are not well known, but there could be a production of attractive molecules.

Algae, a source of inspiration

With an estimated thousand or more macroalgal species, the lagoons and reefs of New Caledonia provide an exciting playground for phycologists. Since the early work of missionaries and amateur naturalists in the late 19th century important knowledge has been accumulated. Different aspects of this diversity have been revealed throughout various disciplines and methodological approaches. Adding on to the taxonomic work needed to understand what is being protected, other studies have shed light on the issues surrounding the future of these communities in the context of global change. At present, phycologists (box 14) investigate the evolutionary history of macroalgae, analyze their biological interactions with other reef organisms, and also look for molecules of interest to man in this reservoir of complex substances produced by algae to grow, defend and reproduce.

Box 14

Etymology

Scientists who study algae are called “phycologists”, and not “algologists” who study the science of pain! In English, “algae” comes from the Latin “algae”, while “algologist” and “phycologist” come from the ancient Greek. In Greek “algos” means “pain” (e.g., also found in “analgesic”), “phycos” means “algae”, and “logos” means “study or knowledge” (e.g., also found in “musicologist”).

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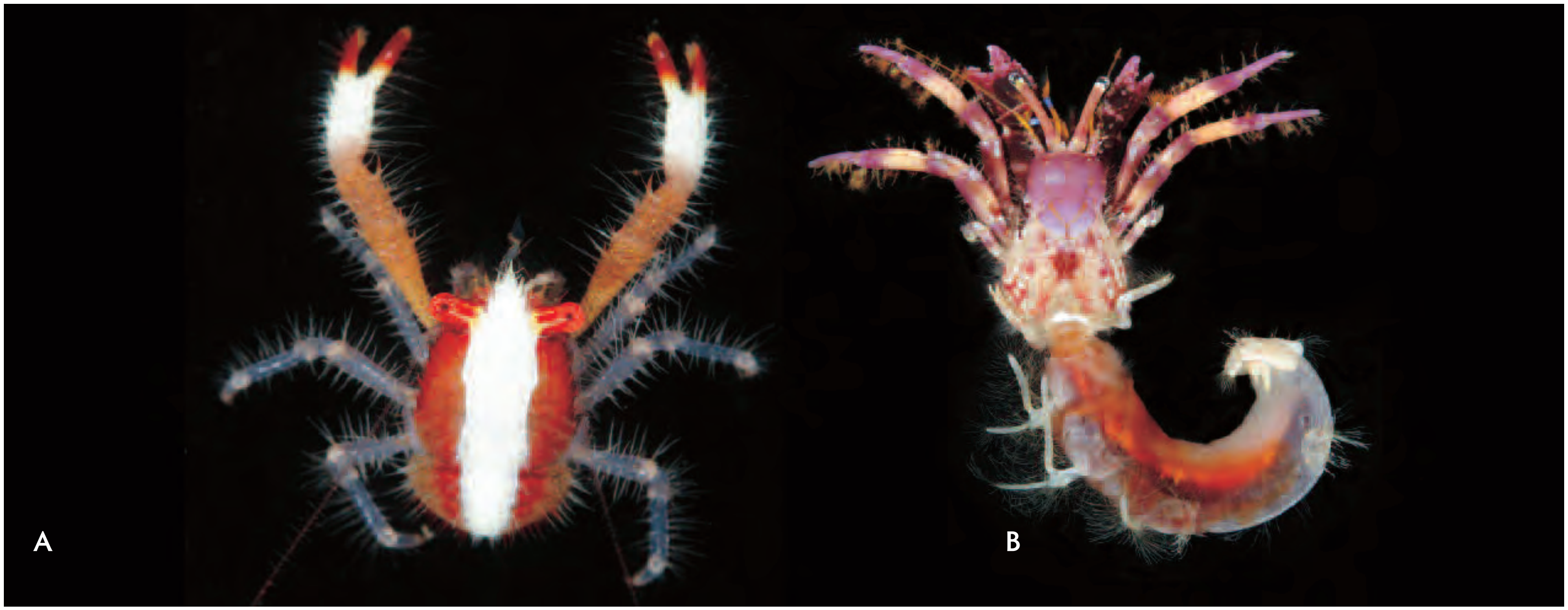
Chapter 10

Marine invertebrates of New Caledonia

Gustav Paulay



A: *Galathea n.* sp., yet another *Galathea* species from New Caledonia.
B: *Calcinus spicatus*, a southern subtropical endemic; the species ranges from New South Wales to the Gambier Islands. © G. Paulay

Unsuspected biodiversity

The marine biota of New Caledonia is one of the best studied and most diverse in the Pacific, with over 9,000 species recorded in the literature. However much of the work has focused on deep water, while reef organisms have been less investigated.

Focused faunistic and systematic studies nevertheless demonstrate that New Caledonian reefs are among the richest in Oceania. For example, until recently only 4 species of the squat lobster genus *Galathea* were recorded from New Caledonia, but a 2015 study increased that to 34 species, more than from any other region of the world. Yet half of the New Caledonian species are deep water, even though the greater diversity of the genus is at reef depths, again suggesting that even more diversity remains to be documented, as new work is demonstrating. The New Caledonian reef biota is also remarkable for its diverse biogeographic relationships and significant endemism.

An exceptional habitats diversity

Reefs hold the greatest diversity of marine life because their structural complexicity provides diverse microhabitats that support a bewildering variety of organisms. Reefs are already complex on a microscale – a single dead coral head can harbor hundreds of animal species. Large reef systems add to this complexity on several scales, as different exposures, depth, distance from oceanic waters and land, etc. create a mosaic of environments. Habitat and species diversity thus rapidly increases with reef size and complexity.

With the second longest barrier reef in the world, New Caledonia is one of the great marine diversity hotspots. Regional reefs range tropical to subtropical waters from oceanic reefs to muddy lagoons under terrigenous influence. The complex geology of Grand Terre creates unique and unusual habitats that harbor striking marine life. Muddy lagoons are home to fluorescent corals literally float on (boxes 6 and 7), and soft corals and sponges rooted in, the sediment, while cowrie shells are deformed and melanistic, perhaps because of the impact of heavy metals leaching from ultramafic bedrock. At the other extreme, reefs around limestone islands like Mare and the oceanic d'Entrecasteaux Reefs are at the oceanic end of the reef spectrum. The diversity of reef habitats is greater here than anywhere in Oceania outside New Guinea.

The link between biodiversity and latitude

In addition to habitat size and diversity, geography and age are important drivers of diversity. Diversity in the Pacific changes markedly with both latitude and longitude. Across longitude, diversity in the world ocean peaks in the Indo-Malayan region of the west Pacific, decreasing eastward across the Pacific. New Caledonia lies close to this global diversity center.

The inverse relationship between diversity and latitude is the most striking biogeographic pattern on Earth. The tropics hold the greatest diversity, but most tropical species range broadly between the Tropics of Cancer and Capricorn and there is little differentiation in diversity within this zone. However, around the Tropics an additional, subtropical fauna makes its appearance, and many species are restricted to a narrow latitudinal belt here. New Caledonia is at the crossroads of these two great biotas and enriched by species from both. It hosts a full tropical, Indo-Pacific fauna, as well as species that live only in a narrow band from subtropical Australia out to the Pitcairn and Easter Islands (e.g., *Calcinus spicatus*, a south Pacific subtropical endemic). A portion of this subtropical biota has an antitropical distribution, leading to interesting connections with the northwest Pacific, Japanese regional biota.

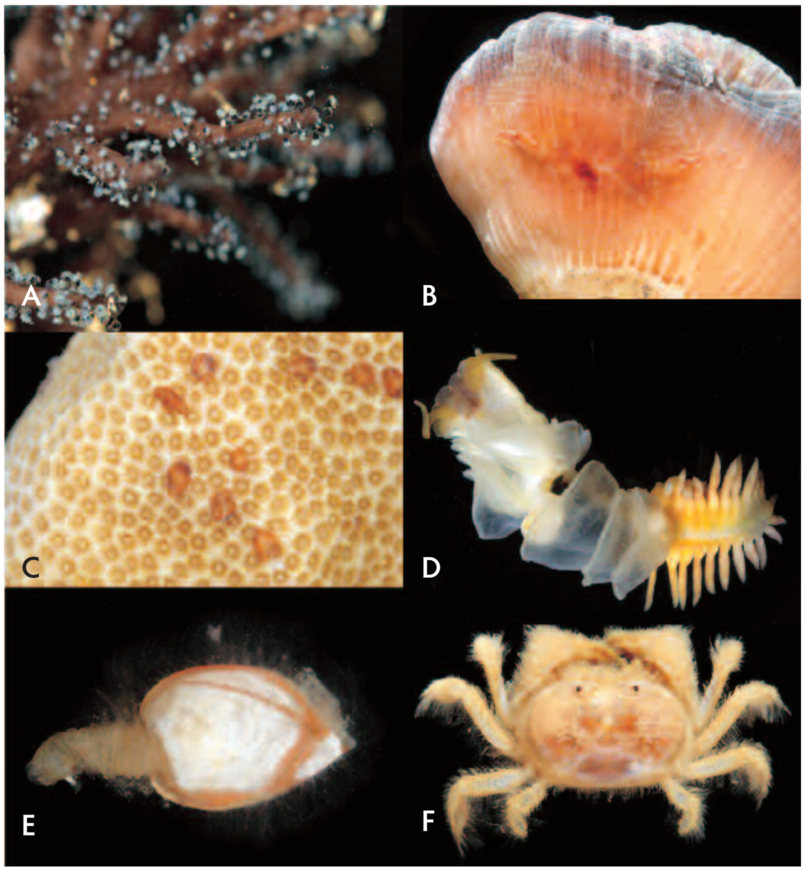
Hidden biodiversity

Diversity tends to accumulates with time – young ecosystems are not as rich as old ones. New Caledonia is the only tropical microcontinent in Oceania, a fragment of Gondwana that predates the oceanic islands of the Pacific. While the island has undergone submergence, it has been emergent since the Oligocene and shallow water habitats likely have persisted in the region since the Mesozoic. The impact of age in driving the high diversity and endemism of the land biota of New Caledonia is well appreciated. The occurrence of numerous old endemic lineages (especially well demonstrated in the deep-water biota) suggests age is also important in the sea. The Great Barrier Reef system itself is a product of age and stands in contrast with the limited reef and habitat diversity surrounding the young volcanic islands of neighboring Vanuatu.

Marine endemism remains poorly explored around New Caledonian reefs. There are some highly conspicuous endemics, such as the sea cucumber *Holothuria altaturricula*, but overall the level of endemism is modest (~5% in shallow-water sea cucumbers). However, the revolution in molecular taxonomy has shown that many species that we thought were widespread are complexes of short-range endemic forms missed by previous taxonomists. For example, genetic work has shown that the gastropod *Astralium "rhodostoma"* in New Caledonia, is two species, both of which are endemic to the island.

Symbiosis is a major source of diversity in all ecosystems, and especially on reefs. Hosts are diverse, with the abundance of large sponges, cnidarians, echinoderms, and tube-builders like chaetopterid polychaetes. Some of the most diverse taxa in New Caledonia are symbiotic, such as galatheoid crabs, eulimid gastropods, and galeommatoid clams. Symbionts also include such unusual animal groups as acoels, ctenophores, and entoprocts. The polychaete genus *Chaetopterus* is more abundant and diverse in New Caledonia than anywhere I have seen in the tropics; one of its symbionts, *Tetrias fischerii* was described from Nouméa and known until now only from a single dried holotype, yet it is one of the most common crabs around Nouméa.

Much work remains to be done to document and understand New Caledonian reef biota. Few reef areas in the world provide as much reward in discovery and excitement as this area, making research in the area highly rewarding.



Unusual symbionts.
A: *Loxosomella n.* sp., an entoproct on a sponge.
B: The benthic ctenophore *Coeloplana n.* sp. symbiotic on the coral *Trachyphyllia geoffroyi*.
C: The acoel *Waminoa* on Porites.
D: The tube-dwelling polychate *Chaetopterus luteus* outside its tube.
E: *Dianajonesia* sp. a stalke barnacles symbiotic on *Nautilus macromphalus*.
F: *Tetrias fischerii* a pea crab symbiotic with *Chaetopterus*. © G. Paulay

Examples from the rich galeommatoidean bivalve fauna of New Caledonia. These small, typically symbiotic clams, are the most diverse group of bivalves in New Caledonia. © G. Paulay

Chapter 11

The exceptional mollusk diversity of New Caledonia

Philippe Bouchet

Nautilus macromphalus is endemic to New Caledonia and belongs to a group of cephalopods that are often referred to as "living fossils". Currently, there are five species of *nautilus*. They live in deep water and rise up to the surface at night along the outer slope of the barrier reef, Chesterfield, 2015. © IRD/C.E Payri

Coral reefs are often compared to tropical forests: they are the two most species rich and extensive ecosystems on Earth. In terms of numbers, coral reef species are mostly invertebrates. To date, at least 9,000 invertebrate species have been recorded in the coastal marine ecosystems of New Caledonia. This exceptional biodiversity can be discussed using the following keywords: richness, rarity, singularity and endemism.

Biodiversity richness

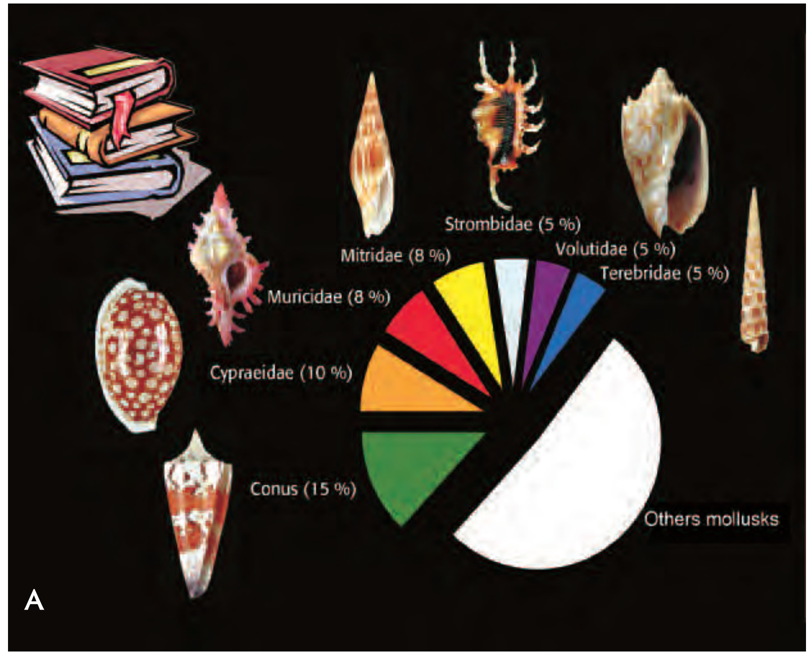
Besides corals, mollusks and decapod crustaceans are undoubtedly the most documented groups in the reefs and lagoons of New Caledonia. Between 1975-2000, echinoderms, gorgonians, ascidians and sponges were targeted by research programs looking for natural substances. Although parasites are still only patchily known, a model study has specifically targeted the parasites - particularly helminths (monogeneans) - of groupers (Serranidae).

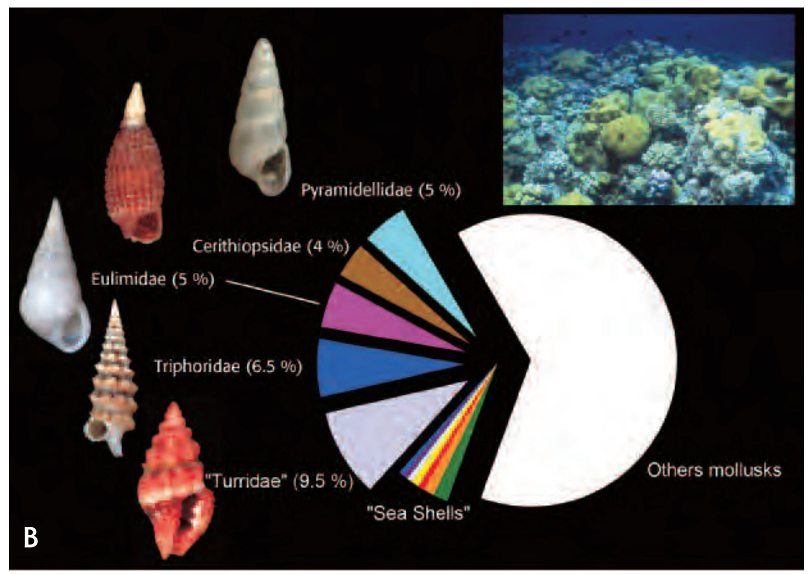
At four sites in particular – Koumac and Nouméa (west coast), Touho (east coast), and Lifou (Loyalty Islands) – mollusks have been intensively sampled using unconventional tools such as suction samplers and brushing baskets. These tools are only effective for the collection of small cryptic fauna, which then requires monumental sorting effort. The Koumac case study, which required the equivalent of 400 person-days of work, has become a gold standard in macro-ecology. It has documented a total of 2,738 morphospecies of mollusks over an area of 29,500 ha: a "world record" of the number of species for a single tropical marine coastal site. However, this number better reflects the intensity of sampling and sorting efforts than an exceptional richness in local species. The same methods applied to sites in Vanuatu, Papua New Guinea and the Philippines produced comparable, or even larger, figures. Most of the species are small or very small: only 10% have an adult size of 40 mm or more (and represent what is commonly known as "seashells"), while a third are less than 4 mm at their largest dimension.

An abundance of rare species

The study carried out at Koumac highlighted an important spatial heterogeneity, with 32% of the species found at only one of the 42 sampling sites. It also emphasized the large proportion of rare species: 20% of the species were represented by only one specimen, and 48% by 5 or less. The real number of species present at the Koumac site was estimated between 3,500 and 4,000 by statistical analyses.

These phenomenal figures can be explained by the extreme diversity of specialist groups such as commensals, associates and parasites. While guides for shell collectors classically depict miters, strombs, auger snails and cones, these represent under 10% of the mollusk diversity on coral reefs. Most of the diversity is actually made of Eulimidae (echinoderm parasites), Triphoridae and Cerithiopsidae (sponge eaters), Pyramidellidae (ectoparasites of other invertebrates) and turrids (polychaetes hunters).



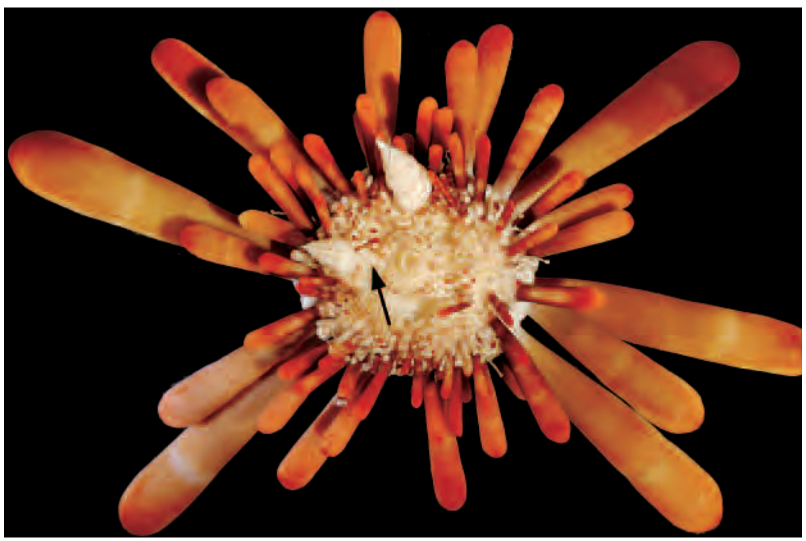


Mollusks and seashells are often erroneously seen as equivalent.
A: Numerous guides present a biased view of mollusk diversity, and only show cones, cowries, miters and conchs.
B: In fact, most of the mollusk diversity is found in families of microgastropods - commensals, associates and parasites. © P. Bouchet

Singularity

New Caledonia stretches over five degrees of latitude and the windward and leeward coasts of Grande Terre are strikingly different. The windward coast is drained by short but fast rivers carrying terrestrial sediments and has a very fragmented barrier reef enclosing a deep lagoon. In contrast, the leeward coast is drained by slow flowing rivers and has a more continuous barrier reef, with only a few passes, enclosing a shallow lagoon. In contrast, the Loyalty Islands, and the Bellona and Chesterfield reefs have no lagoon (with the exception of Ouvéa), no barrier reef, and no rivers. This means that there are significant differences between the two coasts of Grande Terre and those of the separate islands and reefs, which are reflected in the faunal composition of their coastal ecosystems.

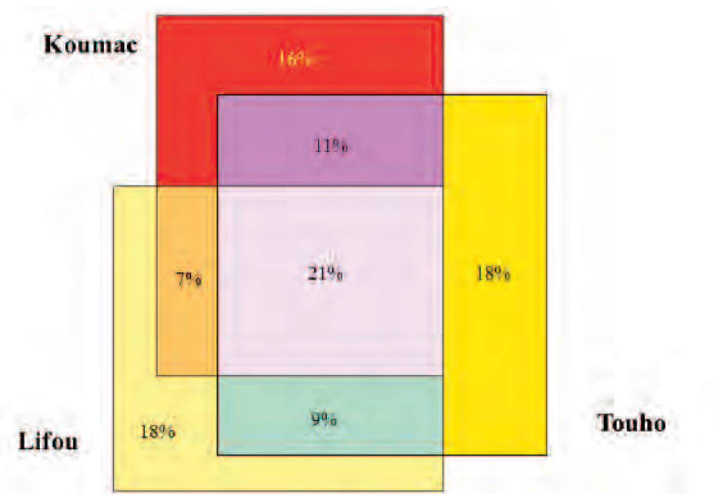
Thus, only 21% of species are common between the three sites of Koumac, Touho and Lifou, and 52% of species are present only at one of the three sites. In addition to species richness, which is very high at a local scale, geographical disparity also, in this way, is a major contributor to the exceptional diversity of the reefs of New Caledonia.



All the species in the family Eulimidae are echinoderm parasites – temporary or permanent, external or internal. All echinoderm classes have their own parasites. Here, a species of the genus *Echineulima* on a sea urchin of the genus *Heterocentrotus*. Note the sexual dimorphism, with the male (indicated by an arrow) distinctly smaller that the female. © W. Rudman

A low level of endemism

New Caledonia, like the high islands of French Polynesia, is famous for the high level of endemism of its terrestrial fauna and flora: 40 to 100% depending on taxa. In comparison, the level of endemism of coastal marine invertebrates is extremely low: probably less than 5% and maybe only 2-3%. The intensity of research carried out in New Caledonia has meant that a large number of species are known only because they have been found there and it would be tempting to consider them as New Caledonian endemics. However, much less effort has been made to make inventories of the neighboring archipelagos and reefs in the region, which suggests that this apparent endemism is not a reflection of reality. For example, Alberto Cecalupo and Ivan Perugia described 64 new species of Cerithiopsidae snails found on the reefs of New Caledonia (box. 15), but it would be misleading to consider these 64 species as endemic in the absence of comparable studies for the Solomon Islands or the Australian Great Barrier Reef. If we only consider species whose distribution is significantly restricted to New Caledonia, it is still possible to identify some real endemics, and even micro-endemics.



Do not put all your eggs in one basket! This is the lesson learned from the comparison of three sites that were very thoroughly sampled at Koumac (west coast), Touho (east coast) and Lifou (Loyalty Islands). Of 1,711 species of mollusks belonging to 17 families, only 21% were found at all three sites, while 52% were found at one site only. This evidence challenges the idea of a "representative site" which has no scientific basis and has consequences for the planning of management strategies for protected areas. © P. Bouchet

For example, the distribution of the volute *Cymbiola rossiniana* ("the volute of the Isle of Pines") is limited to the reefs of New Caledonia located between the Isle of Pines and Nouméa. Similarly, *Cymbiola deshayesiana* has a distribution limited to the Northern Lagoon (Grand Lagon Nord), and *Cymbiolacca thatcheri* and *Lyria grangei* are endemic to the Chesterfield Atolls in the middle of the Coral Sea. Volutes are characterized by an intracapsular larval development, without a planktonic dispersal phase, which explains why four out of the five New Caledonian volute species are endemic with (very) restricted distributions.

In other well-inventoried gastropod groups, 13 of the 150 Muricidae species (or 8.5%) recorded in New Caledonia down to a depth of 100 m, can be considered endemic. In contrast, only two of the 93 species of cones (Conidae) and none of the 69 species of cowries (Cypraeidae) recorded from New Caledonia are endemic.

However, this low level of endemism must be considered with care as most New Caledonian reef species are described and identified based on a morphological approach only. Once sequenced, species known to have a large geographical distribution will likely prove to be species complexes, some with more restricted or even endemic distributions.

After 40 years of continuous research into New Caledonia's marine fauna and flora, the glass of species inventory and description is half full. The archipelago attracts scientists from all over the world for the richness and integrity of its lagoon and reef ecosystems: one square kilometer of lagoon and reef ecosystems in New Caledonia contains more species than the entire Mediterranean! However, the glass is also half-empty: the actual number of species present in New Caledonia is probably 5 to 10 times greater than the 8,000 invertebrate species already inventoried, and there is still much to be done to better understand this incredible abundance of species.

Particularly sought out by collectors, melanistic and rostrate cowries are the emblematic seashells of New Caledonia. The processes of melanisation and rostration only affect certain individuals, to varying degrees, and only in the Southern Lagoon of Grande Terre. It has been suggested that nickel, or winter temperatures could be responsible for these processes, but these hypotheses have not yet been tested scientifically. Melanistic and rostrate specimens (right), and "normal" specimen (left) of *Bistolida stolida*. © F. Lorenz

Suction sampler and brushing basket: two unconventional tools operated by scuba divers, which are very efficient for sampling small benthic organisms on hard and soft bottoms. © Right Reserved

Conus omaria (the feather cone) is a carnivorous predator (right) that feeds strictly on mollusks with a preference for conch (left). It catches its preys by projecting a sting connected to a gland filled with a very powerful venom. The cone then swallows its prey with a large proboscis and digests it slowly using enzymes it secretes. Chesterfield, -15 m, July 2008.
© IRD / J.L. Menou

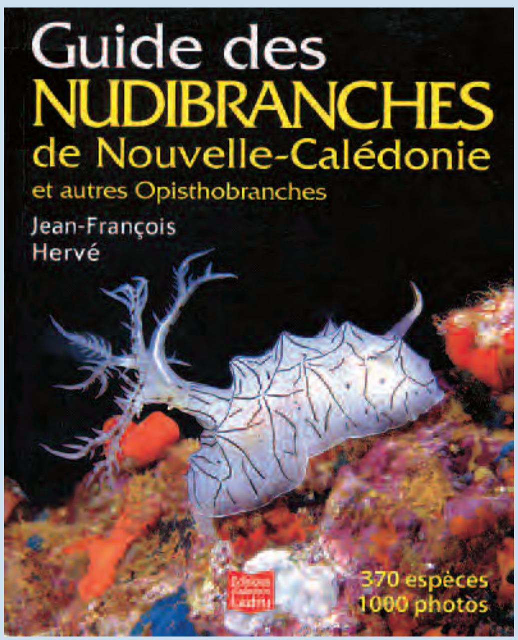
Box 15

The role of citizen scientists

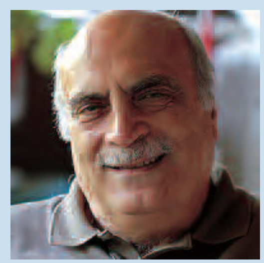
In marine biology, entomology or botany, amateurs play an essential role in the inventory and description of biodiversity. Some groups are more favored than others, and it is fair to say that mollusks have attracted a significant part of non-academic taxonomic expertise. We live in an era where people are generally more educated, have more time for hobbies, and have easier access to scientific literature through the Internet. Even scanning electron microscopy has become more accessible, and molecular tools are probably the only techniques that are beyond the reach of amateurs.

As a consequence, vocational amateur taxonomists exist for all biodiversity groups: mollusks of course, but also crustaceans, echinoderms, bryozoans and even hydrozoans.

An amateur malacologist is not a "shell collector", even though many may have started by collecting shells. Like a professional academic researcher, an amateur creates new knowledge and publishes results in scientific journals. Like a professional academic researcher, an amateur taxonomist often specializes in the study of a particular family, and the description of new species ignites his or her passion. Between 2000 and 2015, 57% of the new marine mollusk species worldwide were described by amateurs. If we consider the low institutional and programmatic support for biodiversity inventories, it is clear that the role of non-professionals must be recognized and encouraged.



Nudibranchs are one of the favorite attractions for scuba divers, some of whom become experts on the group. The author of the guide to the sea slugs of New Caledonia (*Guide des Nudibranches de Nouvelle-Calédonie*) is a medical doctor in Nouméa. Before him, and before scuba diving existed, Jean Risbec, a mathematics teacher at Lapérouse high-school, had been studying nudribranchs in the 1930s. The species *Verconia catalai*, which was described from New Caledonia but is not endemic, was named after René Catala, the founder of the *Aquarium des Lagons*. © J.-F. Hervé.

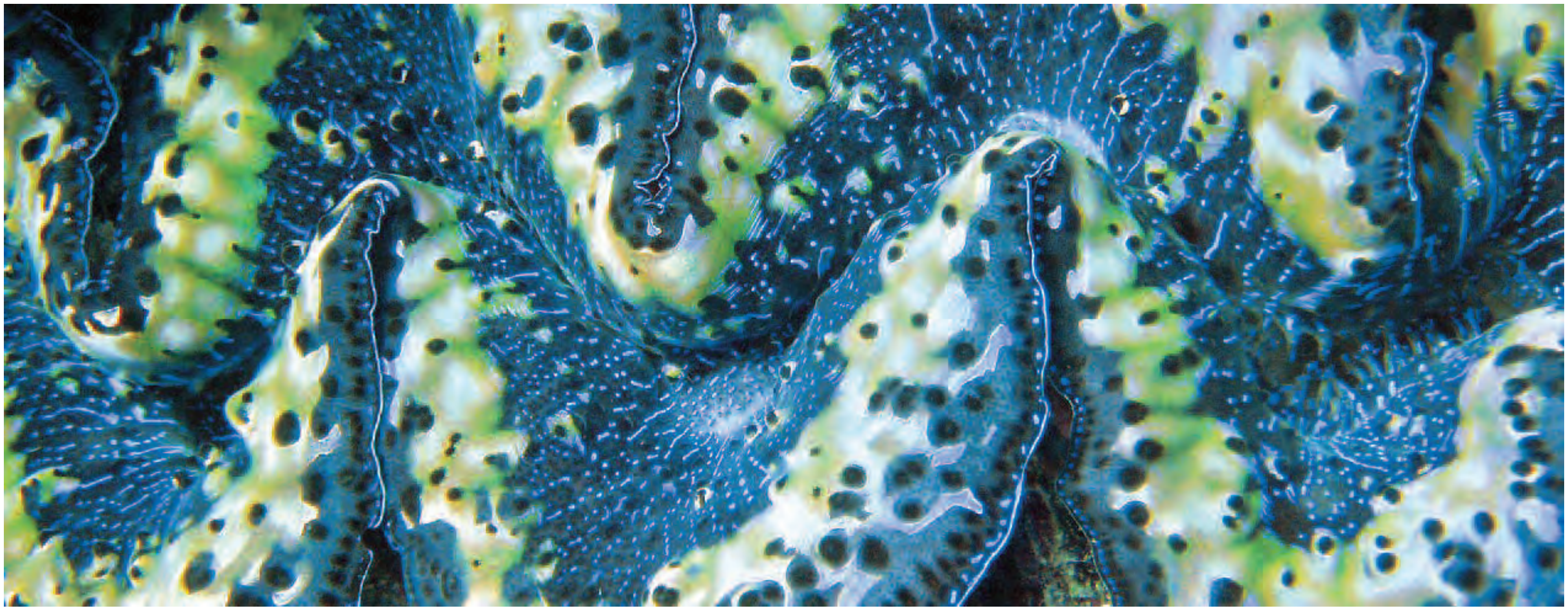


Malacology (the study of mollusks) has the support of a community of high-level amateurs who, like professionals, publish on complex and specific topics. Before retirement, Alberto Cecalupo was a car dealer and Ivan Perugia was a climate engineer. Since they retired, the duo has become the leading experts on Cerithiopsidae, a family of minute sponge eating gastropods. In 2017, they published a regional monograph of New Caledonian species, including the description of 64 species new to science.
© A. Cecalupo and I. Perugia

Chapter 12

Giant clams: jewels of New Caledonian reefs

Cécile Fauvelot, Philippe Borsa, Serge Andréfouët, Josina Tiavouane, Simon van Wynsberge and Pascal Dumas



The shimmering colors of giant clams are due to microalgae that live their mantle. *Tridacna maxima*. © IRD/S. Andréfouët

Massive but relatively little-known seashells

Giant clams are marine bivalve mollusks (class Bivalvia[2] like oysters, mussels, clams, etc.), which live in the warm coastal waters of the Indo-Pacific region. They are mainly found in shallow lagoons and on the outer slopes of reefs down to 30 m deep, depending on the species. They contribute to the construction of coral reefs and act as a physical substratum for many reef organisms. Giant clams have long been exploited for their flesh and shells, and they have important economic, food and heritage significance for many communities in the Indo-Pacific region.

Out of the dozen species currently known, seven that belong to two distinct genera are present in New Caledonia: *Tridacna maxima, T. crocea, T. squamosa, T. derasa, T. mbalavuana, T. noae* and *Hippopus hippopus*. Their density and distribution vary widely from one species to another, due to different ecological requirements, but also because they undergo different fishing pressures, as fishermen tend to target particular species and reefs.

[2] Mollusks whose body is protected by a calcareous shell in two more or less symmetrical parts

Tridacna maxima, with a maximum length of 35 cm, is the most common species. It lives in densities of, on average, about a hundred individuals per hectare of reef but because of its relatively small size and because it generally lives embedded in hard substratum, it is fished very little or not at all.

Tridacna crocea (maximum length: 15 cm) has an average density similar to *T. maxima*, but its spatial distribution is highly heterogeneous, as individuals often tend to cluster in particular areas of the reef. This species is small and deeply embedded in corals, which make them difficult to extract; it is not collected in New Caledonia but is harvested elsewhere, such as in Vanuatu.

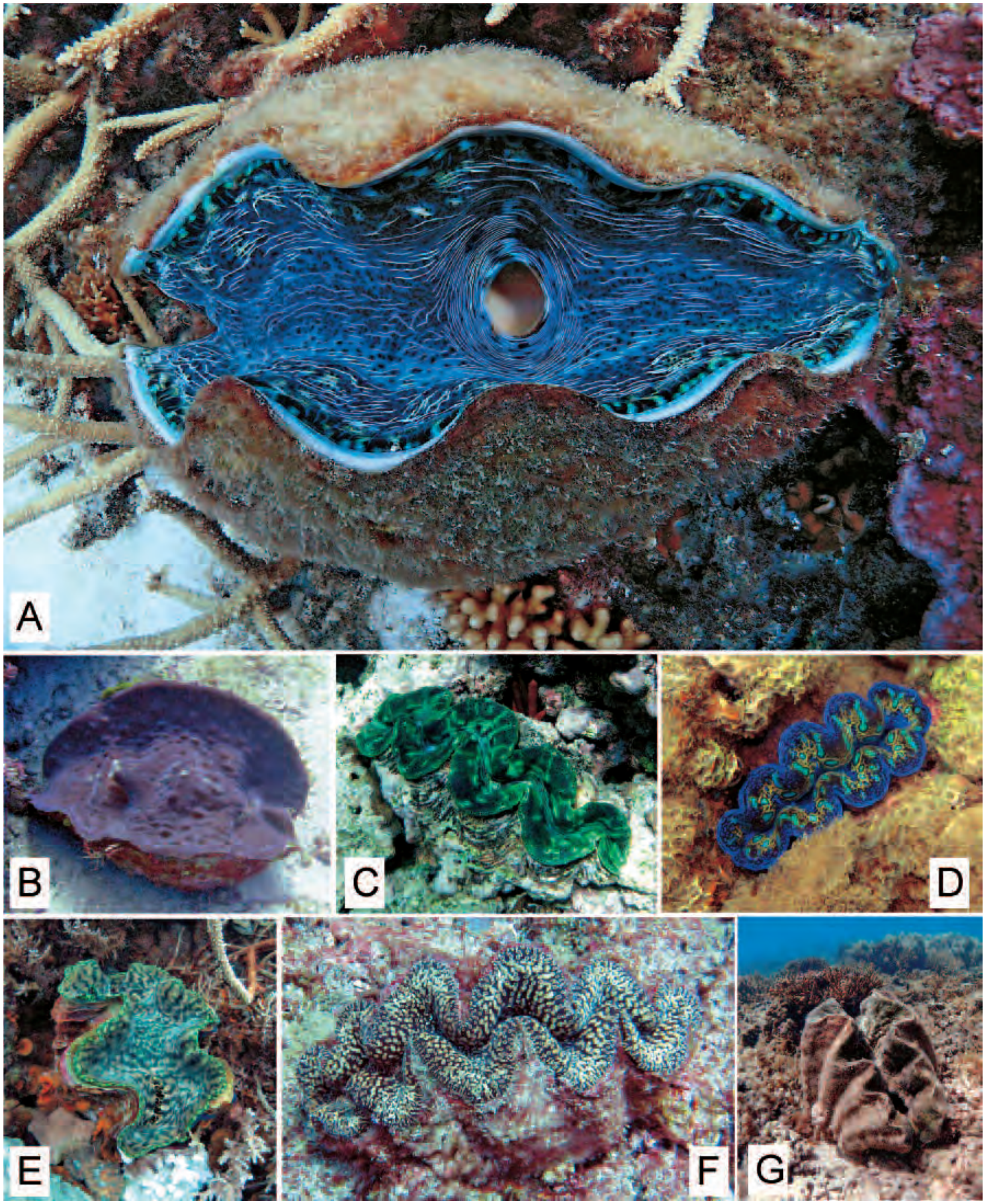
Larger in size (maximum length: 42 cm) and easier to take than the previous two, *Tridacna squamosa* is sought-after by fishermen. Their density is relatively low with only a few individuals per hectare of reef. Even larger and not attached to the substratum, *Tridacna derasa* (maximum length: 60 cm) is highly sought-after by fishermen. As a consequence, it is now rare in New Caledonia (approximately two individuals per hectare). The situation is similar for the "rolling" giant clam (bear paw clam) *Hippopus hippopus* (maximum length: 50 cm), which is also particularly easy to collect because individuals are not fixed to the substratum and they mainly live on shallow and sandy-detritic bottoms. The very low densities that have been observed (less than one individual per hectare) are likely to be the result of overfishing throughout the territory.

Besides these five species, two others have only recently been recorded in New Caledonia. Their distributions are limited to the northeast of Grande Terre and to the Loyalty Islands. *Tridacna noae* (maximum length: 30 cm), is relatively rare and was recently distinguished from *T. maxima* by genetics. *Tridacna mbalavuana* (maximum length: 56 cm) is the rarest species in New Caledonia, with only a few isolated individuals identified to date. Lastly, *T. gigas*, a species formerly present in New Caledonia, is now considered to be extinct and observed only in the form of fossils or sub-fossils.

The ecological importance of giant clams

Like corals, giant clams host photosynthetic unicellular algae called zooxanthellae. Zooxanthellae provide their host with part of the energy necessary for their growth, reproduction and survival. These symbiotic microalgae are also responsible for the shimmering colors of the giant clams' mantle. As with corals, environmental stress can disrupt the symbiotic relationship and lead to bleaching followed by the death of the animal. During their adult stage, giant clams also filter seawater to feed on particles and micro-organisms. The symbiosis with zooxanthellae provides them with the products of photosynthesis (glucose, oligosaccharides, and amino acids) and supplements the nutrient intakes resulting from seawater filtration. Through this process, giant clams filter seawater by absorbing plankton, sediment particles and pollutants and as such, are often seen as good indicators of water quality and of the health of the coral reef ecosystem. In addition, giant clams contribute to the carbon cycle through the absorption of dissolved inorganic carbon and respiration, and through the photosynthesis of their symbiotic zooxanthellae.

Giant clams have a two-phase life cycle, with a pelagic larval phase and an adult benthic phase. Adults are usually attached to the substratum with their byssus or simply rest on the bottom. Giant clams have a hermaphrodite mode of reproduction, where each adult individual has both male and female gonads. Male gametes are released first, followed about 30 minutes later by female gametes, which limits the possibility of self-fertilization. Fertilization takes place in open water within a few hours of gamete release, and embryos turn into larvae after 24 hours, which are called trochophores and then veligers depending on their stage of development. When they start developing a "foot", they become pediveligers and attach to the substratum (about 15 days after fertilization) to metamorphose into juveniles. This larval phase ensures population connectivity (box. 16) and some giant clams can live for several decades.



Giant clam species known from New Caledonia.
A: *Tridacna derasa*, Aboré Reef Reserve.
B: *T. mbalavuana*, Touho Reef.
C: *T. maxima*, Merlet Reserve.
D: T. crocea, Port-Bouquet Reef
E: *T. squamosa*, Prony Bay.
F: *T. noae*, Tiga Island.
G: *Hippopus hippopus*, reserve of Larégnère Islet.
B: © IRD/C. Fauvelot; F: © IRD/D. Grulois;
A, C, D, E, G: © IRD/S. Andréfouët

Emblematic species threatened by overfishing

In the Pacific, the use and consumption of giant clams began shortly after the arrival of the first human populations. This is evidenced by the numerous human artifacts found throughout their distribution range. Prestigious objects and more durable than wood, giant clams have been a popular currency and continue to play an important role in the cultural practices of most Pacific islands. Their flesh, including the adductor muscle, gonads and mantle, is also an important source of protein. Traditionally a subsistence resource, this fishery has gradually evolved towards commercial exploitations, leading to the local extinction of large giant clams in the most populated areas of the Southwest Pacific. The vulnerability of giant clams to overfishing, coupled with uncertain population dynamics (slow growth and erratic recruitment), has led to the decline of most species.

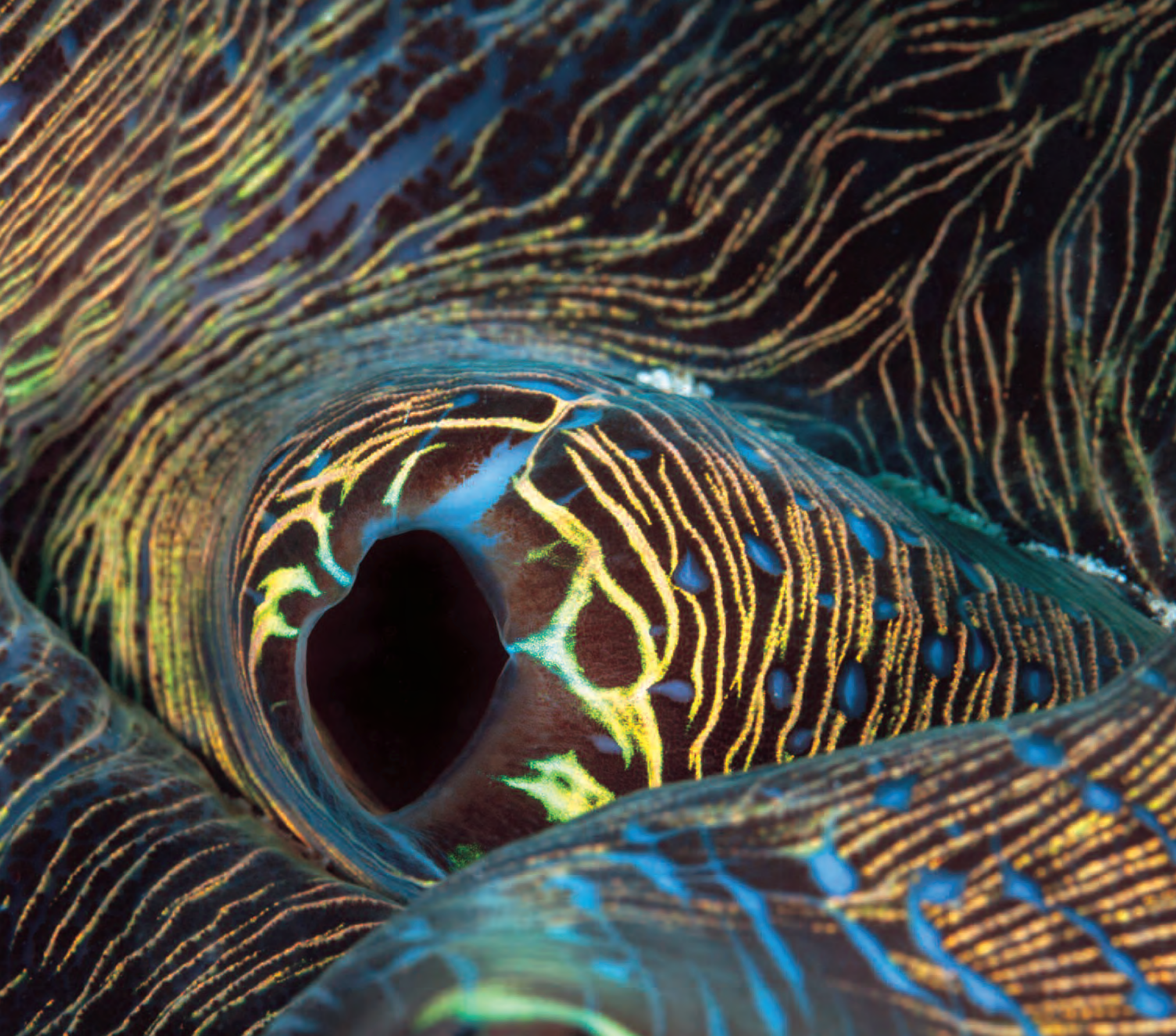
Four of the 12 known species are listed as "vulnerable" in the Red List of Threatened Species established by the International Union for Conservation of Nature (IUCN). Three species are estimated to be "low risk and dependent on conservation" and only one species, T. crocea, is still in the "low risk/least affected" category. Although the remaining four species have not yet been assessed by the IUCN, all giant clams are listed in Appendix II of a convention regulating the international trade in endangered wildlife (CITES, Convention on International Trade in Endangered Species of Wild Fauna and Flora). This indicates that (i) they are not necessarily threatened with extinction, but their international trade must be controlled to avoid certain types of exploitation that would be incompatible with the species' survival and (ii) their international trade cannot take place without a permit.

Giant clams are popular aquarium animals for their colors (the most colorful being *T. maxima, T. noae, T. crocea and T. derasa*) and their role in the filtering of aquarium water and are listed among the 10 marine invertebrates most sought-after by aquarists.

Giant clam fishing is a traditional and widespread activity in New Caledonia. At least two species (*Hippopus hippopus* and *Tridacna derasa*) are commonly used for food and commercial purposes, either consumed directly or sold on markets, or sometimes exchanged through customary practices. Around the year 2000, an average of 4 tons of flesh was fished annually by professional fishermen. This number highlights the significance of giant clam exploitation to supply the local market, but is likely to have been underestimated given the lack of quantitative data on subsistence and recreational fishing. In addition, according to declarations by CITES, the export of giant clam shells remains significant (with over 19,000 shells between 1994 and 2003, mostly *H. hippopus and T. maxima*), although exports have been declining recently. The increase in fishing pressure due to the demographic development of New Caledonia raises serious concerns about the current and future state of the resource. Giant clam populations are showing signs of local overfishing (reduced densities, smaller sizes) in the most visited sections of the lagoon. Several conservation measures have been implemented in New Caledonia to try to manage the activity and stop overfishing (chap. 35).

Pollution and urbanization of the coastline can also affect giant clam populations, as do predation, diseases (viruses) and global warming. Impacts can include the loss of zooxanthellae (bleaching) due to increased water temperature, changes in growth associated with ocean acidification, and increased mortality of juveniles due to the combined effects of ocean warming and acidification. Adults and juveniles are consumed by many predators: the mantle, gametes, eggs are eaten by turtles, octopuses, some fish (triggerfish and wrasses) and some gastropods (families Pyramidellidae and Ranellidae). Boring sponges can weaken the animal by digging small holes in the valves. Lastly, flatworms of the genus *Stylochus* can slip in between the valves, and eat the tissues.

Giant clam's exhalant siphon (cylindrical opening) through which filtered water is expelled. © G. Boussarie



Box 16

Giant clam population connectivity

Population connectivity refers to the flow of individuals of the same species between sites. For fixed marine species such as giant clams, it refers to the flow of larvae that are exchanged between reefs. In New Caledonia, our studies have shown that the populations of giant clams *Tridacna maxima* and *Hippopus hippopus* were genetically heterogeneous, indicating limited connectivity. For *H. hippopus*, the exchange of larvae was limited between d'Entrecasteaux Reefs and the rest of New Caledonia (for sites that have been sampled), as well as between the Loyalty Islands and Grande Terre, albeit to a lesser extent. A higher connectivity was measured for *Tridacna maxima*; this connectivity seems to mainly depend on the geographical distance between reefs. For all species, results indicated that very few larvae originate from reefs outside of New Caledonia, meaning that giant clam populations cannot rely on an allochthonous supply of larvae to repopulate New Caledonian reefs.

Hand-picking of giant clams. © M. Juncker

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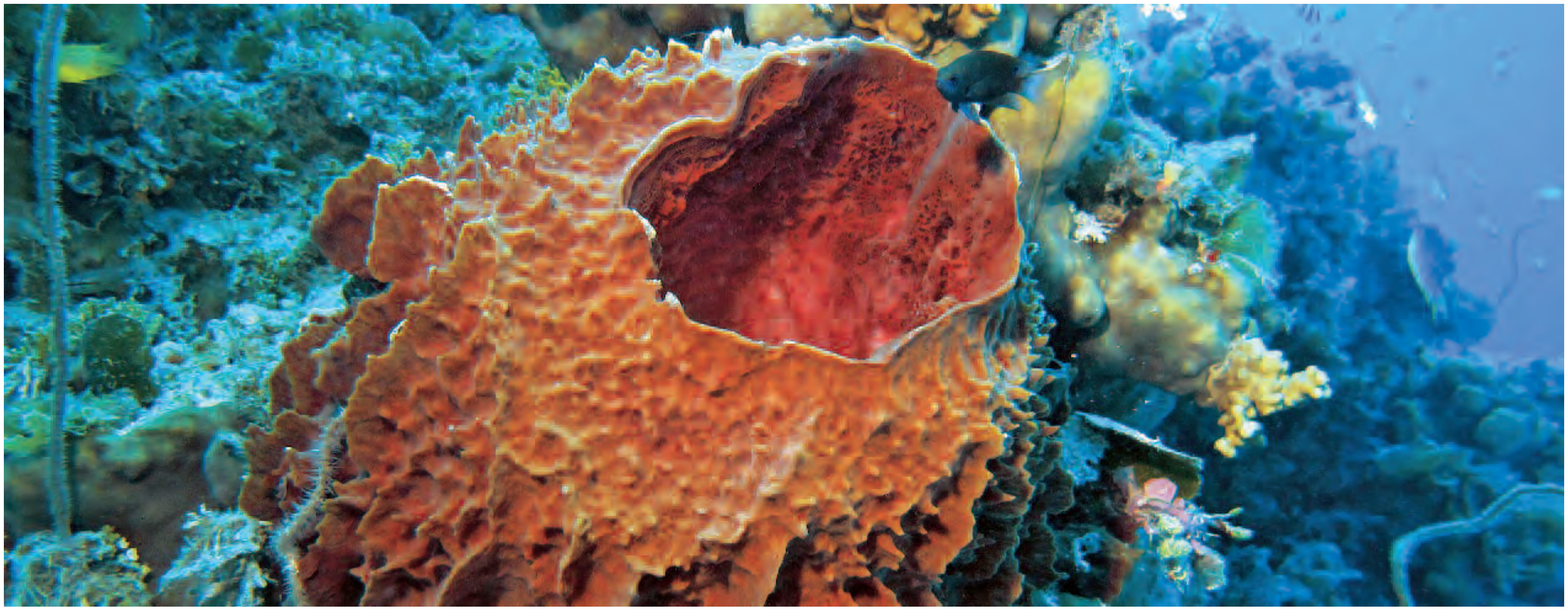
Chapter 13

Sponges: miniature ecosystems within the reef

Sylvain Petek

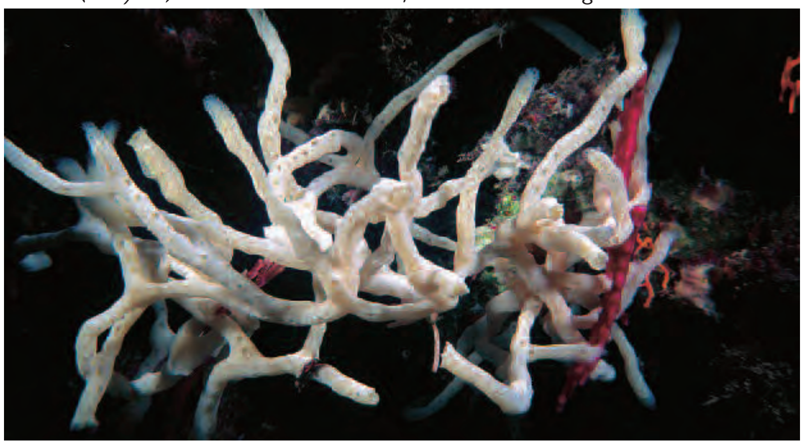


Barrel sponge *Xestospongia* sp., outer reef slope, Chesterfield Islands © IRD/J.-L. Menou

Most divers and snorkelers have observed these colorful and apparently simple animals, probably without knowing what they were. Sponges are still relatively unknown to the general public, with the exception of the traditional bath sponge, which is only the skeleton of particular species. Sponges are widely distributed invertebrates, which inhabit all oceans at all latitudes, from the surface to a depth of 3,000 m. They are among the oldest and most primitive multicellular animals still alive on Earth. The oldest fossils date back to the Cambrian period, 540 million years ago.

Their anatomy is particularly simple, and, unlike most animals, they have no digestive tract, mouth, anus, organs or specialized tissues. They absorb oxygen, nutrients and micro-organisms present in the surrounding environment by filtering water through their pores and can filter several hundred liters of water per day. Sponges are usually attached to a substratum and, for the most part, are unable to move. Their color, texture and consistency vary considerably from one species to another, and their shape varies according to the currents they are exposed to.

Clathria (Thalysias) hirsuta. HOOPER et LÉVI, 1993. © IRD/G. Bargibant



Leiosella ramosa. BERGQUIST, 1995. © IRD/J. L. Menou

Lamellodysidea herbacea. KELLER, 1889. © IRD/E. Folcher

The body of a sponge is like a miniature ecosystem (microcosm). They host many micro-organisms, which can represent up to 50% of their biomass, some of which are symbiotic. The most massive forms also shelter, in their cavities, a variety of mollusks, crustaceans and echinoderms.

Their roles in the reef ecosystem can be very different depending on the species. Some contribute to erosion by perforating coral structures, while others contribute to the food chain. There are some capable of absorbing 99% of the surrounding bacteria and suspended organic matter, and the nitrogen they produce contributes to growth of reef algae. Some species are eaten by turtles, fish, nudibranchs and starfish.

In New Caledonia, about 300 species have been recorded and identified. However, it has been estimated that this is probably only half of the diversity present in the archipelago's lagoons and reefs, most of which could be species new to science. Considering these species, it would raise sponge endemism to 71%.

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Chapter 14

Fishes of New Caledonia unveiled

Michel Kulbicki, Laurent Vigliola, Laurent Wantiez and Gérard Mou-Tham

Fish diversity is highest on habitat-rich reefs, with up to 300 species per hectare. © R.-F. Myers

How many fish in the lagoons?

Reef fish are the most diverse vertebrates on the planet, and New Caledonia has an exceptional number of species (KULBICKI *et al.*, 2013; LABOUTE and GRANDPERRIN, 2016). However, the exact number is unknown as it is difficult to account for all species in a reef. Many species are very difficult to catch or detect, either because they live hidden in reef crevices, because they live in deep waters or because they have a behavior that makes them inaccessible. Furthermore, once caught or photographed, it is sometimes difficult to identify a species with certainty, especially when there are many other species that look similar and species checklists are very heterogeneous. Although the surroundings of Nouméa or Ouvéa have been well explored, the North Province, Maré, Tiga, the Côte Oubliée or the Isle of Pines, as well as most of the distant reefs (Astrolabe, Petri, Durand, Surprises, etc.) have been less documented. However, numerous visual censuses and occasional faunal inventories make it possible to regularly add to the fish diversity of New Caledonia.

The most comprehensive checklist was published in 2011 (FRICKE *et al.*, 2011). It listed 1,740 reef fish species out of a total of 2,343 marine fish species known to exist in New Caledonia. Since then, knowledge has evolved, and the number of known reef fish species is approximately 1,800. The total number will probably never be known but is unlikely to exceed 2,000 species. In comparison, over the whole of Europe, only 900 species are known for the continental shelf (down to 100 m deep) from the north of Norway to the southeastern Mediterranean, an area about 30 times larger than the lagoons and reefs of New Caledonia. This exceptional diversity is directly related to the proximity of the "Coral Triangle" delimited by Indonesia, the Philippines and the China Sea. The highest levels of diversity in the Indian and Pacific oceans is found in this particular region, where diversity exceeds 2,500 species in some areas (Fig. 1).

Moving away from this Coral Triangle, the diversity decreases eastward as islands become smaller and more isolated. A similar decrease is observed north and south towards higher latitudes and as the water temperature cools down. For example, in Tahiti, the number of reef fish species is only 740, in Easter Island it is 148 and in Norfolk, which represents the southern boundary for tropical fauna, there are only 304 species.

The result of history and geography

The underlying reason for the considerable diversity of New Caledonia's reef fishes is essentially historical. New Caledonia is part of the "Southwest Pacific Province" (KULBICKI *et al.*, 2013), which encompasses the southern Coral Sea, the southern Great Barrier Reef, Norfolk, Lord Howe, Elisabeth and Middleton reefs.

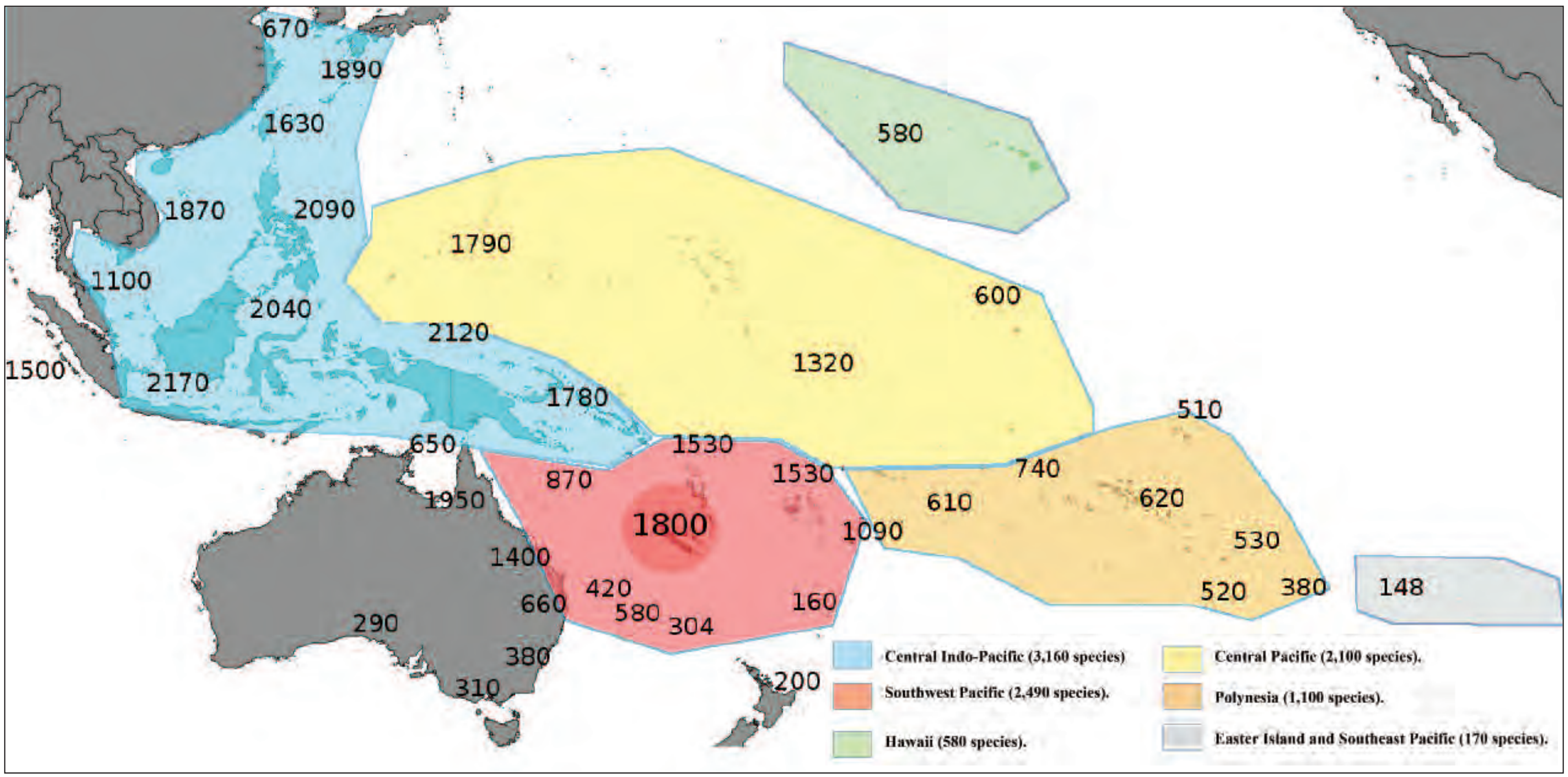

Figure 1: Distribution of the number of reef fish species according to biogeographic zones in the tropical Pacific. New Caledonia is indicated by a red circle.
Adapted from KULBICKI *et al.*, 2013a

The Southwestern Province is adjacent to the central Indo-Pacific region, which includes the "Coral Triangle". The very high number of species in this region (3,160 species) and province (2,490 species) has been linked to the evolutionary history of these areas as the seawater temperature and salinity have fluctuated considerably over geological ages. This resulted in large variations of sea level and coral cover. During the Quaternary glacial episodes, the sea level was very low and there were only a few areas where corals persisted. These areas were refuges for the fauna of areas where corals had disappeared. The central Indo-Pacific region included large areas of such refuges, and except for during the coldest periods, New Caledonia was one of them.

This is how New Caledonia has accumulated a marine fauna whose diversity is exceptional but also largely shared with neighboring regions that have had a very similar evolutionary history. The reef fish fauna of New Caledonia includes a majority of species that are also found on the Great Barrier Reef to the west (about 60%), a smaller proportion (30%) coming from the Melanesian arc formed by Papua, Solomon and Vanuatu, and a few species from the south (Norfolk and Loyalty ridges) (10%). As a consequence, in New

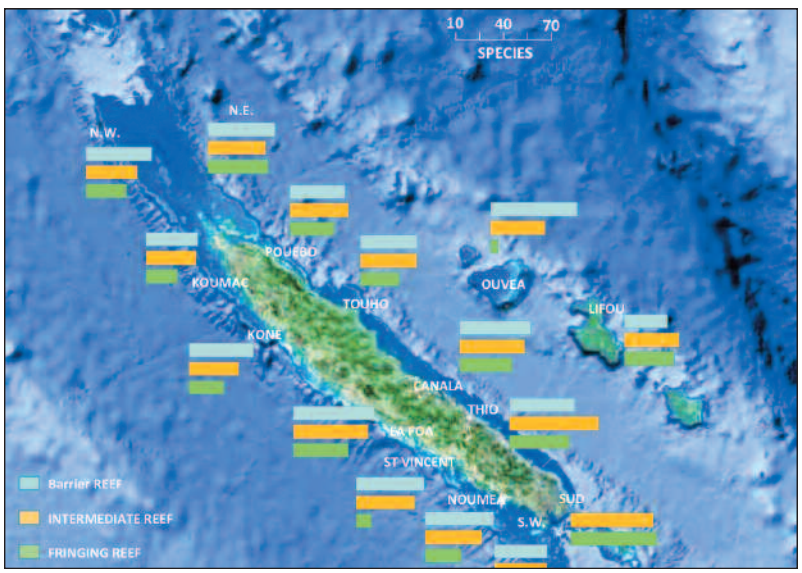

Figure 2: Number of reef fish species for an area of 250 m² according to the type of reef. Adapted from KULBICKI *et al.*, 2013a

Caledonia, fish endemism (chap. 36) is low and it has been estimated, depending on the methods, that only 1.8% to 3.8% of the species are unique to the archipelago.

A number of geographical factors also contributed to the species richness of the New Caledonian lagoons. It has been shown, for example, that in the Indo-Pacific, the number of species is proportional to the available reef area, the size of the islands and their degree of isolation. The smaller, more isolated and reefless an island is, the fewer species it will have. Due to its large size and vast reef and lagoon areas, Grande Terre has over 1,400 species of reef fish, while the smaller Loyalty Islands have only about 800 species, although these two geographical areas are relatively close. Similarly, the Chesterfield Reefs, which are very isolated and have virtually no land, harbor only 800 reef species despite large submerged reef areas. Likewise. Polynesia, which is made up of small remote islands, has only 900 reef species, which can be related to its total land surface (4,200 km² versus 18,700 km² in New Caledonia) and its remoteness to the Coral Triangle.

Water temperature is also an important factor influencing the number of species, as reefs with warm water support more species. This temperature gradient is significant over large geographical scales, but its effects are already noticeable for Grande Terre as studies have shown that the number of reef species is higher in the north of Grande Terre than in the south. However, in New Caledonia, the specific richness and composition of reef fish populations vary mainly according to the type of reef habitat (Fig. 2).

Generally, the number of species increases from the coast to the barrier reef, a gradient which is more pronounced in areas where fringing reefs are under strong terrigenous influence, for example when they are located in large bays. Ouvéa is an exception (with very little terrestrial input), as the low number of coastal species is explained by a relatively small number of reefs along the coast. Early studies based on fish censuses carried out over restricted areas (250 m²) did not show a marked gradient in the mean number of species per sample along the north-south or east-west axes. However, more recent studies have revealed important differences between the southern end (Isle of Pines, Walpole) and the northern end (Grand Lagon Nord) of the archipelago. In addition, it has been observed that the specific composition varies more between samples in the north than in the south, and on Grande Terre compared to the Loyalty Islands. This means that the number of species per unit area changes only moderately, but, the variability of their composition changes significantly.

Identity card of the lagoon inhabitants

The 1,800 reef fish species of New Caledonia belong to 125 families. The size of these families is very uneven, with 10 families accounting for 51% of the species and 20 families representing two-thirds. Many families are represented by only one species (30 families) or up to five species (63 families). The families that are best represented are gobies (190 species), followed by wrasses (129 species), damselfish (Pomacentridae, 109 species) and cardinalfish (Apogonidae, 87 species). An examination of reef species' life history traits indicates that over 50% of species are less than 15 cm in maximum size, and only 9% are over 80 cm in maximum size. This type of distribution is found throughout the tropical Pacific, where the distribution of sizes is largely related to the number of species. When the species richness is high, the proportion of small species increases and, generally, the abundance of fish is higher when the number of species is high. Consequently, the proportion of large species will be higher in Polynesia or in the south of the Great Barrier Reef than in

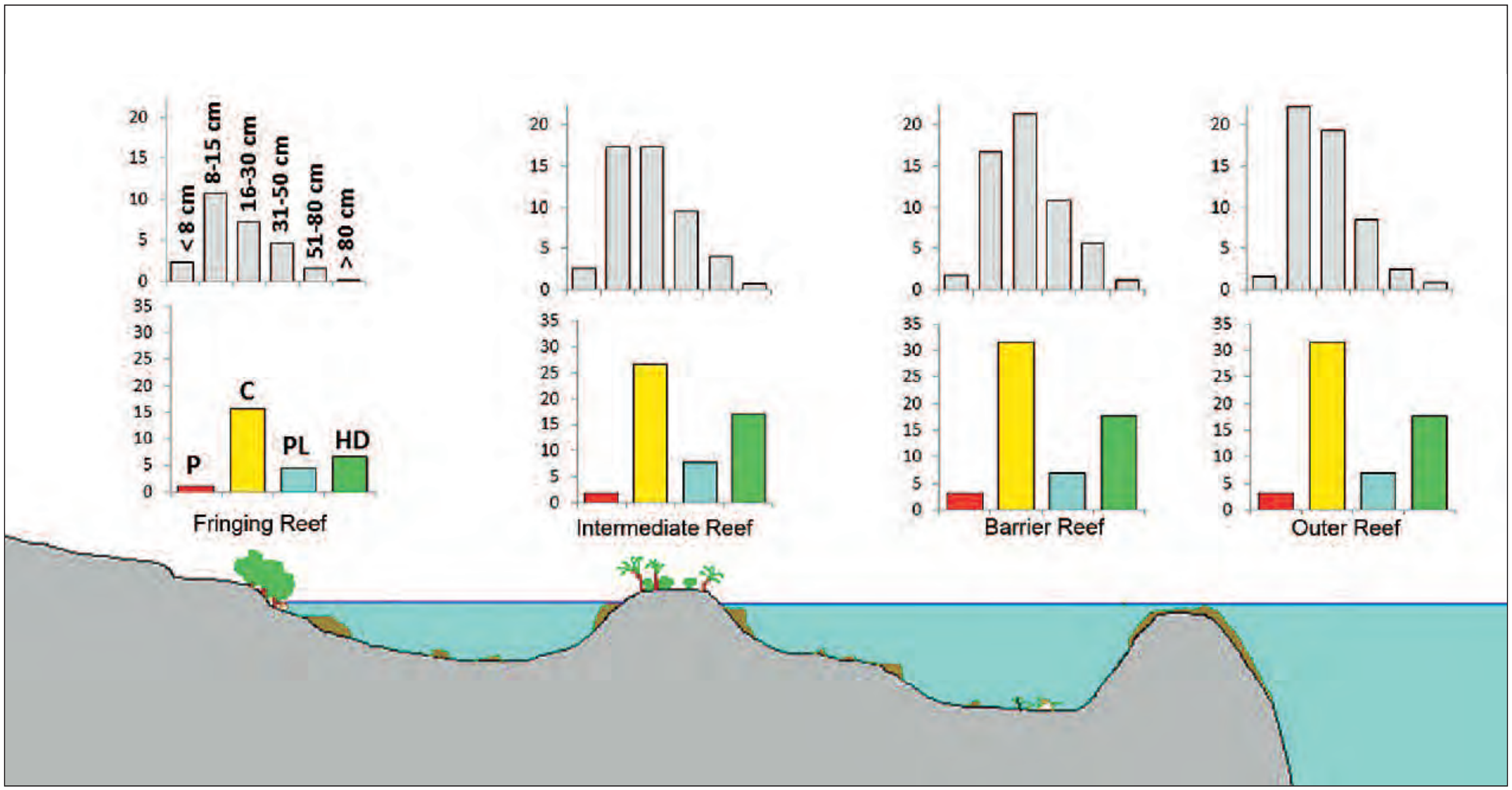

Figure 3: Distribution of size and diet from coast to ocean. P: Piscivorous species. C: Carnivorous species. PL: Plankton feeders. HD: Herbivorous species. Adapted from KULBICKI *et al.*, 2013b

New Caledonia. This has important management implications. Smaller species are generally less vulnerable than larger species, which means that populations in New Caledonia may be more stable and resistant (chap.38).

Reef fish diets are dominated by species that consume mobile invertebrates (40% of species). The next three most common categories are plankton feeders (19%), piscivores (15%) and omnivores (13%). Herbivores account for only 7% of species and corallivorous fish for 3.5%. These proportions are fairly similar to those in the biogeographical provinces adjacent to New Caledonia. However, the proportion of piscivores increases towards colder regions and towards small and isolated islands, with less plankton feeding and omnivorous species and more species that are less specialized in their habitat. This is likely to be related to the distribution of species sizes (the larger the species, the more likely they are to have high trophic levels) and to the proportion of generalist species, which is higher when fish species are large and when there are only a few species.

The distribution of fish life history traits also varies according to habitat, particularly between coastal and offshore habitats (Fig. 3). For example, the proportion of small species is higher on coastal reefs and conversely, the proportion of large species is higher on oceanic reefs. In terms of diet, the increase in herbivorous and plankton feeding species increases with oceanic influence, differences which appear to be related to the stability of environmental conditions. On the coast, nutrient inputs from runoff enhance primary production, which in turn increases the available level of primary resources compared to oceanic reefs.

However, this difference does not translate into more species, and may even have a tendency to translate into fewer species. In contrast, coastal reefs are exposed to very large variations in salinity, turbidity and sediment inputs which can significantly interfere with sedentary species, the most abundant on these reefs. In addition, coastal species have shorter larval durations and are more restricted geographically compared to oceanic reef species. Most reef fish species disperse during their pelagic larval phase and the larvae can remain in the ocean for several weeks.

The longer this period (pelagic larval duration, PLD) is, the more likely the species are to colonize distant reefs. Species with long PLDs tend to be generalist species (for habitat and/or food) and the proportion of generalist species increases with distance to the coast. This means that populations in sheltered areas are mainly renewed locally, which makes them more vulnerable to significant environmental changes

New Caledonia has a diversity of top quality reef fish species which provides a wide range of services to the environment and people. It provides reef fish populations with more stability, resistance and resilience to disturbance (chap. 38) and also allows for better ecological performance leading to the production of more fish. Preserving this diversity requires both the preservation of habitats and the connections between them (chap. 43).

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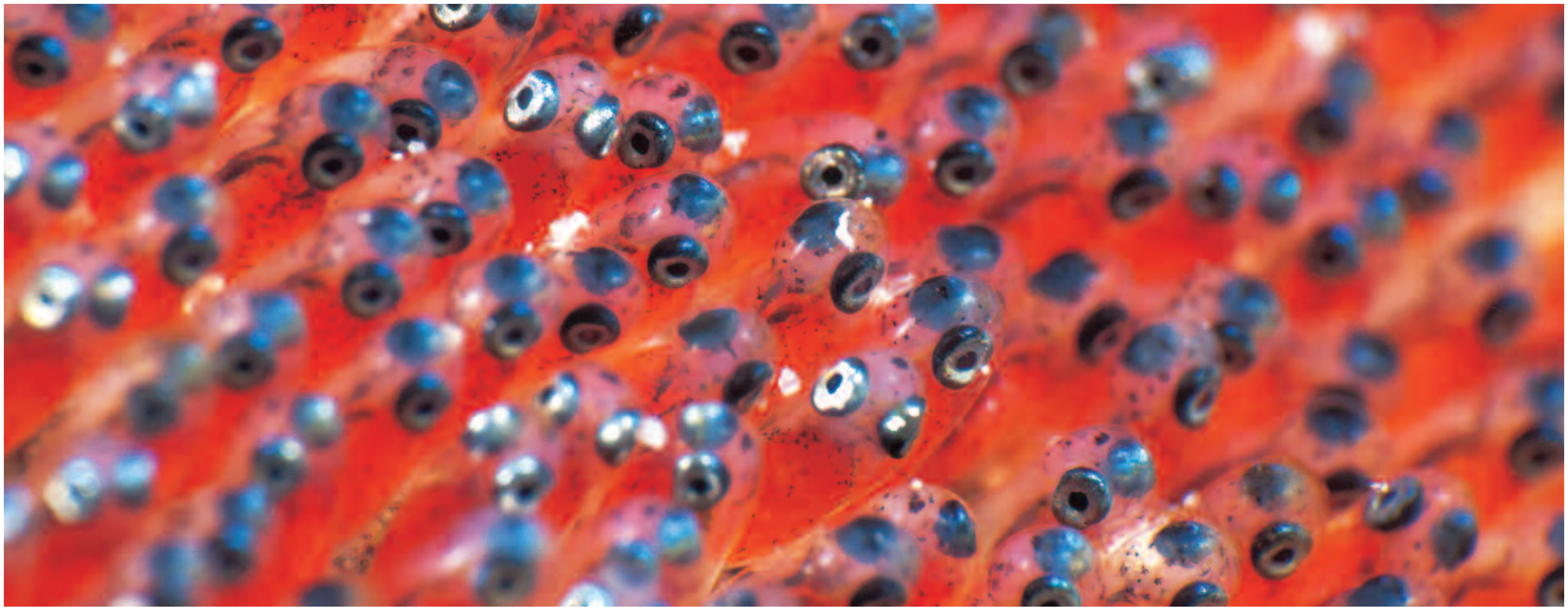
Chapter 15

The precarious survival of fish larvae and juveniles

Dominique Ponton, Laure Carassou and Philippe Borsa



Clown fish eggs. The vitelline reserve is very colourful and the eyes of larvae are clearly visible. © G. Boussarie

Why study the early life stages of fish?

Many reef fish species have a two-stage life cycle characterized by the use of contrasting habitats: a "larval phase", which takes place in open water, followed by a "benthic phase". Once installed near the reef, or on the bottom of the lagoon, larvae become juveniles which, if they survive, will grow to become adult fish. Although few data exist in the literature, it is generally accepted that for the vast majority of species, survival during the larval phase is very low: probably less than 1% of larvae escape predation or disease. As a result, out of several thousand to several hundred thousand eggs, only a few individuals eventually settle on the bottom to grow. Juveniles also suffer a high mortality rate in the very first few days after the installation. This level of mortality has only been assessed for very few species, but is estimated to be about several dozen percent per day. In summary, an "average" young fish has every chance of dying, and only a very small proportion of juveniles reach the adult stage.

Such a demographic "bottleneck" means that the factors influencing the survival of larvae and juveniles largely explain the variation in adult abundance. As suggested more than a century ago by Norwegian researcher Johan Hjort, one of the pioneers in fish larvae ecology: "The main problem that characterizes fisheries science is the description and understanding of the nature of natural fluctuations in stocks" (HJORT, 1914). This quote referred to temperate species, but it is also valid for tropical fish, although there have been very few studies on tropical larval stages. In tropical systems, and particularly in coral reefs, studies on fish larvae and juveniles mainly focus on the installation transition phase, just before, during and just after larvae settle on the bottom.

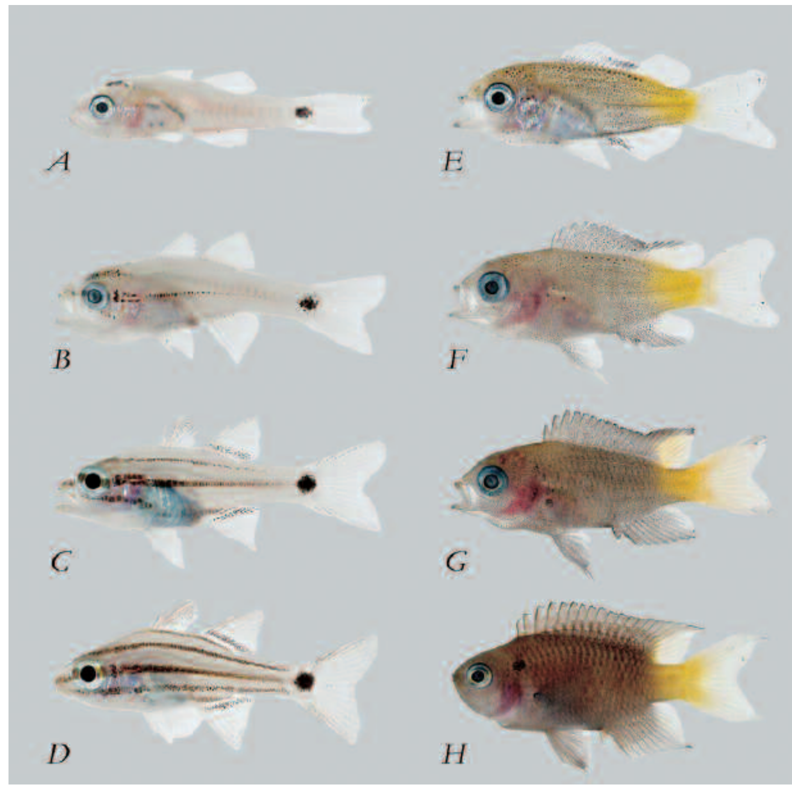
In New Caledonia, our team focused on identifying the environmental factors, zones and favorable periods for the survival of fish larvae during the pre-installation phase (CARASSOU, 2008). We also looked at the growth of juveniles, both during and shortly after their settlement on the bottom (MELLIN, 2007). We were able to demonstrate that the growth of juveniles of different species (survival rates are very dependent on species) was influenced by environmental conditions during the larval phase, as well as the timing and location of installation meaning that larval and juvenile processes are closely linked. However, these early life stages are challenging to study, mainly because of the high species diversity in New Caledonia (over 1,500 reef fish species) which makes identification difficult. To help with these difficulties, we developed methods for the identification of larvae and juveniles of reef fish in New Caledonia.

How to catch them?

Small larvae a few millimeters long are usually caught with very fine mesh nets that are towed behind a boat, or more rarely pushed in front of the boat or beside it. Capturing larger larvae requires larger nets, usually with an opening of several meters, because these faster larvae have better avoidance capacities. At the end of the larval phase, individuals can also be caught with fixed nets as they pass over the reef crest with waves. The larvae of some species are attracted to light and can be captured using light traps and at the time of their installation on the bottom, juveniles can also be caught in artificial reefs made available to them. Older juveniles can be caught in seagrass beds using bottom seines pulled by divers, or in coral colonies in which they shelter, using an anesthetic such as clove oil.

How to identify reef fish larvae and juveniles?

In the reef environment, larvae and even juveniles of most species present very different shapes and colors compared to adults and are seldom described in fish identification books. As a consequence, identifying fish larvae and juveniles is particularly difficult and has considerably hampered research on this subject. Identification guides for fish larvae exist, but either they cover vast geographical areas, and are therefore usually limited to family descriptions, or they cover a few species caught at a particular location only.



Developmental series in two fish species.
A cardinal fish eventually identified as *Ostorhinchus doederleini*.
A: On the day of capture. B: After 7 days of aquarium rearing.
C: After 22 days. D: After 51 days.
A damselfish eventually identified as *Neopomacentrus violascens*. E: On the day of capture.
F: After 7 days of aquarium rearing. G: After 15 days.
H: After 91 days. © IRD/D. Ponton

The most accurate guides are obtained by photographing, or drawing, larvae or juveniles caught in the wild, and then rearing them until they resemble small adults and can be identified by their morphology. This method of identification is long and expensive and cannot be used as a laboratory routine. An alternative and increasingly widespread approach is, therefore, the use of genetic markers such as DNA barcodes (Fig. 1).

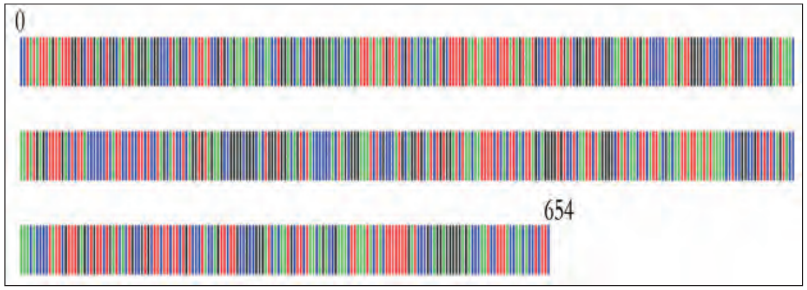


Figure 1: DNA Barcode of a long-nosed emperor *Lethrinus olivaceus*, as represented in the international BOLD database. The four nucleotides that make up the DNA (A, C, G, T) are coded in four different colors. Here, the length of the barcode is 654 nucleotides. Adapted from BOLD (http://v4.boldsystems.org/)

The most common DNA barcode used in fish is the nucleotide sequence of a fragment of mitochondrial gene that encodes an enzyme, which corresponds to the gene of an enzyme in the respiratory metabolism, cytochrome-oxidase 1. The larva's DNA barcode is compared to a DNA barcode database obtained from a collection of adult individuals identified by experts. Each species generally corresponds to a unique barcode, with only a few mutations, due to natural variability between individuals of the same species. In most cases, it is possible to identify larvae by their DNA barcodes alone. However, there are exceptions. For example, closely related species may sometimes share the same DNA barcode following more or less recent hybridization events that allowed mitochondria of one species to colonize the other species.

New Caledonia fish larvae and juveniles

Reef fish larvae and juveniles have a wide range of colors and sometimes extravagant shapes. As mentioned above, it is difficult to identify them with a species based on their external morphology alone. This is particularly true for the large-eye seabreams, long-nosed emperors (individuals 28 to 32) and rabbitfishes (individuals 63 and 64) in which the shape of the body and patterns of spots and colors are very similar from one species to another.

Clear temporal variations and misunderstood interannual variations

Understanding which larvae are present in open water, and their timing, is important in order to anticipate changes in the abundance of juvenile fish in reef environments, as these depend, for example, on the global climatic context or local human population pressures. To this end,

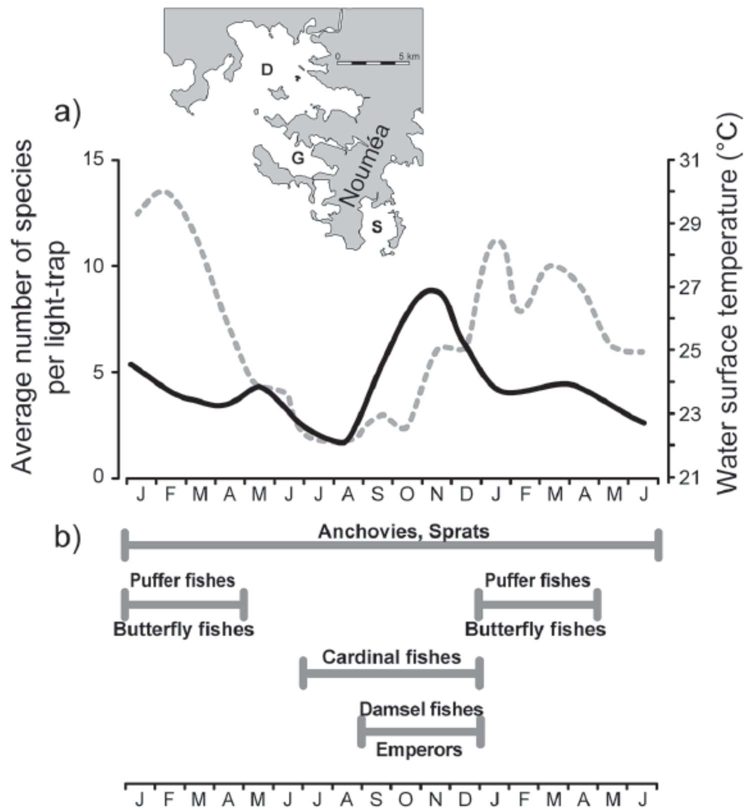


Figure 2: Temporal variation of larvae catches in light traps.
A: Average number of species per trap (black line) in Dumbéa Bay (D), Grande Rade (G) and Sainte-Marie Bay (S) and water surface temperature (dotted grey lines).
B: Periods during which the main families are observed. Adapted from CARASSOU, 2008

Examples of the shape and color diversity observed in reef fish larvae and juveniles of New Caledonia.

01 to 03: Acanthuridae.
04: Antennariidae.
05 to 07: Apogonidae.
08: Balistidae.
09 to 12: Blenniidae.
13: Bothidae.
14: Centriscidae.
15 to 18: Chaetodontidae.
19: Gobiesocidae.
20: Gobiidae.
21: Haemulidae.
22: Hemiramphidae.
23: Holocentridae.
24 to 27: Labridae.
28 to 32: Lethrinidae.
33: Lutjanidae.
34: Microdesmidae.
35 and 36: Monacanthidae.
37 and 38: Mullidae.
39: Ophidiidae.
40: Platycephalidae.
41: Plesiopidae.
42: Poecilopsettidae.
43 and 44: Pomacanthidae.
45 to 54: Pomacentridae.
55 to 57: Scaridae.
58: Scorpeanidae.
59 to 62: Serranidae.
63 and 64: Siganidae.
65: Soleidae.
66: Syngnathidae.
67: Synodontidae.
68 and 69: Tetraodontidae.
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School of juvenile fish sheltered under an overhang. © G. Boussarie

it is important to identify the time of year when larvae of different species colonize the lagoon. In New Caledonia, studies using light traps in bays around Nouméa have indicated that larval diversity is the highest during the austral summer from September to December (Fig. 2, A), but larvae have different preferences according to their family (Fig. 2, B). These studies have only been carried out over an 18-month period between 2002 and 2003 and cannot be generalized because seasonal patterns can vary from one year to the next, depending on climatic conditions, for example. Unfortunately, extending sampling efforts over several years is difficult because it is costly.

Larvae and juveniles: a way to study biodiversity?

An unexpected result obtained during our genetic analyses on the larvae of reef fish in New Caledonia was the presence of previously unknown species in our samples. These included a relatively rare fish, the oblong large-eye seabream Gymnocranius oblongus and a cryptic species of the long-nosed emperor, which has yet to be formally described. This example illustrates the power of molecular techniques for identifying and describing species, and the value of working on larvae for the discovery of previously undetected reef species.

Juvenile sailfin tang (*Zebrasoma veliferum*). © G. Boussarie

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Chapter 16

Functional biodiversity in the lagoon

Laurent Vigliola, Nicolas Guillemot, Laurent Wantiez and Michel Kulbicki

The humphead parrotfish *(Bolbometopon muricatum)* is a good example of species that combine several ecological traits essential to the good functioning of reefs. © National Geographic Society/E. Sala

Each species has its own function

In Nouméa as in Koné, in Moindou or Pouébo, in cities or in tribes, everywhere in New Caledonia as in the rest of the world, human societies function according to the same principle: the farmer plants, the baker makes bread, the bricklayer builds, the teacher teaches, the artist creates... Each person has a function, a more or less important role that contributes to the good functioning of our societies. In the lagoon, as everywhere else in nature, the same principle applies: herbivores graze, carnivores hunt, detritus feeders recycle... Each species has one or more functions which are of variable importance. However, there is a golden rule: the role played by each species is key to the functioning and very existence of ecosystems. For the reef and lagoon to be maintained, it is essential that all functions be performed by one or more species.

Functional diversity is defined as the number of functions or roles played by species within an ecosystem. Assessing functional diversity is a complex process for many reasons. First, each species can perform a multitude of roles, and each role can be of variable importance. A species can be useful to the ecosystem as prey because it feeds its predators. Being prey is therefore one of the functions of this species. This same species also eats and performs several other functions. For example, herbivores control the growth of algae and thus help regulate the competition between algae and corals. The humphead parrotfish is a well-studied example of a species with several essential functions. This species nibbles at corals and algae that cover the reefs, allowing other species to colonize the newly available area which leads, therefore, to a renewal of the local fauna and flora. The small pieces of coral that the fish cannot digest are expelled as a cloud of fine sand, which adds to sedimentary zones that shelter other species. The sediment produced by a single school of these fish can reach several tons per year. Through this example, it is possible to conceptualize the link between the life-history traits of species and their functions in the ecosystem.

Complementary functional entities

Species have a set of life-history traits, not just diet traits, the combination of which is unique to each species. Currently, our level of knowledge is insufficient to define the exact roles of each species. However, by categorizing the traits of each species, it is possible to classify species into groups with similar characteristics, which are assumed to have very close ecological functions. As illustrated in the previous example, diet is an important functional life-history trait. For fish, a distinction is generally made between piscivores, carnivores, herbivores and detritus feeders, omnivores and plankton eaters. Each of these categories can be broken down further. Other life traits commonly used to classify fish into functional groups are the size of species, mobility, their position in the water column, period of activity and gregariousness, to which could also be added traits related to reproduction and behavior. In all of these traits, size plays a key role. In fact, it influences most other traits, particularly in prey-predator relationships, as it determines the energy required for metabolism and thus the amount of food needed for the survival of individuals. Mobility is also a life-history trait linked to energy needs, as mobile species take their resources from a wider territory than sedentary species. In addition, by moving, they transfer energy between the different habitats of an ecosystem. The period of activity also has functional implications because nocturnal and diurnal species are not accessible to the same predators and do not feed on the same prey. The level in the water column is an important functional trait that contributes to energy fluxes between the bottom of the lagoon and the surface, and between open ocean and reefs. Finally, gregariousness is linked to the functional footprint of species, with individuals living in large schools having a massive impact on nutrient transfers within the ecosystem.

Each of these life-history traits can be either quantified (e.g., a species that can reach a maximum size of 48 cm in adulthood) or codified into categories (e.g., a medium-sized species). The combination of these characteristics makes it possible to define more or less complex functional classification schemes. For example, a simple scheme would combine size and diet, with functions (or functional entities) such as "large-sized piscivore","medium-size herbivore" or "small-sized carnivore", and a complex scheme would combine all the available life traits (e.g., "very mobile large-sized solitary nocturnal piscivore hunting in open water"). These classifications allow the estimation of functional diversity, simply by counting the number of existing combinations. These combinations or functional entities are an approximation of the true functional diversity which remains beyond our measurement capabilities.

Numerous studies based on this approach show that, on a reef, the number of functions is less than the number of species. The number of functions increases only very slowly above a certain number of species, as indicated by a study of the Koné lagoon in New Caledonia (Fig. 1). New functions keep emerging when the specific diversity is very high. These functions are represented by few species and, in general, few individuals, making them highly vulnerable, especially since they appear only with exceptional levels of diversity. This is very important because the more functions within an ecosystem, the more productive, stable, resistant and resilient it will be. This is linked to the concept of ecological niches, which states that each species has a specific habitat and role in an ecosystem, but at the same time each new species adds a new resource on which new species can establish themselves. New functions are therefore generated by pre-existing functions in a process of enrichment and optimization of the ecosystem.

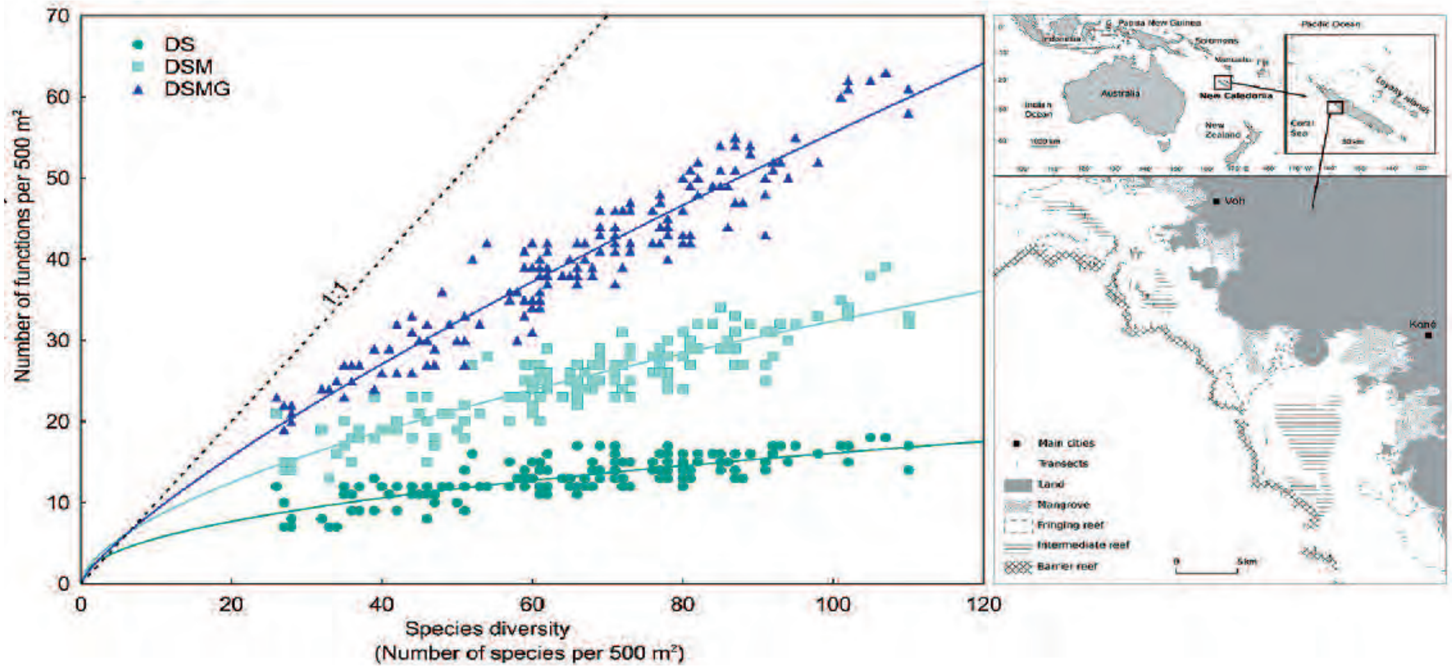

Figure 1: Relationship between specific and functional diversity for Koné coral reef fish species and for different functional classification schemes.
D: Diet. S: Size. M: Mobility. G: Gregariousness. Adapted from GUILLEMOT *et al.*, 2011

Diversity: a factor of resistance to disturbances

As seen earlier, the more species an ecosystem has, the more functions it will have, and the more likely it is to have the necessary function(s) to resist disturbance. In other words, functional diversity provides a sort of insurance for ecosystems. Similarly, when several species have the same function, it protects the ecosystem against the consequences of a local species extinction (following a disease, for example). On a particular reef, many species appear and then disappear with changes in recruitment, habitat or resources. As long as all functions are retained, then the ecosystem can be maintained, regardless of the exact identity of the species that make up the community. Functional redundancy increases the resilience of an ecosystem (i.e., its capacity to last over time), because several species with the same function ("functionally interchangeable species") will have to be impacted before the function is lost. Conversely, poorly-redundant functions are vulnerable, the most vulnerable being functions performed by a single species. When this is the case and the function is essential to ecosystem functioning, it is referred to as a "keystone species" whose presence or absence can influence the whole ecosystem.

There are, therefore, two opposing forces in action. On one hand, having many functions increases the resilience of a system in case of disturbances. On the other hand, functional redundancy makes each function less vulnerable. An increase in the number of species is likely to reinforce the redundancy of existing functions and the appearance of new ones. The Koné study has found these two forces in action. In New Caledonian reefs, the number of functions observed in fish assemblages is lower than expected by chance, given that the number of species present at each site was below a threshold of about 90 species per 500 m^2 (Fig. 2).

Below this threshold, species diversity tends to reinforce functional redundancy, and therefore the ecosystem's resilience to local species loss. Beyond the threshold of 90 species, the number of functions in assemblages does not differ from what can be expected by chance. Therefore, beyond this threshold of 90, the functional diversity tends to increase with the addition of new functions, which are rare and vulnerable but allow for a better partitioning of resources and therefore a more energy efficient system.

The world's last wild reefs

New Caledonia has an EEZ (Exclusive Economic Zone) of 1,740,000 km^2. In this immense maritime domain, some reefs are under strong human influence, particularly those near the capital Nouméa, which attracts two-thirds of the New Caledonian population. Other reefs, such as the Chesterfield Reefs, are extremely isolated in the middle of the Coral Sea, sometimes over 40 hours away from any human population. A recent study compared the functional diversity of coral reef fish along this decreasing gradient of human impact. It shows that the fish functional diversity is maximal on coral reefs located more than 20 hours from Nouméa. The study also revealed that this functional diversity declined by 60% in the inhabited areas of the archipelago (Fig. 3).

This means that the lagoon is seriously short of the work force it needs to function properly, as many functions have been severely affected, particularly by fishing. This functional erosion has serious consequences for the lagoon because a poorly functioning ecosystem degrades quickly. However, solutions do exist. The provinces of New Caledonia have created numerous marine reserves, which are capable of partially restoring functional diversity. More recently, the government of New Caledonia has created the Natural Park of the Coral Sea, which includes most of the isolated reefs of the archipelago. Protecting these reefs is a huge responsibility for New Caledonians, as our latest estimates (MAIRE *et al.*, 2016) indicate that only 1.5% of the coral reefs located over 20 hours away from human populations, are left in the world. New Caledonia has one third of these last functionally intact reefs. To formally protect the planet's last wild reefs unaffected by most human impact, would be a strong symbolic action by New Caledonians in 2018, the year of coral reefs.

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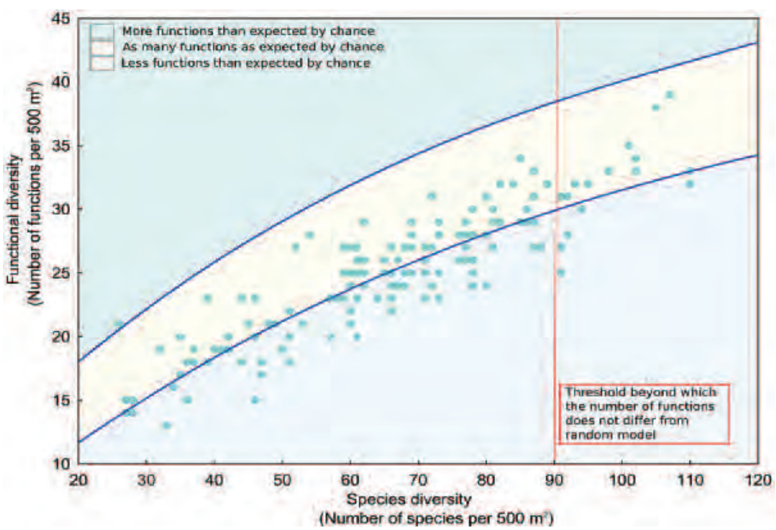


Figure 2: The relationship between the species and functional diversity of coral reef fish in New Caledonia. Adapted from GUILLEMOT *et al.*, 2011

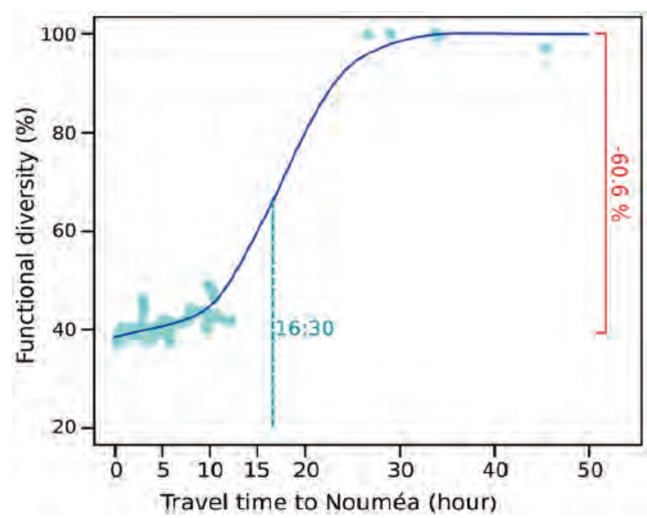


Figure 3: The relationship between the functional diversity (in %) of fish in New Caledonian coral reefs and travel time to Nouméa. Adapted from D'AGATA *et al.*, 2016

School of yellowfin goatfish *Mulloidichthys vanicolensis*. This occasionally gregarious species lives on sandy bottoms in reefs and lagoons. Adults are often solitary and live on sandy slopes where they feed on small invertebrates. © M. Juncker

Chapter 17

Sea-snakes of the coral reefs of New Caledonia

François Brischoux, Xavier Bonnet, Richard Shine and Claire Goiran

Laticauda laticaudata (blue-banded sea krait) on a sandy bottom with many burrows, probably searching for prey. © IRD/P. Laboute

General information on sea-snakes

During the Miocene, snakes experienced four independent events of transition to marine life, which gave rise to four phylogenetic groups using more or less extensively the marine environment. Only two of these groups are present in New Caledonia, the Laticaudinae (sea krait) and the Hydrophiinae ("true" sea-snakes). They are part of the family Elapidae. These two phylogenetic groups include the snake species that are best adapted to the marine environment. They are widely distributed in coral reefs of the Indian and Pacific oceans, including the reefs of New Caledonia. Laticaudinae are amphibious and oviparous: they feed at sea but must return ashore for all other activities (digestion, reproduction, including egg laying, etc.). Of the eight currently recognized species of sea krait, two are present in New Caledonia, one of them is endemic. They are the yellow-banded sea krait (*Laticauda saintgironsi*, restricted to New Caledonia) and the blue-banded sea krait (*Laticauda laticaudata*, more widely distributed). Hydrophiinae are often referred to as "true" sea-snakes, because species in this group are emancipated from the terrestrial environment. They are viviparous and spend their entire lives at sea without ever returning to the shore. This phylogenetic group is very rich with about 70 species, 12 of which are found in New Caledonia.

Laticaudinae (sea krait)

The two New Caledonian species of sea krait are widely distributed throughout the lagoon: most of the islands and islets in the lagoon harbor populations of at least one (or most often, both) species. On land, like most snake species, sea kraits live hidden in shelters that protect them from excessive temperatures, dehydration and predators. While most islands and islets in the lagoon offer a diversity of habitats rich enough to suit both species, specific characteristics of the terrestrial environment are essential for their occurrence. The yellow-banded sea krait is more terrestrial than the blue-banded sea krait. Its locomotor capacity on land is superior, enabling it to access coastal microhabitats (rock mounds, seabird burrows, interlaced roots, fallen trees, etc.). The blue-banded sea krait is less agile on land and is present only if this type of micro-habitat is located close to the intertidal zone. Unlike the yellow-banded sea krait, blue-banded sea kraits often shelter under rocks in the intertidal zone.

The shape of islets and shoreline also influences the population structure of these snakes. Not all islands and islets in the lagoon offer the ecological features that are appropriate for all life stages.

Yellow-banded sea krait (*Laticauda saintgironsi*, endémic) mating on Amérée islet (Merlet Reserve). One female is courted by several males. © X. Bonnet

For instance, eggs have different requirements than do growing juveniles or reproductive adults. While some sites are favorable to all these life stages, the demographics of New Caledonian sea krait populations can also be geographically structured. Some sites act as nurseries by hosting mainly egg-laying sites and newborns (e.g., Ouen Island), while others have populations consisting mainly of adult individuals (e.g., Améré Island within the Merlet Reserve). Other sites can accommodate all these life stages (for example, Île Verte or Signal Island). Population structure over large spatial scale across the lagoon of New Caledonia is important for conservation biology. Local disturbances (e.g., at a key nursery island, or islands hosting populations of breeding adults) could have consequences over a very large scale and affect other relatively distant populations.

Sea kraits use the marine environment to feed, mainly on anguilliform fish (conger and moray eels, and snakefish). In New Caledonia, the two sea krait species together consume a very large number of species (at least 43 different taxa), most of which are benthic predators that are sedentary and very high in the food chain. By feeding on these apex predators, sea kraits play a fundamental role in the functioning of food webs. The population of a single site, such as Signal Island (approximately 4,000 snakes), can consume over 45,000 anguilliform fish per year, a biomass of about 1.5 tons. By doing so, sea kraits efficiently sample the cryptic ichthyofauna of the lagoon. The study of their diet revealed the presence of at least 15 species of anguilliform fish that had not yet been recorded in New Caledonia. In many cases, studies of the diet of sea krait have changed our understanding of predatory fish densities, which had previously been underestimated.

In combination, the two New Caledonian sea krait species "sample" a large range of habitats when they forage. The yellow-banded sea krait mainly specializes in anguilliform fish species that live in reef crevices. It consumes at least 34 different species that live on hard bottoms. The blue-banded sea krait is more likely to eat species living on soft bottoms (mudflats, sandy areas, seagrass beds) and, while its diet is also mainly based on anguilliform fish, it feeds also on catfish and dartfish. On soft bottoms, the blue-banded sea krait feeds on up to 28 different species.

Because of their emblematic characteristics, sea kraits have become one of New Caledonia's iconic species. But they are more than just charismatic marine animals; they also play a key role in the functioning of the lagoon of New Caledonia. They are also particularly relevant models for exploring fundamental research questions (e.g., the transition from terrestrial to marine life), large-scale ecosystem functioning (through their role in the food web) or conservation biology (through the spatial structuring of their populations).

Hydrophiinae ("true" sea-snakes)

Unlike sea kraits, Hydrophiinae sea-snakes are viviparous and spend their entire life at sea. They are ecologically and morphologically very diverse. They are divided into two groups, that have evolved adaptations to marine life (like flattened tails) independently of each other. In New Caledonia, the first group is represented by three species: the Dubois' sea-snake *(Aipysurus duboisii)*, the golden or olive sea-snake *(A. laevis)* and the turtle-headed sea-snake *(Emydocephalus annulatus)*. The second group is represented, in New Caledonia, by nine species, all belonging to the genus Hydrophis: *H. coggeri, H. curtus, H. laboutei, H. macdowelli, H. major, H. ornatus, H. peronii, H. platurus and H. spiralis*. In general, snakes of the *Aipysurus-Emydocephalus* group tend to occur in shallow reef habitats. The turtle-headed snake feeds exclusively on fish eggs (blennies, gobies and damselfish). It is not venomous. It is extremely sedentary, to the extent that populations living in two adjacent bays of Nouméa (Anse Vata and Baie des Citrons) are genetically different. *Aipysurus* species have a more diverse diet, which includes various species of fish and possibly fish eggs or crustaceans. The olive snake *(A. laevis)* is the best known because it is very abundant in New Caledonia and often approaches divers.

The genus *Hydrophis* diversified very rapidly during the last few million years. It has about 50 species that hunt very different prey. Some are highly specialized and consume only one type of prey, whereas others are generalists. These species can live in deeper ecosystems than the snakes of the *Aipysurus-Emydocephalus* group, or even completely offshore for *H. platurus*. This does not prevent some species such as *H. major*, *H. peronii* and *H. coggeri* from also visiting shallow bays such as Baie des Citrons in Nouméa.

Regurgitation of a moray eel *(Gymnothorax eurostus)* by a yellow-banded sea krait (*Laticauda saintgironsi*). This technique has revealed the species richness of New Caledonia's anguilliform fish. © X. Bonnet

Yellow-banded sea krait *(Laticauda saintgironsi)* swimming through a seaweed bed at Amédée islet. © IRD/P. Laboute

Aipysurus laevis. © UNC/C. Goiran

Hydrophis major swallowing a catfish (*Plotosus lineatus*). © UNC/C. Goiran

Some species, including *H. macdowelli* and *H. coggeri,* have a small head which they can insert into burrows in search of anguilliform fish, while others (such as *H. major*) have a large head which allows them to catch and ingest fish of an impressive diameter compared to their body. The diet of *H. major* is well known because this species hunts during the day, in shallow areas where it is easy to observe. In New Caledonia it feeds exclusively on the catfish *Plotosus lineatus*. The population size of *H. major* around the Nouméa peninsula is under study. It is likely to include a few hundred individuals, putting significant pressure on the *P. lineatus* population. This catfish, which has toxic mucus and poisonous spines, is an invasive species in the Mediterranean where it has a negative impact on fishing.

Representing the extreme marine adaptation of sea-snakes, *H. platurus* is a small (about 70 cm long) and completely pelagic species. It floats long distances with ocean currents and mainly feeds on fish larvae that gather at the surface of the ocean under floating debris. The species has a remarkably wide distribution in the tropical Indian and Pacific oceans. Although it is not very common in New Caledonia, this very unusual species sometimes comes into the lagoon.

New Caledonia offers a very favorable environment for the study of "true" sea-snakes. It has rich and diverse reef and lagoon ecosystems which host many species. Some of these ecosystems (e.g., Baie des Citrons) are easily accessible, making it possible to study snake populations over the long term. Two species of "true" sea-snakes are currently being investigated in New Caledonia: *Emydocephalus annulatus* and *Hydrophis major*. The aim of the research program is to understand the ecology of these species and how they adapt to changes in their environment.

The yellow-banded sea krait *(Laticauda saintgironsi)*, more terrestrial than the blue-banded sea krait *(Laticauda laticaudata),* is frequently observed on the beaches of the islets. © P.-A. Pantz

Emydocephalus annulatus. © UNC/C. Goiran

Mating of *Aipysurus laevis*. © IRD/E. Folcher

Box 17

Why do sea-snakes come to see divers?

A curious sea-snake approaching a scientist (Chesterfield scientific campaign, CHEST 2015). © IRD/ C.E. Payri

Terrestrial snakes never approach humans for close observation, and instead prefer to "run" away from them. Sea-snakes, on the other hand, do not avoid divers and sometimes even come to have a closer look. Why this difference?

Snakes don't have very acute eyesight. In order to identify the other animals that they encounter (like prey or sexual partners), snakes use their tongues to collect molecules present in the environment and analyze them in the vomero-nasal organ located in their palate. Land snakes collect molecules from the air or on the ground to find out which other animals share their surroundings. In the marine environment, the molecules emitted by other animals are too rapidly dispersed in the water for snakes to use them as a source of information. Instead, they have to collect the molecules from the animal they want to identify directly with their tongue. During the breeding season, usually in winter, males very actively survey their environment in search of females. They often come to see divers, but as soon as they realize that they are not potential partners, they move away from them. Humans sometimes interpret this behavior as an attack, but it is only curiosity.

Chapter 18

The trophic networks of coral reefs

Marine Julie Briand and Yves Letourneur

Green turtle *Chelonia mydas* eating in a *Halophila* seagrass bed, west coast of Grande Terre. © M. Juncker

The seaweed *Sargassum spinuligerum* absorbs nutrients from the water; the crab *Pilumnus vespertilio* nibbles on this seaweed; the moray eel *Gymnothorax chilospilus* catches the crab; the sea krait *Laticauda saintgironsi* swallows the moray eel, and the tiger shark *Galeocerdo cuvier* eats the snake. This is how life goes on in the coral reefs of New Caledonia. Trophic interactions between prey and predators are very diverse and complex. Each reef organism plays a specific role and occupies a particular niche in this fragile network, where species are all interconnected.

A perfect network

Many food chains coexist in the coral reefs of New Caledonia. Each one is built from an initial link which represents the primary food source, multiple intermediate links involving very diverse consumers, and it culminates in a terminal link represented by large carnivorous predators (Fig. 1). All these food chains together form a closely interconnected network comparable to a spider's web. Within this trophic network, important exchanges of organic matter and energy take place.

There are five main trophic compartments.

– I: Primary food sources, represented by primary producers (phytoplankton, microphytobenthos, algal turf, benthic macroalgae, marine phanerogams) and organic matter reservoirs (particulate and dissolved parts of the sediment, and seawater). These primary sources are numerous and sometimes complex. Some of them result from the accumulation of organic matter of various origins (marine or terrestrial, pelagic or benthic, indigenous or allochthonous).

– II: Primary consumers, which feed on primary producers or organic matter. They consist mainly of zooplankton organisms, filter feeders (e.g., oysters), herbivores (e.g., parrotfish) or detritus feeders (e.g., holothurians and some shellfish).

– III: Secondary consumers, which feed on primary consumers, including mainly omnivorous or carnivorous species.

– IV and V: Tertiary and quaternary consumers, which are the top predators of coral reefs and whose diet is strictly carnivorous (e.g., groupers and sharks), or even exclusively piscivorous (e.g., barracudas).

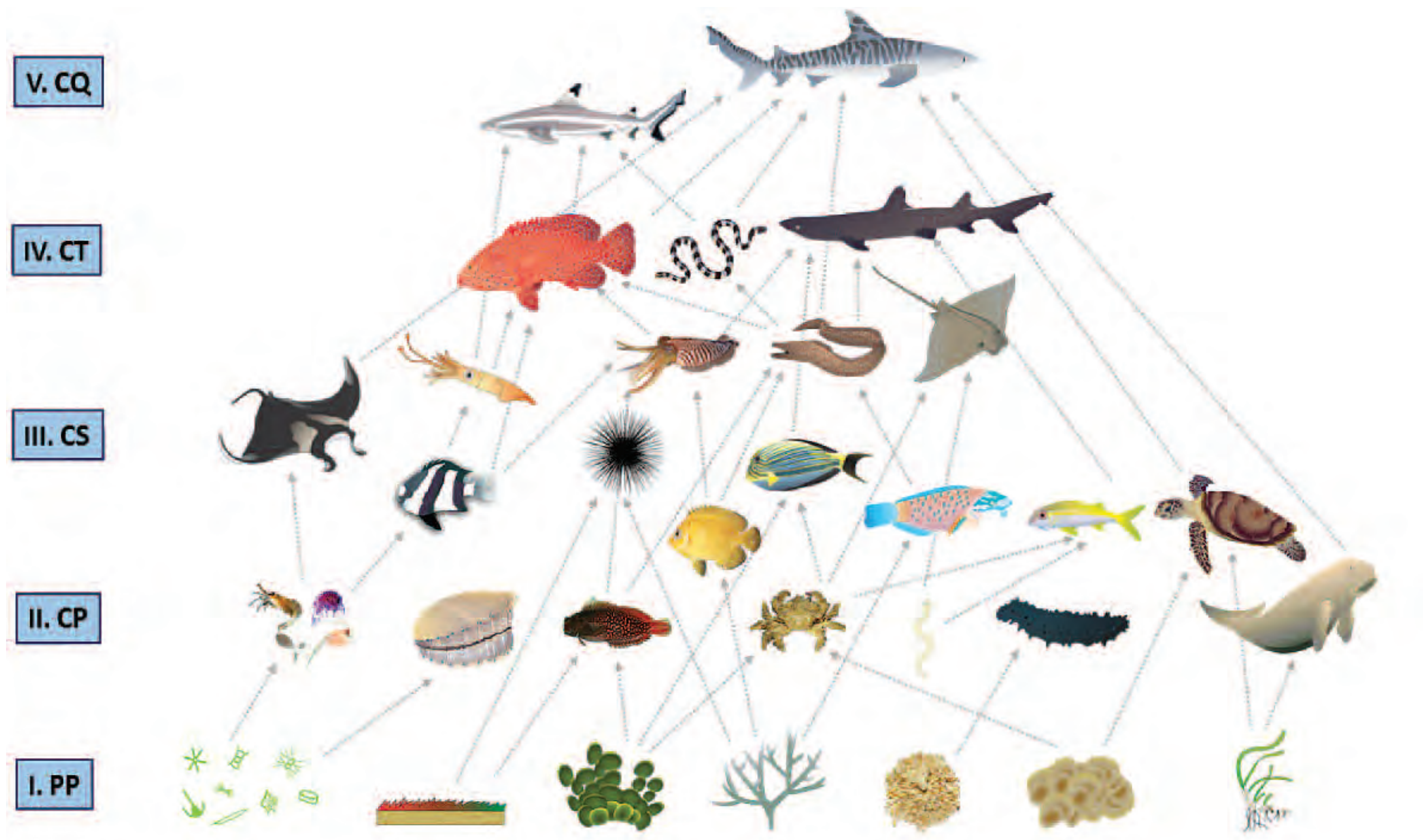


Figure 1: Simplified diagram of trophic networks of the reef and lagoon ecosystem of New Caledonia. Arrows indicate food interactions between organisms in the five main compartments. I: Primary producers (PP). II: Primary consumers (PC). III: Secondary consumers (SC). IV: Tertiary consumers (TC). V: Quaternary consumers (QC).
© M.J. Briand, images http://ian.umces.edu

A giant triton *(Charonia tritonis)* devouring a coral-eating starfish *(Acanthaster planci)*. © M. Juncker

Several of the major food webs of the lagoons of New Caledonia are already known (BRIAND, 2014). These are the "sedimentary network" (i.e., those based on organic matter associated with sedimentary particles), the "reef network" (based on organic matter essentially related to "algal turf"), the "lagoon network "(based on organic particles and/or phytoplankton present in seawater) and the "detritic network"(based on marine phanerogams and algae debris that are not directly digestible by the majority of herbivores). The first two networks are the largest in terms of organic matter fluxes within coral reefs, while the contribution of latter two is more indirect. These four food webs are supplied by different sources of organic matter, but they are closely linked. They are often found in very close habitats, and their primary resources or prey can be used by the same consumers.

The export of organic material (various debris, particulate and dissolved matter) between the different reef and lagoon habitats clearly demonstrates the importance of ecosystems associated with coral reefs such as seagrass beds and mangroves. It is possible that the discovery of other food webs will help to better understand the functioning of New Caledonia's coral reefs.

Complex relationships

The complexity of the relationships between these compartments lies in the multitude of diets that are interacting. This complexity is found, for example, in the association of specialist organisms such as the obligatory corallivorous butterflyfish *Chaetodon trifascialis* with opportunistic species such as most medium-sized carnivorous fish. Furthermore, each organism may change its diet over the course of its life depending on several biological (e.g., size, reproduction) or environmental factors (e.g., season, habitat characteristics, disturbances). For example, the juvenile short-nose unicorn fish *(Naso unicornis)* is a zooplankton feeder, which becomes herbivorous as an adult. Similarly, herbivorous organisms such as gastropod mollusks graze specific algae assemblages which are seasonal.

Knowledge about the diet of reef organisms is regularly updated and even re-evaluated following an evolution in research methods. Traditional research methods mostly involve the observation of stomach contents of organisms. However, in the past few years, new biochemical tools have started to provide additional information for the interpretation of diets and trophic relationships. These methods include the analysis of the composition in carbon and nitrogen stable isotopes, fatty acids and amino acids present in an organism's tissues.

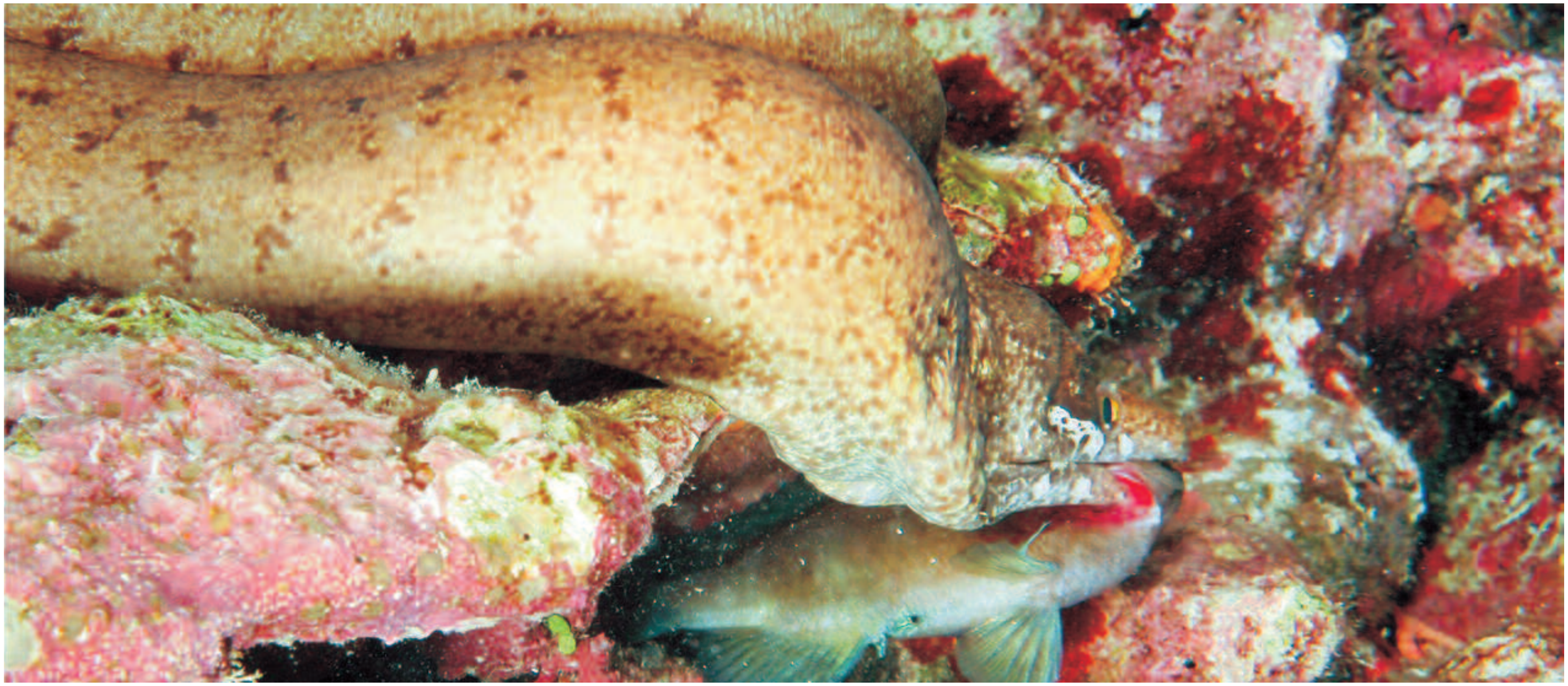
For example, biochemical tools have shed new light on the diet of the reef urchins *Parasalenia gratiosa* and *Echinometra mathaei*. Following the traditional observation of their stomach contents, these two species were classified as herbivores; but the high isotopic nitrogen signatures of their tissues suggested a more omnivorous, sometimes even carnivorous, diet. This finding can be explained by their feeding mode, which involves "substratum scraping". In addition to the consumption of algae, this feeding mode favors the ingestion of invertebrates attached to the substratum, such as sponges, bryozoans and even young coral (BRIAND, 2014).

Recent mathematical models can predict the relative contributions of each prey to a predator's diet and based on the knowledge of an organism's diet and habitat, it is possible to delineate the extent of its trophic niche and to develop hypotheses about its competitive interactions for nutrient resources. Biochemical tools are also particularly useful for identifying the origin of the various food sources that make up the reservoirs of organic matter that support food webs in coral reefs. Similarly, models are used to estimate the contribution of each food source to the organic matter reservoir.

A fragile equilibrium

The study of trophic networks identifies the key ecological role of the different groups or guilds of reef organisms with similar diets, known as "trophic groups". Some species are clearly identified as key elements of the New Caledonian reefs. For example, the role of herbivores (in its broadest definition) is particularly fundamental to coral reefs as, through grazing, they significantly control the development of algae, thus making it possible for corals, which grow more slowly, to remain competitive for space occupation. An imbalance in the functioning of feeding

The nudibranch (sea slug) *Hypselodoris infucata* grazing on green algae *Halimeda* in the Southern Lagoon. © M. Juncker



The moray eel *Gymnothorax zonipectis* attacking a fish. Lifou. © M. Juncker

interactions can have important consequences, but it is possible to anticipate the effects of disturbances on these fragile food webs. Cascading effects known as "bottom-up" and "top-down" effects are characterized by imbalances which affect the entire network either from the bottom (i.e., from the primary resources) or from the top (i.e., from top predators), respectively. While these effects are largely studied on a global scale, they are not yet precisely described for the coral reefs of New Caledonia.

The pollution of the New Caledonian lagoon by various contaminants such as metal and metalloid trace elements (e.g., arsenic, cobalt, mercury, nickel, etc.) or organic compounds (e.g., pesticides, polychlorinated biphenyls, etc.) can be seen in food webs. All trophic compartments contain detectable levels of contaminants at variable concentrations depending on the compounds and organisms considered. A recent study has identified the pathway of selected trace elements such as mercury, selenium and, to a lesser extent, arsenic in the food web structures and the "sedimentary" and "reef" networks were identified as the main channels (BRIAND, 2014). Other elements are present in different organisms but there are no clear links between the level of contamination and the position of the organism in the food web.

These networks are essential in the functioning of an ecosystem. Studying them in reef ecosystems is challenging, but crucial for improving protection and management plans. The coral reefs of New Caledonia are a formidable environment for research because of the exceptional natural heritage that they represent, but also because of the many natural (cyclones, heavy sedimentation, bleaching events) and anthropogenic threats (mining discharges, urban pollution, nautical activities) that they face.

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Chapter 19

The New Caledonian lagoon: dolphins' shelter and restaurant

Marc Oremus

The Indo-Pacific bottlenose dolphin *(Tursiops aduncus)* has a relatively uniform color, grey or light brown depending on light. © M. Oremus

Of the 12 dolphin species identified to date in New Caledonia, two visit the lagoons on a daily basis: the bottlenose dolphin *(Stenella longirostris)* and the Indo-Pacific bottlenose dolphin *(Tursiops aduncus)*.

A part-time shelter for some

The day of the spinner dolphins is runs like clockwork. At night, they survey offshore waters in search of small fish that come up from the depths. At sunrise, they reach the reefs where they can socialize and rest, away from large oceanic predators. There, they usually form large groups of 15 to 60 dolphins. In the evening, they begin an acrobatic ballet that strengthens their relationships, before returning to the ocean.

A permanent home for others

The life of the Indo-Pacific bottlenose dolphins is closely linked with lagoons because it is the place where they feed, reproduce and rest. Several small resident populations, which are socially and genetically distinct, have been observed around Grande Terre. Often in small groups of two to ten dolphins, they are less acrobatic than their spinner counterparts, but they can be curious, and it is not uncommon to see them bow riding.

A group of spinner dolphins *(Stenella longirostris)* resting on a shallow reef area. © M. Oremus

Key players for the reefs

The role played by dolphins in coral environments is poorly known, but there is little doubt that it is major. Indo-Pacific bottlenose dolphins are top predators and therefore play an important role in regulating the food chain in reef ecosystems. While spinner dolphins do not feed in lagoons, they bring in a significant amount of organic matter from the open ocean with their droppings. The extent of this phenomenon has yet to be determined, but it is known to benefit reef fish.

Chapter 20

Vulnerable and threatened: the seabirds of the Coral Sea

Philippe Borsa and Éric Vidal

Bridled tern (*Onychoprion fuscatus*), Chesterfield Islands © IRD/E. Vidal

The Coral Sea, a tropical sanctuary for seabirds

The term "seabirds" refers to several families of birds that mostly live at sea or on the shore, and mainly feed on marine animals: fish, crustaceans, squids and other marine invertebrates. Shearwaters and petrels are typical oceanic birds. They are remarkably efficient gliders, good divers, and are capable of transoceanic migrations. The birds of two other families, frigatebirds and tropicbirds, also spend most of their lives offshore, flying over very long distances across the oceans. The foraging range of boobies extends more or less offshore where they usually plunge-dive to catch fish, although they are also able to catch flying fish in midair. Terns and noddies include both oceanic and coastal species and seagulls feed at the coast or in the lagoon. All these species come back to the shore for breeding because seabirds, like most birds, incubate their eggs and raise their chicks at, or near, the nest for several weeks to several months

The Coral Sea is one of the last tropical regions on the planet where the impact of human activities has been relatively low. Therefore, seabirds, which are sensitive indicators of the state of preservation of marine ecosystems, are still diverse and abundant. Because of their isolation and proximity to feeding areas at sea, coral cays and islets are prime sites for nesting seabirds and are also used for resting outside the breeding season. Although small, these coral cays are essential habitats for seabirds. During the breeding season, they can host entire populations of birds that usually occupy hundreds of thousands of square kilometers over the ocean.

Most of the seabird colonies of New Caledonia are concentrated on four groups of reefs: the Chesterfield-Bampton Archipelago in the middle of the Coral Sea, the d'Entrecasteaux Reefs to the north of Grande Terre and the islets of the northern and southern lagoons. Uplifted and uninhabited coral reef islands, such as Beautemps-Beaupré and Walpole, are also favorable sites for the reproduction of seabirds. Walpole Island alone is home to at least 11 species of breeding seabirds, including a large colony of brown boobies and one of the few white tern colonies in the Southwest Pacific.


Red-footed boobies *(Sula sula)* in velvetleaf soldierbush, Chesterfield Islands. © IRD/P. Borsa


Black noddy *(Anous minutus)* Surprise Island. © IRD/E. Vidal


Masked booby *(Sula dactylatra)* and chick, Loop Islet, Chesterfield. © IRD/R. Proner

Engineers of coral cays and islets

Different breeding seabird species colonize islets with different vegetation types. For example, the fairy tern lays its eggs in the sand or among coral debris on beaches and sandy cays. Other terns, such as the roseate tern or the sooty tern, nest in dense colonies on cays with almost no vegetation. Others, such as the white tern and the black noddy nest in trees, and therefore only settle on tree-covered cays and islets. Brown noddies can arrange rudimentary nests on the ground or build large and very elaborate nests made of intertwined thin twigs, low down in shrubs. Similarly, the brown booby and the masked booby lay their eggs on the ground, while the red-footed booby and the great frigatebird build large nests made of branches in the trees. Among the petrels, the wedge-tailed shearwater and the Tahiti petrel dig burrows either in sand patches consolidated by herbaceous vegetation or sheltered by the roots of trees. Black-winged petrels also nest in burrows, but they tend to prefer tree-covered islets.

Seabird colonies established on bare cays promote the development of vegetation by fertilizing the islet with their droppings, which contain nitrates and phosphates. An ephemeral ecosystem develops during the breeding season and takes part in the genesis of the soil of the islet, with the contribution of organic matter from unhatched eggs, uneaten regurgitated preys, and dead

Brown bobby *(Sula leucogaster)*, île Surprise. © IRD/E. Vidal

bird carcasses. The vegetation contributes to the stabilization of the islet, increases its resilience to tropical cyclones, and therefore maintains the habitat available for breeding seabirds. Lastly, the decomposition of terrestrial plants, algae and other floating debris used for nests, as well as the accumulation of seabird droppings contribute to the vertical growth of the islets. Nutriments leaching into the water, or seabird droppings that are released directly into the ocean, possibly also contribute to the growth of corals. In conclusion, not only do seabirds play a key role in the growth and stabilization of coral reefs and islets, but it is possible that they also increase their resilience to extreme weather conditions.

A remarkable biodiversity

Twenty-four seabird species breed in the New Caledonian archipelago (Tabl. 1). The Gould's petrel is the only seabird that nests exclusively in the mountains of Grande Terre. All the other species have been reported to nest on coral cays and islets. The New Caledonian populations of fairy terns, silver gulls and Tahiti petrels are considered to be subspecies endemic to the Coral Sea, although the latter two still have to be confirmed by genetic analyses.

Fairy terns nest in the Chesterfield-Bampton Islands, and on cays of the northern and the southern lagoons. This species used to have a wider distribution in New Caledonia, but the total population is now limited to a few dozen breeding pairs. This makes fairy terns one of the most threatened species in New Caledonia. They are particularly sensitive to disturbance from visitors, which causes reproductive failure.

The most abundant seabird of New Caledonia is the wedge-tailed shearwater. The numerous colonies on islets of the southern and northern lagoons, and in the Chesterfield-Bampton Archipelago, each include several hundred to several tens of thousands of breeding pairs. With a total population exceeding 500,000 breeding pairs, New Caledonia hosts a significant part of the world's population for this species (estimated at about 5 million individuals). Such an abundance can be explained by several factors. Firstly, the availability of nesting sites free from natural predators; secondly, the availability of prey in sufficient densities within the seabirds' prospecting radius, their adequate size and quality (squid and small pelagic fish), and their accessibility (marine predators such as tuna and cetaceans bring schools of fish closer to the surface and make them more accessible to seabirds). Wedge-tailed shearwaters, like other petrels, are also able to adapt their foraging strategy to the spatial availability of resources according to the phase of their breeding cycle. During the breeding season, the seabirds go out to sea for short trips of one or two days in the proximity of the colony. When they return, they regurgitate their prey to feed their chicks. These short trips alternate with longer trips (of up to 12 days) further offshore, during which they forage for themselves. Once relieved from the constraints of breeding on land, the wedge-tailed shearwaters migrate across the ocean to reach the tropical water resources of the North Pacific, between Micronesia and the Line Islands.

Two other emblematic species breed, or have bred, on New Caledonian coral cays: the Herald petrel and the Polynesian storm-petrel. The Herald petrel was described from three specimens, presumed to have been collected during a visit by the British ship Herald to the Chesterfield Islands in the mid-nineteenth century. This was before the intensification of whaling expeditions to the Coral Sea and before guano mining. Since then, there has been no other observation of breeding Herald petrels in New Caledonia. The Polynesian storm-petrel was reported from the Northern Lagoon (Grand Lagon Nord) in the 1990s but has not been observed since and is presumed to have disappeared. According to the IUCN, this species is threatened by extinction, mainly because of introduced predators.

Populations threatened by anthropic activities

On Walpole Island and on many coral cays and islets around Grande Terre and in the Coral Sea, seabirds are exposed to predation by rodents that have been introduced by humans: the Polynesian rat, the black rat and the domestic mouse. Other undesirable invasive species include the electric ant, which harasses the nesting birds, and the cactus opuntia, which colonizes breeding sites and obstructs access to burrows. Environmental changes induced by invasive species have a direct impact on seabird populations and can, in extreme scenarios, lead to local extirpation, which is likely to be the case for the Polynesian storm-petrel. Over the past two decades, rodent eradication campaigns have provided some respite for breeding seabirds at d'Entrecasteaux Reefs, in the Northern Lagoon (Grand Lagon Nord), and in the Southern Lagoon (Grand Lagon Sud).

Past human activities have also been a major cause of the degradation of nesting habitat. The Chesterfield Islands served as a land base for whalers operating in the Coral Sea and crews chopped wood for fire and collected eggs and chicks. Today, humans are still predators of seabirds on remote islets, as fishing vessels that venture to the Chesterfield-Bampton and d'Entrecasteaux reefs still capture booby and frigatebird chicks for food. Guano extraction, which took place at Chesterfield and d'Entrecasteaux, devastated the vegetation and soil of the islets, exposing them to extreme weather events. This may have caused the extinction of the Herald petrel and the red-tailed tropicbird in the Chesterfield Islands, and that of the silver gull on the d'Entrecasteaux Reefs.

The landing of visitors on the islets is another threat that is too often overlooked. A boat approaching an island is sufficient to flush out the breeding seabirds, and therefore expose eggs and chicks to scorching sun and dehydration. This can compromise the whole breeding season of a colony. Furthermore, visitors on foot can trample tern eggs and petrel burrows, and their dogs can catch both chicks and adults. The disturbance is at its highest during the holiday season, with fireworks, loud music and people partying on islets. The development of tourism increases the number of visitors on islets and decreases habitat availability for breeding seabirds. A tourist cruise company has recently decided to stopover at one of the most remote islets of the Southern Lagoon and at the Chesterfield-Bampton Islands. It advertises a "true paradise for nature lovers, which offers long pristine beaches to visitors and is home to thousands of seabirds". The huge size of a cruise ship anchoring near the islets, and the hundreds of tourists that would disembark, would be likely to seriously threaten the breeding season of the seabirds.

To the list of depredations experienced by seabird colonies, we can add the censuses done by amateur naturalists as without proper scientific supervision they represent a risk of disturbance and trampling, or the "health monitoring" program led by the veterinary authorities in the 1990s and which has leads to the sacrifice of many seabirds of the Chesterfield Islands and Entrecasteaux.

Paths for future research on New Caledonian seabirds

With the miniaturization of electronics, it is now possible to fit seabirds with Argos transmitters, GPS trackers and other devices such as diving recorders and heart rate sensors. Recorded data help us to better understand seabird movements and biology, as well as their behavior during their time away from the colony. In the future, it should be possible to automate the collection of data with recorders positioned near the nests. These devices will be able to download data every time a seabird visits its nest without any human action, thus minimizing the risk of disturbance. In addition to the knowledge that is acquired on seabirds themselves, it is now possible to consider using seabirds as "auxiliaries" for research programs. For example, seabirds will be able to inform scientists about sea temperature, or about the nature, depth and density of their prey. All this information will help us to better understand the ecology of the Coral Sea and the impact of global change on oceanic ecosystems.

Black noddy *(Anous minutus)* fishing at the Longue Island Pass, Chesterfield. © IRD/P. Borsa

Species	Scientific name	Nesting sites						
		Chest.	d'Entr.	GTL	N. Lag.	S. Lag.	W	M., H.
Seabirds *sensu stricto*								
Silver gull	*Chroicocephalus novaehollandiae*	-	†	-	X	X	-	-
Fairy tern	*Sternula nereis*	X	-	†	X	X	-	-
Black-naped tern	*Sterna sumatrana*	X	X	X	X	X	-	-
Roseate tern	*Sterna dougallii*	X	-	-	X	X	-	-
Crested tern	*Thalasseus bergii*	X	X	X	X	X	-	-
Bridled tern	*Onychoprion anaethetus*	-	-	-	X	X	-	-
Sooty tern	*Onychoprion fuscatus*	X	X	X	X	-	-	X
White tern	*Gygis alba*	-	-	-	-	X	X	X
Brown noddy	*Anous stolidus*	X	X	-	X	X	X	X
Black noddy	*Anous minutus*	X	X	-	-	X	X	X
Grey noddy	*Anous ceruleus*	-	-	-	-	-	X	X
Red-tailed tropicbird	*Phaethon rubricauda*	†	X	X	-	-	X	X
White-tailed tropicbird	*Phaethon lepturus*	-	†	-	-	-	X	-
Brown booby	*Sula leucogaster*	X	X	X	X	†	X	X
Masked booby	*Sula dactylatra*	X	X	X	X	†	-	X
Red-footed booby	*Sula sula*	X	X	-	-	X	X	X
Lesser frigatebird	*Fregata ariel*	X	X	-	-	-	X	X
Great frigatebird	*Fregata minor*	X	X	-	-	-	X	X
Wedge-tailed shearwater	*Ardenna pacifica*	X	X	X	X	X	?	X
Tahiti petrel	*Pseudobulweria rostrata*	-	-	X	X	X	-	-
Herald petrel	*Pterodroma heraldica*	† ?	-	-	-	-	-	X
Gould's petrel	*Pterodroma leucoptera*	-	-	X	-	-	-	-
Black-winged petrel	*Pterodroma nigripennis*	-	-	?	-	X	-	X
Polynesian storm petrel	*Nesofregetta fuliginosa*	-	-	-	†	-	-	?
SHOREBIRDS								
Great cormorant	*Phalacrocorax carbo*	-	-	X	-	-	-	-
Little pied cormorant	*Phalacrocorax melanoleucos*	-	-	X	-	-	-	-
Osprey	*Pandion heliaetus*	-	-	X	X	X	-	-
Beach thick-knee	*Esacus magnirostris*	-	-	-	X	-	-	-

Table 1: List of breeding seabird and shorebird species recorded over the last two decades at different reef systems in the New Caledonian archipelago
Chest.: Chesterfield-Bampton.
D'Entr.: d'Entrecasteaux.
GTL: Grande Terre-Loyaty.
N. Lag.: Northern Lagoon.
S. Lag.: Southern Lagoon.
W.: Walpole.
M.: Matthew.
H.: Hunter.
†: species presumed locally extinct.
?: species believed to be breeding, but whose reproduction has not been formally recorded to date.
Adapted from SPAGGIARI *et al.*, 2007 and author's original data

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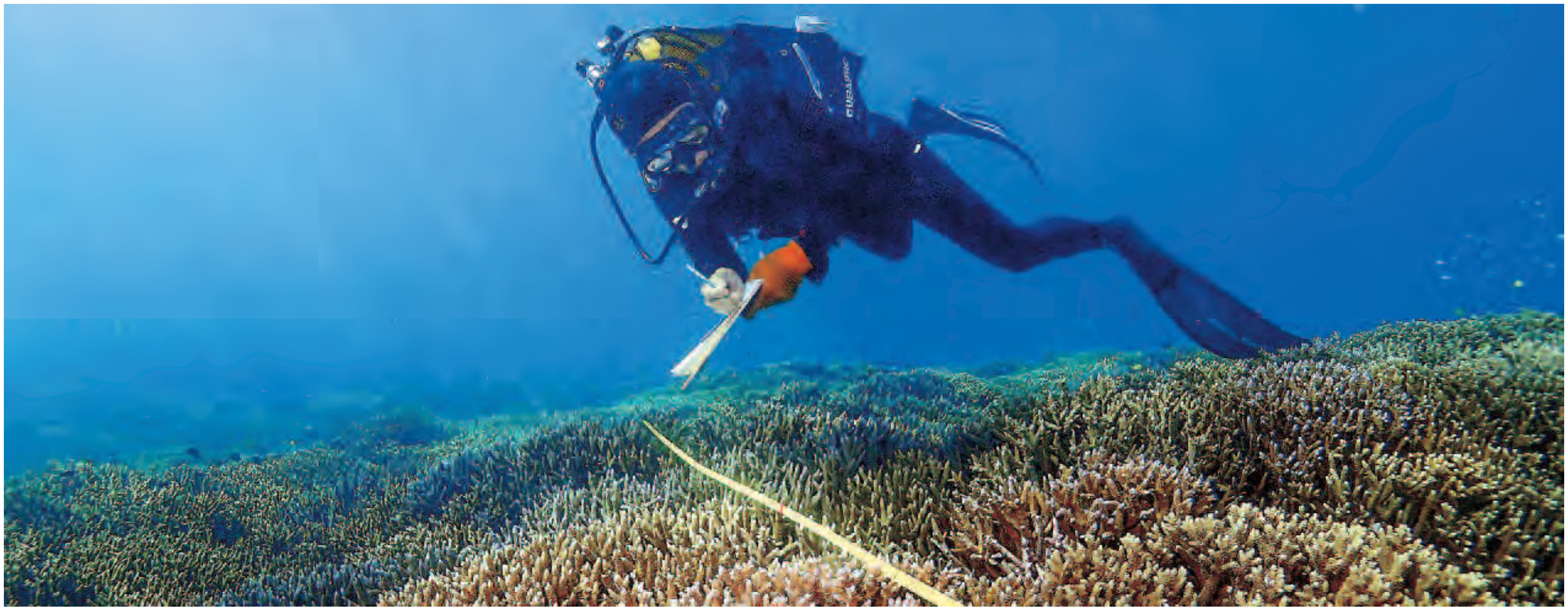
Chapter 21

Inventory of reef biodiversity for knowledge sharing

Éléonore Vandel, Sylvie Fiat, Jeanne de Mazières, Laurent Poncet and Pascale Joannot



Scuba diving survey at Larégnère Reef, March 2017. © IRD/S. Andréfouët

In 2006, IFRECOR (French Coral Reef Initiative) launched an interdisciplinary program on the biodiversity of French overseas coral reefs. From 2008 to 2016, this project was managed by the French overseas delegation at the National Museum of Natural History in Paris (MNHN) and implemented by the Natural Heritage Service (SPN). It aimed to collect all data available on reef biodiversity in the French overseas territories and make it available to as many people as possible on a website dedicated to the "National Inventory of Natural Heritage" (INPN [3]).

[3] http://inpn.mnhn.fr
[4] https://inpn.mnhn.fr/telechargement/referentielEspece/referentielTaxo

Major progress on the inventory of reef biodiversity

In 2006, information on reef biodiversity in French overseas territories was very scattered and there was no data available on the biodiversity of French coral reefs. By 2016, over 24,000 marine species records, available for all overseas territories with coral reefs, were included in the French taxonomic register TAXREF (V10[4]) developed for INPN, thanks to IFRECOR. However, this impressive figure is only a small part of the total number of existing species.

Thanks to this program, distribution maps have been updated for many species and nearly 300,000 occurrence data have been added to the INPN databases. All these data are accessible on the INPN website and have also been forwarded to GBIF (Global Biodiversity Information Facility[5]).

IFRECOR's final report provides a summary of the results obtained in 2015 for each overseas territory (VANDEL *et al.*, 2016). This work was only made possible through several partnerships with scientific experts and coral reef managers, the work of two successive project managers at the Museum's overseas delegation (Julien Ringelstein and Éléonore Vandel) and the involvement of the SPN team who implemented it, particularly Olivier Gargominy (in charge of TAXREF at SPN).

Focus on New Caledonia

The coral reefs of New Caledonia represent 50% of the French reef area and are exceptionally diverse geomorphologically. The 1,600 km long barrier reef is the second largest barrier reef in the world after the Australian Great Barrier Reef and in some places, a double or even a triple barrier reef can be observed. New Caledonia also has 400 km^2 of seagrass beds and about 260 km^2 of mangroves. In 2008, parts of the reefs and lagoons have been listed as UNESCO World Heritage sites.

Species lists

The marine species of New Caledonia were listed in 2007 in the *Compendium of marine species from New Caledonia* (PAYRI and RICHER DE FORGES (EDS), 2007), published by the IRD and produced in collaboration with many partners. Over 50 taxonomists were involved in this work and 43 large species groups were documented although the species lists of some of these groups have since been updated. Research carried out at the IRD has produced additional lists of algae species (works by Claude E. Payri), foraminifers and scleractinians (works by Francesca Benzoni in collaboration with M. Michel Pichon), crustaceans (in collaboration with IRENav, *Institut de recherche de l'école navale*), and fish (works by Michel Kulbicki, in collaboration with the University of New Caledonia and the Stuttgart Museum of Natural History). The Paris Museum (MNHN) regularly updates its species lists, including mollusks (330 species new to science between 2007 and 2015) and pursues its work on fish parasites.

Zoom in on algae

The Compendium of Marine Species of New Caledonia listed 443 species of macro-algae in 2007. This list was subsequently expanded to 500 species in TAXREF using recent publications and additional IRD data (Lagplon[6]). A number of new species have been described (e.g., *Sebdenia cerebriformis*, N'YEURT and PAYRI, 2008) from various locations in the Southwest Pacific, including New Caledonia.

Species distribution

LAGPLON is an Indo-Pacific marine biodiversity data collection, part of the IRD research center in Nouméa. It contributed nearly 5,000 data on approximately 1,000 species of benthic flora and fauna recorded from New Caledonia's coastal waters to the INPN database (box 18).

A collaboration with the IRD also enabled Michel Kulbicki and his research team to integrate and make available all their data on fish occurrence collected between 1984 and 2005. In total, nearly 160,000 data on about 1,000 fish species are now available online and over 25,000 occurrence data from the MNHN collections have also been released (mollusks, echinoderms and crustaceans).

Data from the Pacific Regional Oceanic and Coastal Fisheries Development Program of the SPC (Pacific Community) added 10,800 fish and 7,000 marine invertebrate observations to the French inventory.

Lastly, the data collected in 2001 during the Rapid Assessment Protocol of the Diahot region (northern New Caledonia, WWF and EPHE) made it possible to update the distribution maps of more than 700 scleractinian and fish species.

[5] www.gbif.org
[6] https://inpn.mnhn.fr/espece/jeudonnees/37 ou http://lagplon.ird.nc

Box 18

70 years of georeferenced marine biodiversity data

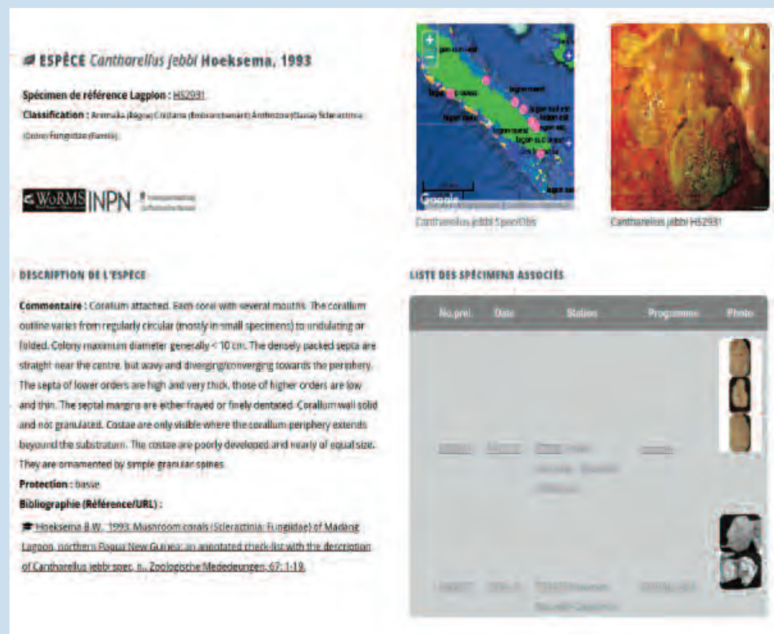
Sylvie Fiat and Claude E. Payri

The 1970s saw the start of hyperbaric diving at the ORSTOM research center in Nouméa (now IRD). The biologist divers of ORSTOM were about to introduce scientists to the astonishing marine biodiversity of the reefs and lagoons of New Caledonia. This journey truly started with the pharmaco-chemical program “SNOM” (Natural Substances of Marine Origin) in 1977 followed by “SMIB” (Natural Substances of Biological Interest) in 1982, and the growing oceanographic vessel fleet: Le Vauban and La Santa Maria in 1976 and Le Dawa in 1977.

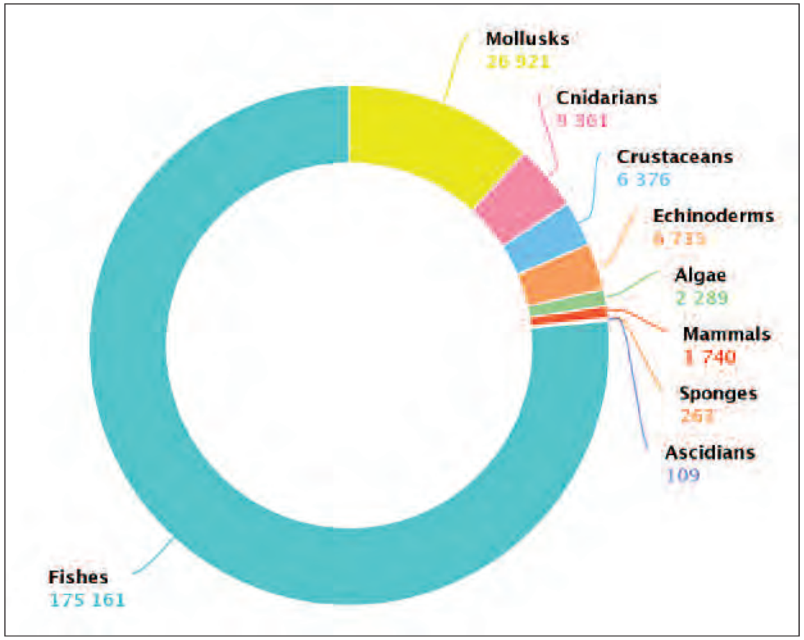
With the arrival of the research vessel Alis in 1987, surveys intensified and provided many specimens which then became reference collections. These collections are still studied today by an international network of taxonomists and are partly housed at the Muséum National d'Histoire Naturelle (MNHN) in Paris and at the IRD research center in Nouméa. From the beginning, the very passionate and involved divers recorded all their observations in logbooks and created an extremely rich bank of images, first on films and later digital. Very early on, they also created a database called "LAGPLON".

60 years later, knowledge has evolved and accumulated. Most species have been identified by taxonomists and published in various volumes of the Fauna and Flora collection of the IRD (formerly ORSTOM) and numerous scientific journals. After the remarkable work of updating all the data, including the digitization of thousands of photographs and the development of a website, the 20,000 specimens in the collection and the 25,000 georeferenced underwater observations are now accessible in a few clicks through interactive maps and modern search engines.

The first biological surveys using scuba began aboard La Santa Maria, commissioned in 1975. They continued with Le Vauban (A), a 24.5 m long trawler equipped for fisheries and hydrology programs, which arrived in Nouméa in 1976. The new vessel Dawa (B), an 11 m long trawler acquired in 1977, marked a particular turning point for diving exploration in the lagoon and reef environments of Grande Terre. Alis (C), a 28.40 m long vessel, took over in 1987 and still navigates beyond the New Caledonian EEZ.
A: © B. Delacroix/IRD; B: © M. Monzier/IRD; C: © S. Andréfouët/IRD



The data compiled in LAGPLON provide information on species and their distribution. Here, an example of a hard coral species. © LAGPLON



Number of marine data available for New Caledonia per taxonomic group.
Adapted from INPN, November 2017

Today, taxonomic studies are still ongoing through various programs carried out by several teams including the Paris Museum (MNHN). The generalization of genetic analyses provides new insights on the extent of this biodiversity, revealing many new species. In Nouméa, special efforts are being directed at the study of regional macroalgae and hard corals. These two major groups represent significant digital collections with nearly 20,000 and 5,000 specimens, respectively. They are studied and processed in several doctoral and post-doctoral programs.

The historic collaboration of the IRD with MNHN has led to the publication of LAGPLON data at the national level and international level: in 2012 in the National Inventory of Natural Heritage (INPN) and since 2015 in the Global Biodiversity Information Facility (GBIF). New Caledonia's marine biodiversity data are also recorded in databases established by other research teams. LAGPLON is linked to these databases and makes these data available to the public.

Perspectives

A few taxonomic groups, such as annelids or hydrozoans, are still little known in New Caledonia. Many areas have not been surveyed and the knowledge of marine invertebrates is still incomplete. With this in mind, since 2016 the "Our Planet Reviewed" program, led by the French National Museum of Natural History, has launched a series of scientific expeditions to carry out an inventory of New Caledonia's "neglected" biodiversity. The program involves many New Caledonian, national and international partners.

Increasing the cooperation between the PAtriNat UMS, a unit dedicated to natural heritage expertise, and most French data-producing organizations is also contributing to the national inventory (INPN) at a rate of over 5 million occurrences per year, as measured by the French National Observatory for Biodiversity indicator (ONB)[7].

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Part 3

Coral reefs: impacted but resilient

Coordinator: Jérôme Aucan

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

Tom Biscéré, Anne Lorrain, Riccardo Rodolfo-Metalpa, Richard Farman, Antoine Gilbert, Andy Wright and Fanny Houlbrèque

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).

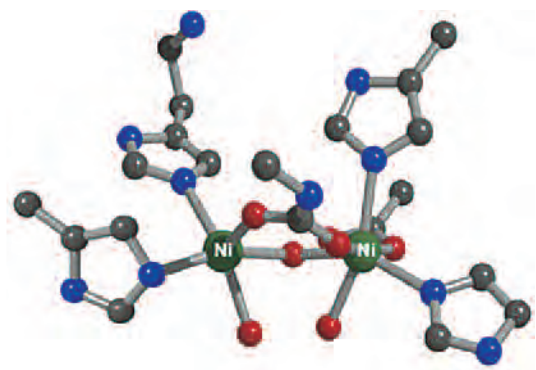


Figure 1: Chemical representation of urease showing the active site containing a double nickel nucleus. Adapted from www.rcsb.org

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.

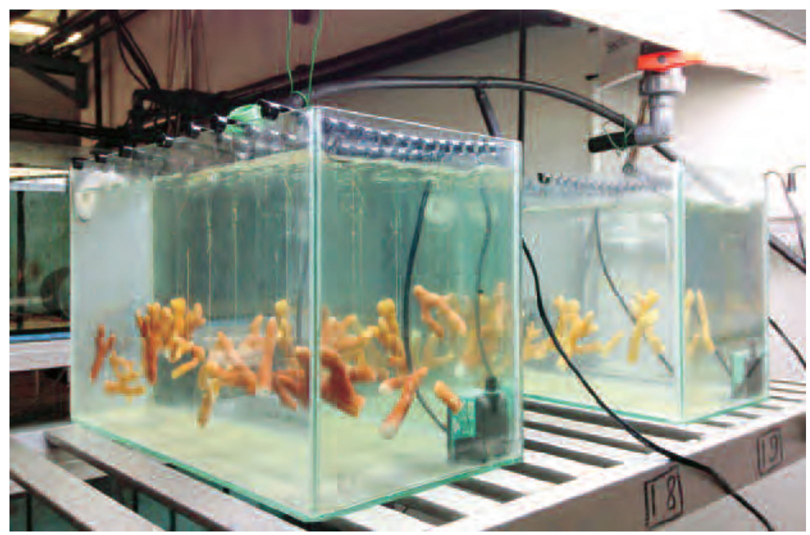
Nowadays, it is difficult to know whether regular inputs of metals, as is the case in New Caledonia with mining operations, will exacerbate the adverse effects of climate change on corals or not. To answer this question, laboratory experiments were carried out to test the combined effects of acidification 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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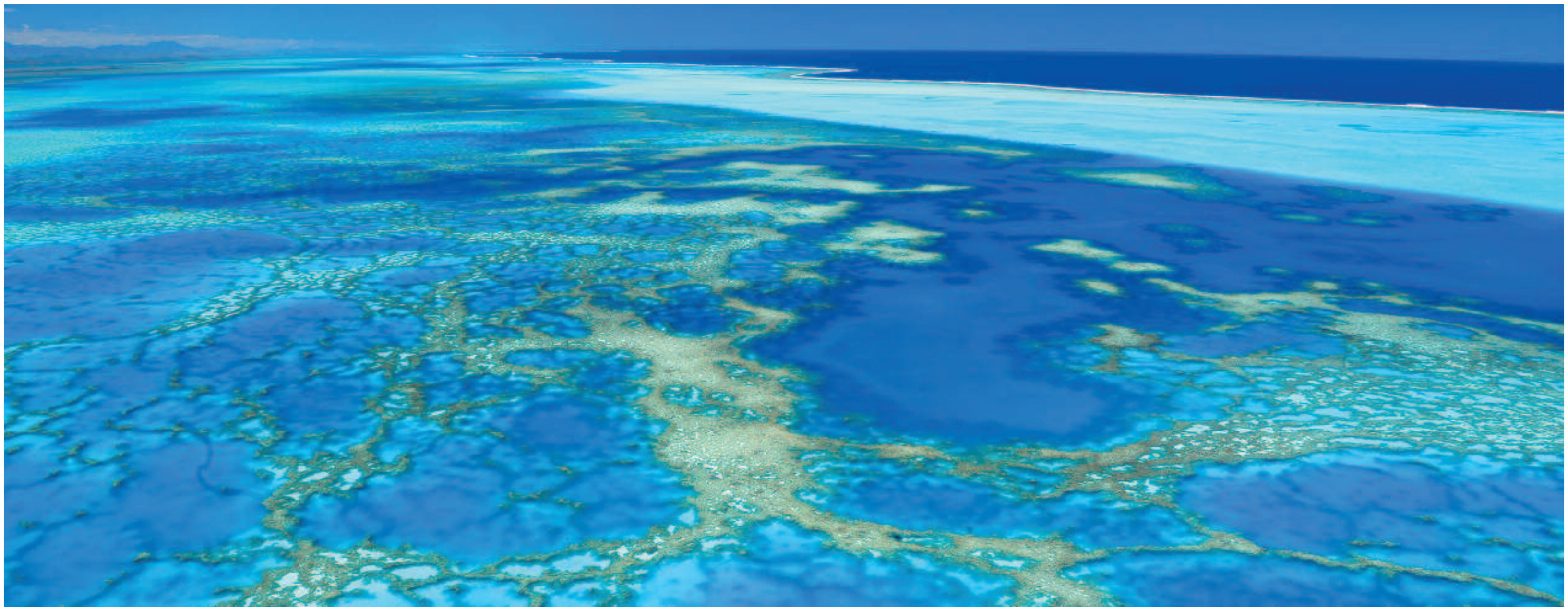
Soil erosion brings metal-rich sediments to the lagoon. © P.-A. Pantz

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

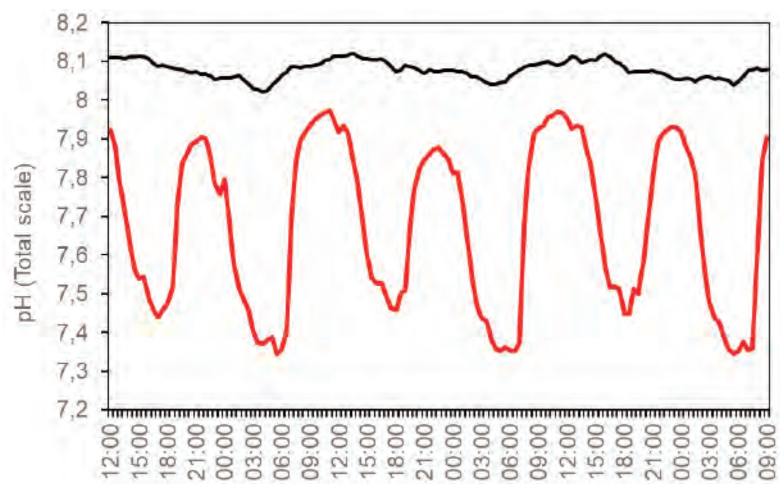


Figure 1: Tidal pH changes at the study site (red) and at a control site, outside the mangrove system (black). © IRD/R. Rodolfo-Metalpa

Box 19

Ocean acidification, a threat to corals?

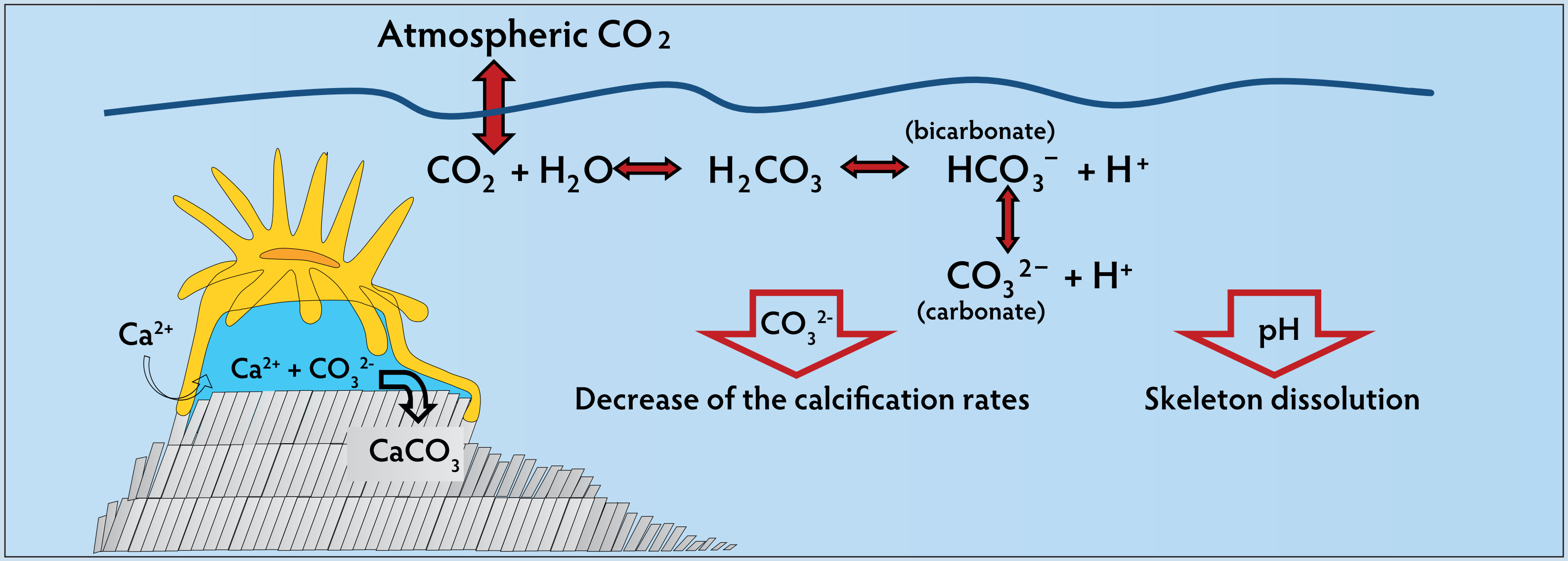


Diagram of calcification and decalcification (dissolution): Dissolved carbon dioxide (CO_2) reacts with water (H_2O) to produce carbonice acid (H_2CO_3): $CO_2 + H_2O \leftrightarrow H_2CO_3$
Carbonic acid is then uncoupled in bicarbonate: $H_2CO_3^- \leftrightarrow HCO_3^- + H$
The bicarbonate ion is 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).

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.

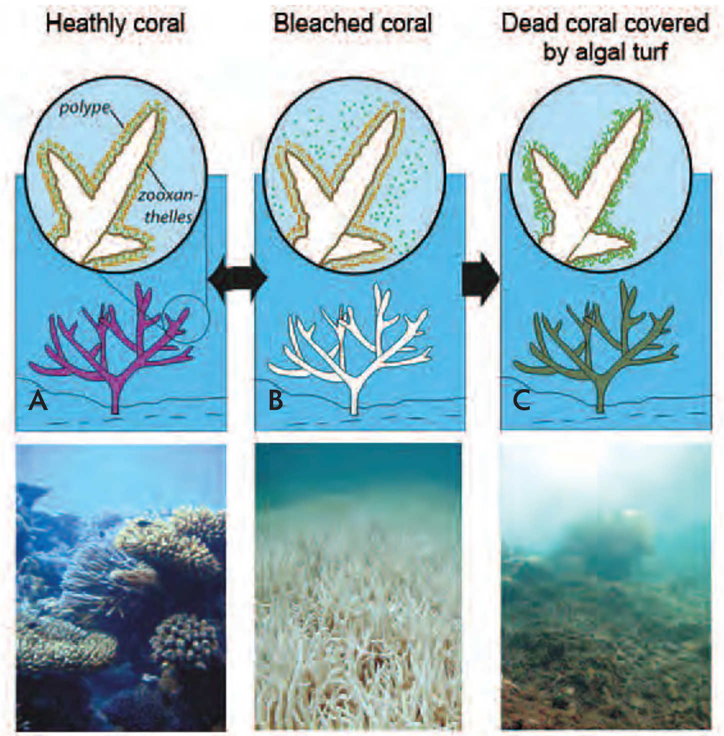


Figure 1: Diagram of coral bleaching at colony level (top) and community level (bottom).
A: Healthy coral with zooxanthellae and normal coloration.
B: Bleached coral after expelling zooxanthellae.
C: Algal turf on dead coral skeleton.
Adapted from http://www.gbrmpa.gov.au/managing-the-reef/tareats-to-the-reef/climate-change/what-does-this-mean-for-species/corals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

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).

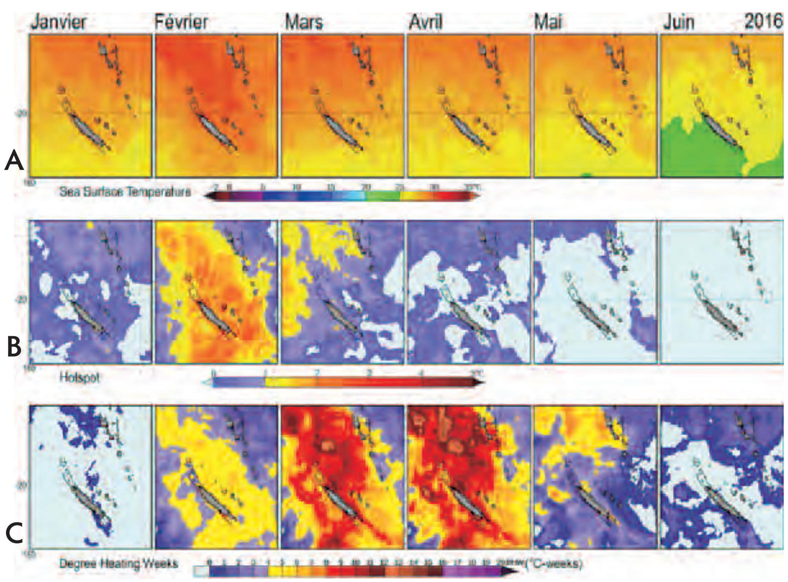


Figure 2: Sea surface temperature maps
A: of the Coral Bleaching Hotspot.
B: of the Degree Heating Week around New Caledonia during first semester 2016.
C: Data for 15th day of each month.
https://coralreefwatch.noaa.gov/satellite/bleaching5km/index.php

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.

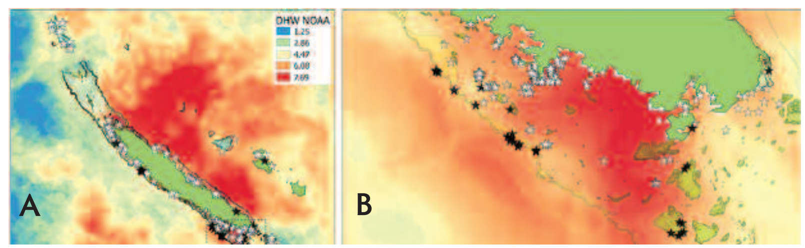


Figure 3: Location of observations (stars) made between March and April 2016.
A: Around Grande Terre.
B: In the Southern Lagoon and compared to Degree Heating Week map in °C-weeks, mid-February 2016 (NOAA 50-km SST Anomaly Product). The presence or absence of bleaching is marked by white (observed bleaching) 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.

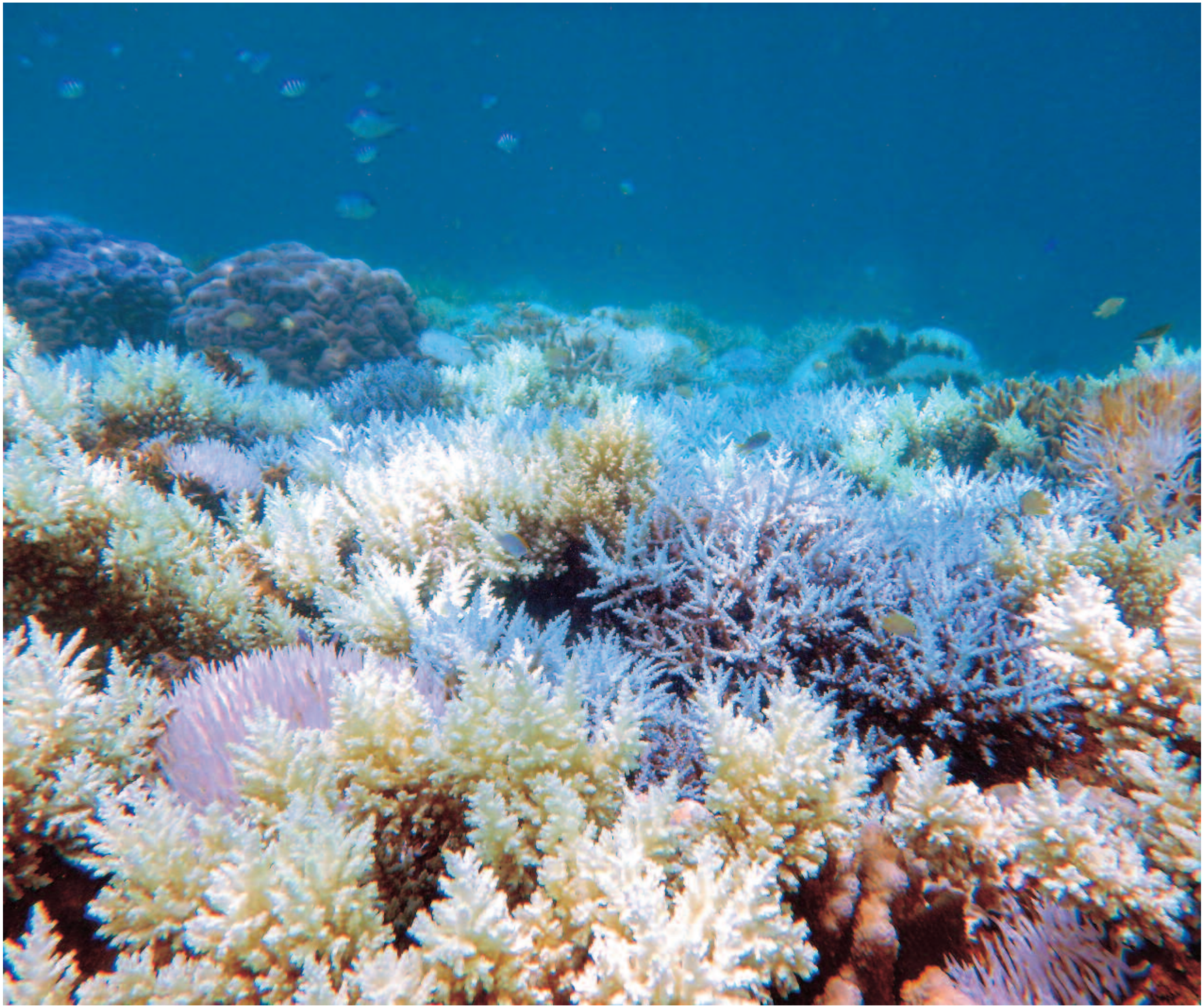
While in January 2017, several areas of the Great Barrier Reef were experiencing a consecutive year of coral bleaching, the vast majority of New Caledonia's reefs were spared. During the February 2017 monitoring (POST-BLANCO campaign[11]), researchers reported a higher mortality rate for coral communities 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,

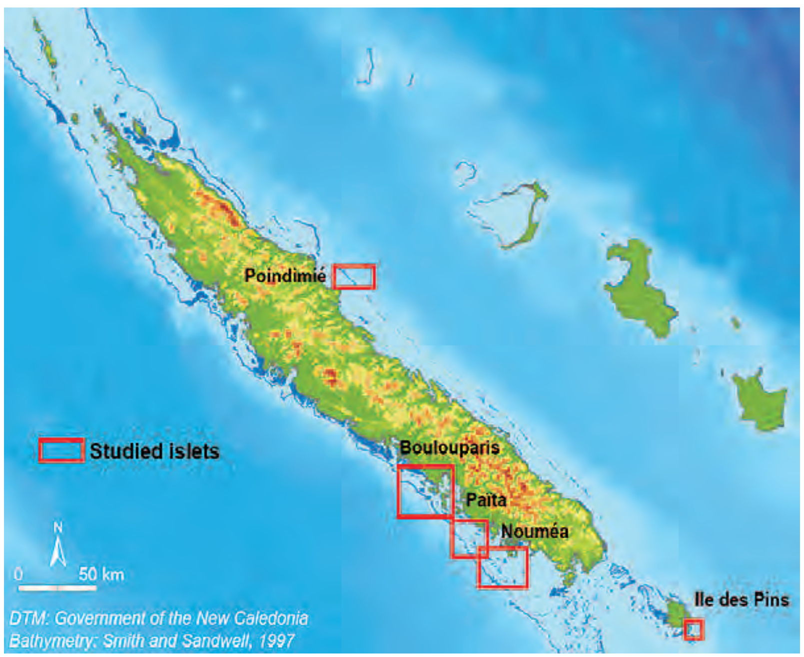


Figure 1: Location of the 21 islets in the New Caledonian lagoon. Altimetry: Government of New Caledonia; bathymetry: SMITH and SANDWELL, 1997

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.

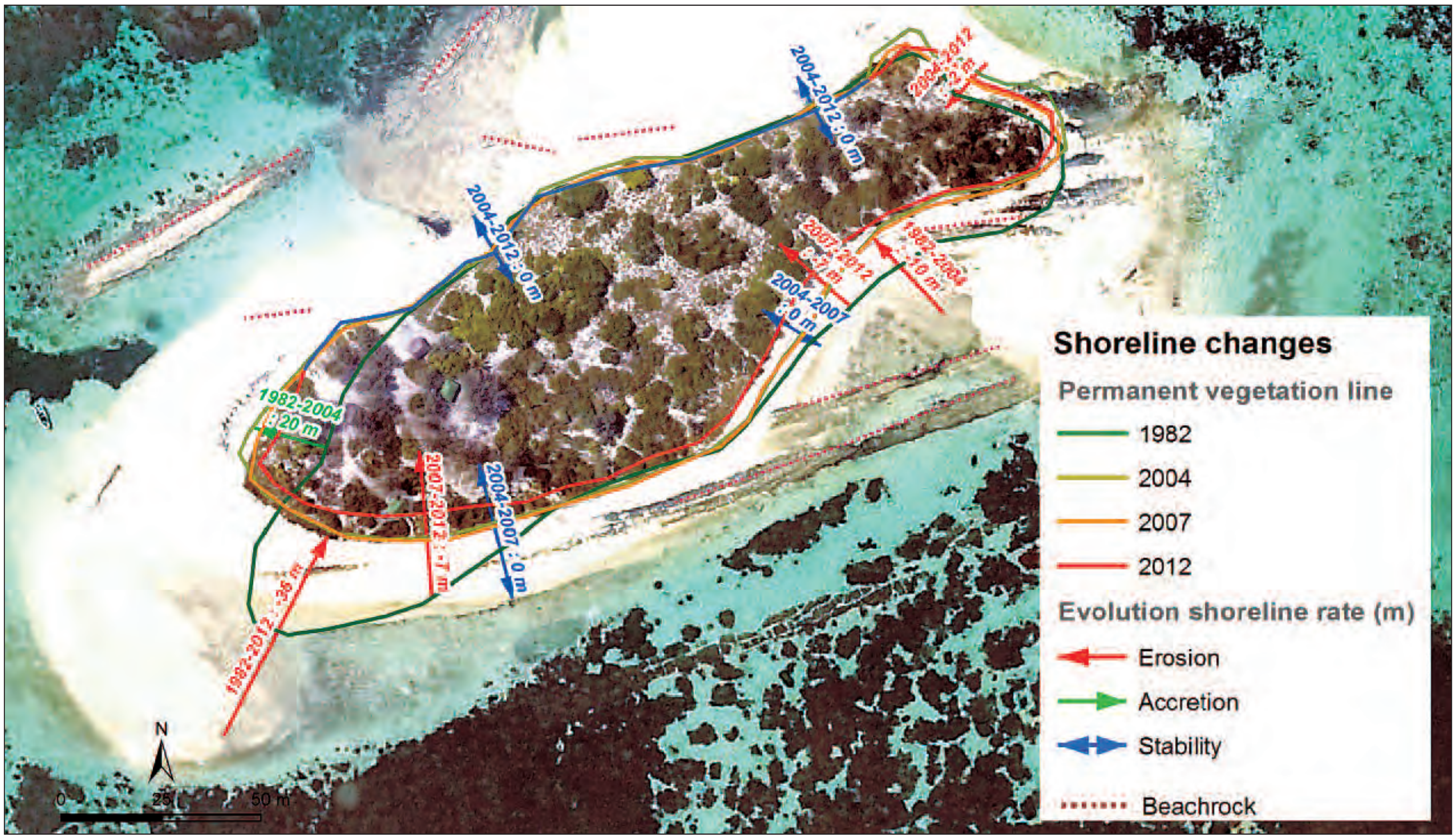
These observations were supplemented by the analysis of the islets' temporal evolution using satellite images and early aerial photographs. The time frame covered by the reconstitutions of each islet varies according to the availability of these media: satellite images are available for the last decade, 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.

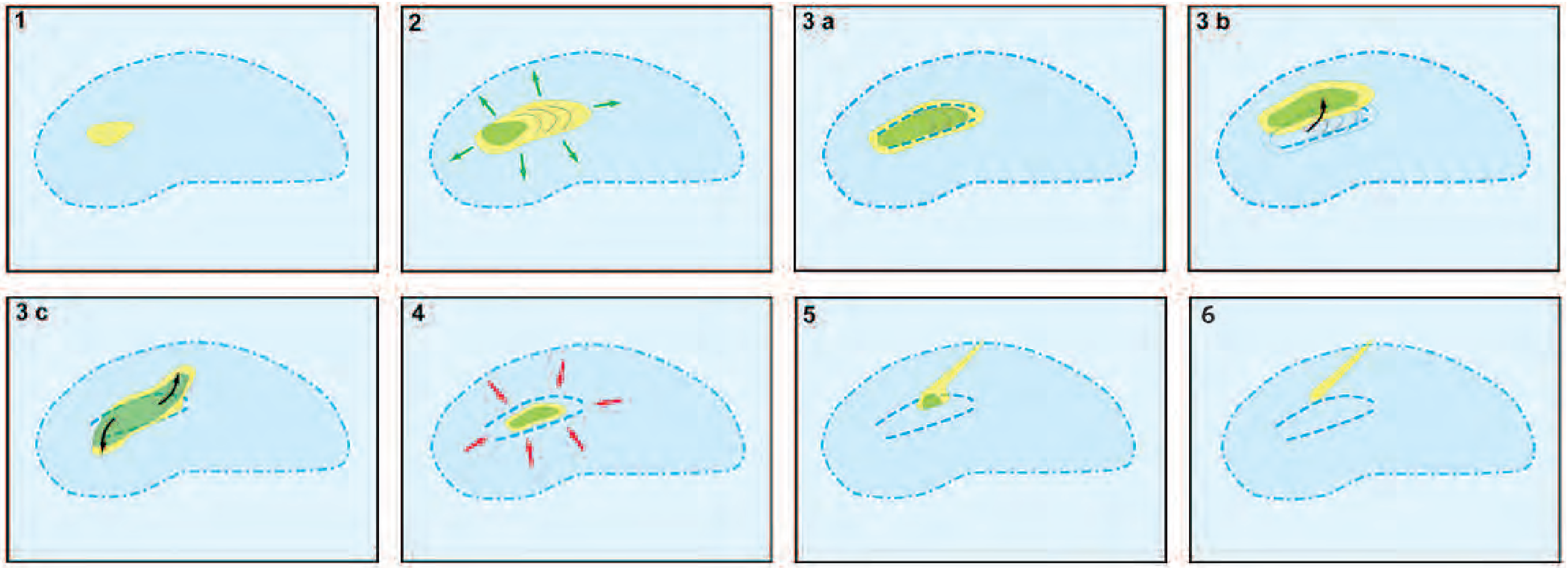


Figure 2: The different evolutionary stages of New Caledonian islets.
Stage 1: Nucleation. Stage 2: Growth. Stage 3a: Stable maturity. Stage 3b: Migration maturity. Stage 3c: Adaptation maturity. Stage 4: Decay. Stage 5: Relic. Stage 6: Disappearance.

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.

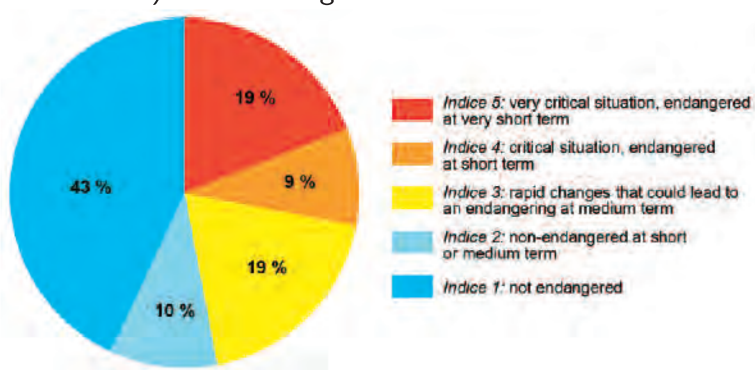


Figure 3: Distribution of islets according to their likely future evolutions (in %). Adapted from GARCIN *et al.*, 2016b

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

Pascal Dumas and Sylvie Fiat

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.

Partie 4

Words, practices and representations around the reefs

Coordinator: Catherine Sabinot

For three millennia, people have been connected to reefs. They spotted them from their outrigger canoes, discovered passes that allowed them to reach the land and settle close to the reef flats and slopes that provided a variety of fish resources. For Kanak people, the lagoon is an invisible world inhabited by ancestors and crossed by the "paths of the dead". It is a place characterized by stories, memories, and fishing trips ("coups de pêche"). Researchers in the social and human sciences, together with their colleagues in natural sciences, decipher what the reef means to New Caledonians.

Chapter 28

Three Millennia windward of coral reefs

Christophe Sand

The Isle of Pines on the horizon. © P.-A. Pantz

Sea-foam on the horizon of a new land

In the insular system of New Caledonia, waves breaking on a reef are always in sight of coastal clans. About 3,000 years ago the first Austronesian-speaking explorers approached the enigmatic and seemingly endless land mass of the northeast coast of Grande Terre, which they could see on the horizon. As they approached the surf of the waves breaking on coral they searched for passes through the reef.

At this unique and fleeting moment in history, the first discovery of a new land, sailors were not interested in the potential resources of the marine environment, but rather in the promise of freshwater, there, on land, ahead of the pass which they entered with their outrigger canoes.

These oceanic explorers originated from the "Great Coral Triangle" region to the far northwest, between the islands of Southeast Asia and northern Melanesia. Knowledge of the reefs had been part of their cultural background and ancestral memory from the beginnings of mankind. When exploring the New Caledonian Grande Terre, they quickly understood that they were faced with one of the most extensive coral reefs they had ever seen. These reefs were much larger than anything they had discovered since leaving the Solomon Islands, colonized tens of thousands of years ago, to venture to islands and archipelagos that no man had ever explored before.

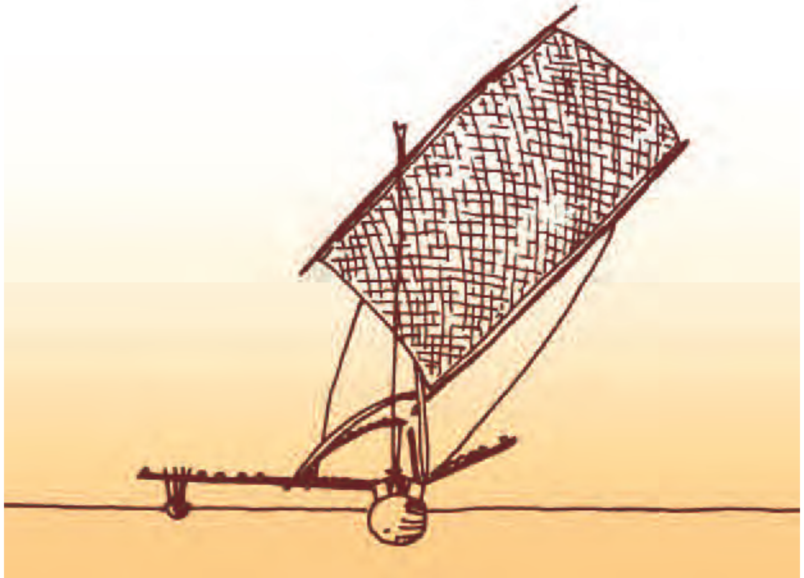


Figure 1: Possible shape of a canoe used for the first settlement in the New Caledonian archipelago 3,000 years ago. © C. Sand

View of the dune of the first settlement of Patho on the east coast of Maré in the Loyalty Islands. © C. Sand

When the reefs were truly "untouched" by any anthropogenic impact

These early groups of sailors had one main objective when they set sail on their canoes for the unknown, beyond the horizon (Fig. 1). They wanted to discover new land and establish permanent settlements. Those who reached the New Caledonian archipelago, quickly realized that the winds had blown them to colder latitudes than those from which they had originated, and that the geology of Grande Terre was very different from anything they had seen during their journey. The terrestrial environment most familiar to them was the coastline, and they demonstrated a clear preference for establishing their first settlements here: a beach near a freshwater spring, close to a coastal reef flat for food, and the whole settlement placed so as to enable quick access to the open ocean through a channel in the reef. The sites of Naïa, Nessadiou, Koné or Koumac on the west coast, Goro or Pouebo on the east coast, and Keny or Patho in the Loyalty Islands all feature these characteristics.

In these early settlement sites, archaeological excavations have uncovered mainly the remains of earth-related artifacts such as pots decorated with motifs of the Lapita tradition, and stone axes. However, the study of shellfish remains revealed a tradition based on the exploitation of all available marine environments. The presence of gastropods, such as trochus and cones, is an indication that at least part of the group's food gathering was from the reef environment. Similarly, the fish bones found in the refuse pits of the Lapita sites in the Loyalty Islands, indicate that Scaridae (parrotfish) were the predominant fish caught from the coral environment, probably using mainly fishing nets. Some carnivorous lagoon fish were caught using simple hooks made from seashells.

Today, it is difficult to imagine what the richness of these marine environments, in the New Caledonian archipelago would have been at the time of the first settlement 3,000 years ago. This was before the repeated harvesting of shellfish and the increase in fishing by expanding clans, which significantly depleted trophic densities. On the central west coast of Grande Terre, where the lagoon is narrow and the barrier reef is rapidly accessed from the beach, archaeological studies have indicated that the economy of Deva's coastal groups had been heavily dependent on seafood for a very long time. For nearly two millennia, in order to avoid the overexploitation of the reef environment, families lived semi-nomadically and were organized in sparsely populated territories. They moved regularly from one area to another along the coast to avoid depleting resources.

Soil on coral

It would be a mistake to believe that this kind of direct harvesting by man was the sole reason for the gradual depletion of coral reefs over the centuries and millennia that followed the first settlements. A massive but indirect phenomenon has considerably contributed to the changing characteristics of the lagoons of the New Caledonian Grande Terre: land erosion. The people of Oceania are, before all, farmers, growers of yams and taros, but also of banana trees, sugar canes, and so on. To expand their crops, the descendants of the first Lapita farmers gradually burned the dry and wet forests that covered the vast majority of the island's terrestrial environments. In a tropical habitat, where natural fire is extremely rare and where thick layers of humus had developed over time, the disappearance of trees led to the repeated erosion of surface soils. Soils have been stripped down the slopes during intense rainfall events, such as tropical cyclones, and the alluvium have been carried away by creeks and rivers into estuaries. The estuaries have gradually silted up as a result, leading to the expansion of coastal plains, sometimes stretching over several kilometers, and the development of mangroves over former coral sand beaches (Fig. 2). Fine particles of sediment were washed into the sea and re-deposited on coral spores in a process that today would be called "pollution". The imbalance suffered by reef environments close to estuaries, has had a cascading impact on the entire food chain, from corallivorous fish to mollusk species.

Living in a fossil coral environment

The traditions of the Loyalty Islands groups to the east of the New Caledonian archipelago have been profoundly influenced by their singular natural environment of raised fossil coral reefs. One of the challenges in living on karst islands is the absence of watercourses, as the porosity of the ground does not allow the formation of creeks. Therefore, the coastal groups initially collected some of their water from the runoff of the freshwater lens (Ghyben-Herzberg lens) on the beaches at low tide. However, this became no longer possible when some families, attracted by more fertile agricultural soils, began to settle on the inland plateaus. The presence of coastal runoff meant that water was present inside the limestone rock and expeditions were organized in search of it in the coral plateaus' caves of the Loyalty Islands.

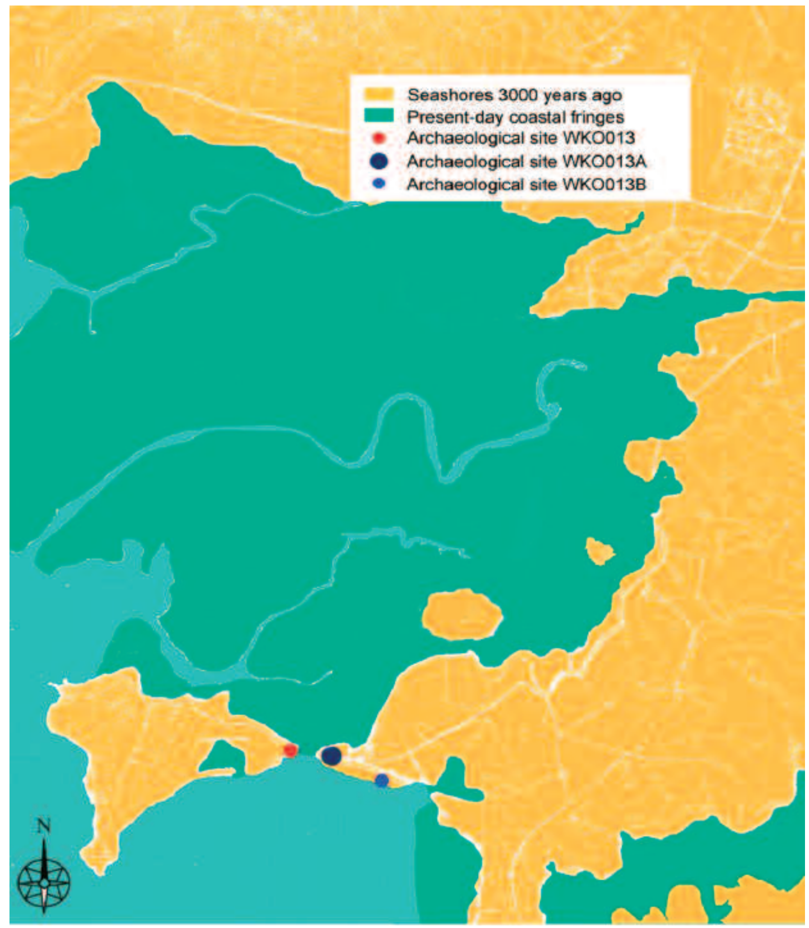


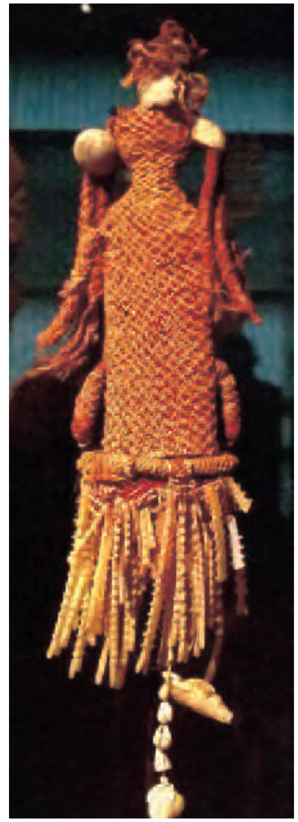
Figure 2: Extension of the estuary of the Koné River over the last 3,000 years. Each code corresponds to a different Lapita site of Foué beach, which is the eponym site of Lapita. © C. Sand

Artificial basin made of blocks of broken stalactites, built in a cave on the island of Tiga for the collection of infiltration water. © C. Sand

These difficult and dangerous explorations, lit only by torches made of dried leaves, led to the discovery of percolating zones where water dripped from the ceilings, and even formed natural pools sealed by the millennial deposits of calcite. Since then generation after generation of men ritually organized visits to the womb of Earth to collect freshwater. They marked their visit with artwork on the cave walls, using their hands as stencils; they used large giant-clams or nautilus shells to collect water drops falling from the ceiling; they set up underground paths to guide themselves in the darkness; and sometimes even created artificial basins to facilitate the accumulation of water.

Mother-of-pearl Kanak exchange currency

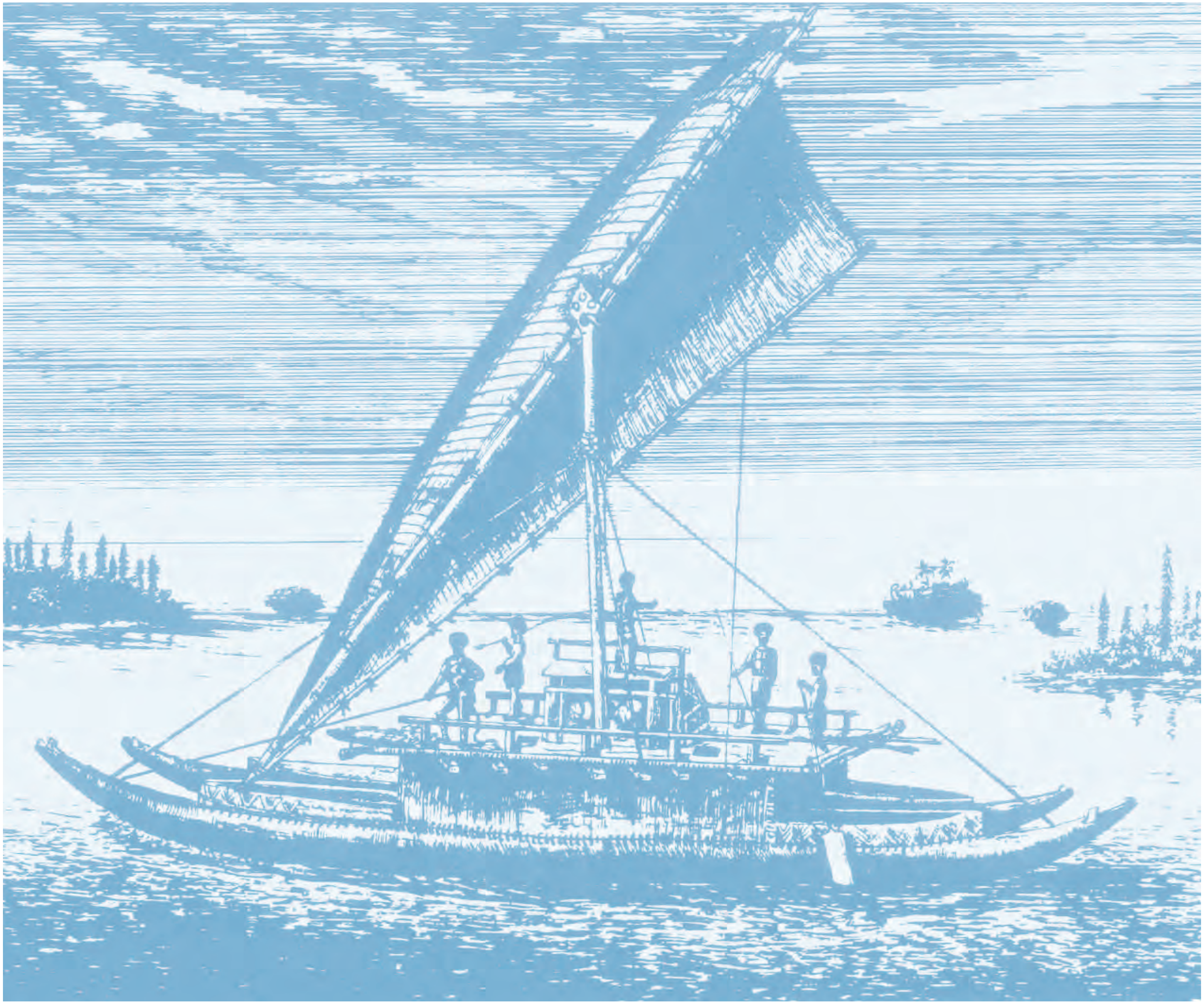
From the end of the first millennium A.D., the development of new cultural traditions throughout the New Caledonian archipelago led to the emergence of a "Traditional Kanak Cultural Complex", characterized by a massive intensification of the use of the natural environment. This has led to a sedentarization of the clans and a growing interest in protecting the island environment. This cultural evolution was also marked by the emergence of new objects for exchange between groups, in particular the conceptualization of a unique form of traditional Kanak exchange currency, characterized by the presence of tiny mother-of-pearl pendants. These are meticulously cut, with lateral projections perpendicular to the central axis, and have a millimeter-shaped hole for attaching a string made with vegetal fibers and braided flying fox (a species of bat) hairs. The mother-of-pearl shells that were used to make these objects that were only a few centimeters long, were collected from reef environments. The oral traditions in the center of Grande Terre say that Kanak money-makers from the region of Houaïlou, on the east coast, followed customary paths through the central mountain chain to collect this raw material in the Bourail region on the west coast, where the barrier reef is only 1.5 km from the coast.



Kanak exchange currency with mother-of-pearl pendants. © C. Sand

James Cook's crew approached the area of Balade, in the northeast of Grande Terre, in September 1774. On several occasions during their short stay, the English sailors were able to observe canoes going out fishing on the reef. This historical connection between the Kanak and the sea is evidenced by the presence of seashells in inland valleys and on plateaus, which are discovered during archaeological surveys throughout the archipelago. The mollusks were transported alive, together with the dried salt packages needed for food preparation, as part of the exchanges between coastal and inland groups.

Archaeological studies also reveal that marine life was illustrated in rock art, which depicted turtles or fish. These drawings and engravings on cave walls or beach-rock slabs are the legacy left by these "people of the sea" as they returned from fishing trips in their canoes out on the New Caledonian reefs. In its protective rock-shelter at the top of Faténaoué-Hwatenewe piton, the mummy of Chief Hmaè Kahouta, a "man of the land", also looks beyond the plain of Temala to the great passageway in the reef of Voh, a place where souls travel to reach the "land of the dead".



Large double canoe in a bay of the Isle of Pines. © Musée d'Océanie, la Neylière /drawings from nature, P. Bournigal

Painted representations of turtles on the wall of a cave at Bocage Cape (Houaïlou). © C. Sand

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Box 22
Megalithic fossil coral fortifications

While the caves in the fossil coral have served as an unexpected source of freshwater for Loyalty Islanders, karst has also been used regularly as a building material. The most spectacular constructions are located on the central plateau of Maré Island, where, during the first millennium A.D., the inhabitants built megalithic fortifications. These were raised by extracting large monolithic fossil coral blocks from open-air quarries at the base of karst pitons. Some of these blocks could weigh several tons each and had to be pulled by hand to the construction site, sometimes several kilometers away from the quarry. There they were placed one above the other, up to 4 m in height, to form retaining walls of 10 m wide and several hundred meters long. These forts had monumental gates where some of the largest blocks were placed.

Monumental entrance to the megalithic fort of Hnakudotit, built on the Maré plateau using fossil coral blocks. © C. Sand

Chapter 29

Reefs, speech and people

Emmanuel Tjibaou

The mouth of the Ouaième River. © P.-A. Pantz

In New Caledonia, as in many Pacific island societies, the connection to the marine environment and its associated reef lands is essential to understanding the political and social organization of human groups. Here, the sea and reefs are a direct extension of the land where the duties, practices and obligations of Kanak customs apply. The similarity between perceptions of land and of maritime space has many possible explanations. While island societies all develop a good knowledge of navigation and the ocean, the sea is also their origin myth.

"The Path of the Dead"

One of the keys to understanding this particular relationship between man, reef and sea comes from representations of what is commonly referred to as the "path of the dead" in northeastern New Caledonia. For example, in the region of Hienghène, in the valleys as well as along the coastline, it is usually recognized that when a person dies, his spirit disconnects from his body. The spirit then uses a path

Ilot Kaavo, marking the entrance of " The Path of the Death", Northern region of Belep. © E. Tjibaou

that will take him from the deceased's home inland (from the creek to the valleys, the stream to mountain ridges), to the entrance of the Ouaième[14] River. This “spirit trail” extends along the bottom of the river, past the guardian of the Hwaiwai Passage, to the spirit kingdom facing the Hienghène pass on the edge of the Tao Reef. In the Fwâi language of Hienghène, this is called *sêêdan ne vi danu*, literally meaning the "path of spirits". This cycle of completion, the drying out of the vital processes in Kanak people, constitutes an initiatory sequence that recalls one's own journey through life: the individual emerges from the flow of the original matrix where the spirits dance at the bottom of the oceans at Tiduuwon[15]; all his life he makes imprints in the ground, moving away from this ocean of origins, which his spirit finds again in death. In the northern region, representations associated with the reef and the underwater environment refer to both the legitimacy of death and the necessity of life.

In the kingdom of the dead, two mythical characters (Doibat and Hwaiwai) represent this original omnipotence of the reef and the underwater environment. Doibat, the spiritual power of the underwater world is depicted with plants and trees covering his body and is the guardian of the entrance to the kingdom of the dead on the Belep archipelago, north of Grande Terre. He is of unequalled grandeur and sits in Lolon (Belep), harassing the spirits of the dead that appear in front of him, before sending them through an underwater passage behind Pott Island, north of the Belep Islands. Hwaiwai, who takes the form of a shark or dugong is the guardian of the entrance to the kingdom of the dead in the Ouaième River in Hienghène and waits underwater with a torch for the spirit of the deceased. He gauges his ear lobes with a stake to verify that his ears have been pierced, a sign of his initiation by the living. These two mythical characters stand at the entrance to the underwater world to ensure that these environments are not defiled by the living. Both organize the passage of the deceased spirits from the world of the living to that of the supernatural underwater spirits in accordance with an established test that reinforces the proper functioning of the kingdom of the dead and which allows them to identify any intruders.

[14] Ouaième: the Weyem River located on the northeast coast bordering the municipality of Hienghène. This river is relatively well known in the region for its symbolic place in oral traditions, especially as a gateway to the kingdom of the dead. This is the last watercourse in New Caledonia where a motor boat is required to cross it.
[15] Tiduuwon: toponym in the Fwâi language of Hienghène, referring to a locality at the mouth of the Ouaième River, near the pass.

Marine species and meaningful places

Certain species of the marine fauna are associated with this spirit underwater journey. These include sharks and particularly basking sharks, sperm whales and other whales. The appearance of these creatures at the surface is seen as a manifestation of the spirits of the kingdom of the dead. Additionally, these animals, which are emblematic of marine spiritual forces, are found in many origin myths in northern New Caledonia. The place of these mythical species at the heart of the marine and reef systems, testifies to the knowledge that Kanak people have of their environment, and also to their imaginary power. Here, reefs, sand banks, coral cays, reef slopes, and passes are mythical or historical markers of human knowledge throughout the course of life. The relationship between man, reef and sea is perceived as a particular entity where the individual finds himself, and where he needs to navigate within an original and densely populated community and follow specific codes. These rules of coexistence between marine and human species are learned from a very early age through games and story-telling associated with rituals, which are carried out for the respect of underwater life. While knowledge of the paths of customary alliances is necessary for someone from inland in order for them to become an accomplished man, for the people of the coast mastering marine currents, passes and trade winds is paramount for crossing this threshold into manhood.

Box 23

Mourning speech to maternal clans

This speech was spoken in Paicî language by Umätu Michel Tiapi Gönô, the Chief of Ometteux (Poindimié, northeastern New Caledonia) and recorded by Dominique Paabu Oye in July 2005 at the Bayes tribe in Poindimié. In essence, the speaker said: "We invited you and called you down this path, to come in through this lane and be present here because your nephew's foot bone (the tibia) has burst and cracked, and the vitality in him was also broken, and he is no longer in the midst of this assembly. He no longer has what makes him live and talk and walk, he has turned his back on the sun and moon. It was taken up by the devil's vortex, up there in the middle of the air, and carried away by the current, down there in the expanse of water with no horizon, and then he was stranded [as a shipwreck] onto the reef flat [fringing coral reef or coral massif contiguous to the land] at Wénégéi[16]. And he entered the dance at Pijèpaa[17] [the dance of the dead]. You are going to take him up there on the stone from which he comes, on the stone object of his respect and his taboos. You will entrust him to the grave and the land of darkness. This is the tree, the fir tree that symbolizes your nephew's disappearance. You will take it and bring it to X [the names of the clan and sub-clans of the maternal uncle who cannot be revealed outside a restricted circle of people]. This is the end. It is over."

« Pwi a popai â nä-é i nä pââ : "bë to mä paci pââ nä-guwë itë-mê nä-näigé bèè-nî nä guwë tö-mê nââ görö-igé bèèni nä guwë tö-mê nau coo-nî nä taö mä mä-biti i duru-â pwi nîaa go-wë nä ta-biti i jawé wâdo-é nä tiëu-é géé nââ pa-ba nä utê go-rë nî ba é-jè ningä mä cèkëé mä cö-mä-cö é nä-cëù tärä tötù mä parui â-jè cëù-é i u-kärä-duée dö gopaé-ré-näo â-jè dëti-é i duru-jawé wâ-boo nä-jawé tacî â-jè tagötù-é nä-gö i paara kë wânâgëi â é-jè pärä nä i cäbu-kë-Pijèpaa guwë mwâ popaé dö-nö-gö i atù nyââ kêê nä-ia-é té-géé-goo i atù au-pi-too mä au-paa-pwicî kêê guwë töpwö-é nââ näcè oolaa mä cè pwaduu wëé-nî i upwârâ cämù kärä nä-tiëu pwi nîaa go-wë guwë mwâ pa-dö nââ… wëé-nî â näbwé" ».

Extract from the 2006 Paicî-Cèmùhî Report. Surveys of the Heritage and Research Department, ADCK-CCT, Paicî-Cèmùhî Customary Council (2006).

[16] Wénéguei: toponym, clan name and chiefdom of the south of the Ouvéa atoll, one of the three Loyalty Islands (New Caledonia).
[17] Pijèpaa: toponym and clan name of the northern part of New Caledonia. This patronym is generally associated with the status of those who perform funeral rituals within a chiefdom.


View of the Fayawa pass from Mouli, Ouvéa. © P.-A. Pantz

In the *jahma*[18] sacred narratives of the Hienghène-Pouebo region and the north coast, the ocean is described as a continuum of the land and it is said to be governed by customary authorities who are responsible for the management and maintenance of these underwater areas. The oral traditions related to these topics demonstrate the specific political organization of underwater spaces, which visitors must respect (for example, the customary practice of *huremeno*[19] before fishing in certain areas; or *hiri ne buai*[20] when passing through certain places, etc.).

It should also be remembered that these spaces, even without any indication of human presence, may be governed by specific rules:

- a "customary sea" depending on a chiefdom on land (Hienghene-Pouebo);
- a "customary sea" depending on a legendary underwater chiefdom from mythology (Belep);
- a remarkable feature of the landscape (e.g., fringing reef, outcrop, sand bank, large coral head, etc.) linked to an oral tradition (e.g., the tale of the Rat and Octopus in Tiga);
- a remarkable feature of the landscape associated with an ancient wave of migration (e.g., zone of the Pleiades Héo in Ouvéa which is linked to matrimonial ties with the Bouarate chiefdom of Hienghène);
- a distinct feature of the seascape associated with specific fishing rituals (e.g., Mangalia and Weyem passes for sharks between Hienghène and Touho). These areas are under the authority of clans that are identified and recognized by the Kanak society.

These few examples fundamentally mark the influence of the Kanak culture on areas that could be considered free of any human impact. The reefs near Grande Terre and the islands, or the barrier reef and passes between the reefs, are all known and symbolize Kanak pathways of both the living and the dead. For almost 3,000 years, the presence of the Kanak society on Grande Terre, together with the tragedies and victories of its people, have been imprinted on both their memories and the reefs themselves.

[18] *Jahma:* a type of oral tradition in the languages of Hienghène (Fwâi, Némi, Pijé, Jawé). It is often translated as "myth" because of the topics it deals with, where the origins of clans, pharmacopoeia, dance, etc. can be evoked. It can also attest to the representation of a political organization, of rules to be respected.
[19] *Huremeno:* literally "end of the journey" in the Fwâi language of Hienghène. This ritual is carried out on land as well as at sea when entering a space inhabited by men or spirits. It is carried out by the visitor who, stating his identity, presents an offering to his visible or invisible host.
[20] *Hiri ne buai:* literally "shouting forbidden", in the Fwâi language of Hienghène.

Chapter 30

Cultural, subsistence and commercial fisheries in reef ecosystems

Catherine Sabinot, Gilbert David, Matthieu Juncker, Séverine Bouard, Camille Fossier, Julie Mallet and Floriane Kombouare

Return from *mïkwaa (Chanos chanos)* fishing, Isle of Pines. © J. Tikouré

For the inhabitants of New Caledonia, the reef is much more than a coral colony, a reef flat or a barrier reef. The reef encompasses the lagoon and its inhabitants, its passes, living beings, souls, stories and memory. For Kanak people, this space is both an invisible and a visible world. The invisible world is where the ancestors live, where the paths lead to the kingdom of the dead. The visible world is experienced and known through fishing practices, among the other things that make up the daily life of many on the "Pebble" ("Caillou" in French, the popular name of Grande Terre). Along the coastline, there is no village or tribe for which fishing is not important. These fishers are men and women, young and old and from diverse backgrounds. They fish for food, to maintain connections with their environment, to strengthen and renew ties between families, clans, and tribes or simply for recreation. Many New Caledonians have "grown up in fishing". Their parents were fishers who transferred their knowledge, their fishing techniques and, above, all, their passion for spending their time at sea.

The fishing practices and the importance of this activity for the inhabitants of New Caledonia raise so many questions that one book would not be enough to fully cover the topic: who is fishing and for what? Are there different fishing techniques? What are the target

Wood sculpture representing the head of a *mikwaa* (milkfish), Isle of Pines. © M. Juncker

species and the quantities collected? How do we know the species that inhabit the reef and their behavior? How do you build a "reef experience"? What is the importance of reefs for fishers from different backgrounds? How are fisheries organized in each territory? What are the social, cultural, symbolic and economic values of the New Caledonian reefs in the eyes of its inhabitants?

Researchers in anthropology, ethno-ecology, and geography are working on these questions. Several research projects have contributed to a better understanding of how New Caledonian people think about this environment and how they use it. This research offers a modest contribution from human and social sciences to characterize lagoon fishing and talk about the fishers who practice it, thereby revealing the importance of coral ecosystems for New Caledonians.

A fisher observes the lagoon, bay of Upi, Isle of Pines. © P.-A. Pantz

Knowing the reef and building fishing experiencer

For many, fishing is a common practice that requires careful observation. The experience is daily for some, regular or less common for others. Fishers know the reefs, they name them, they classify them. They also know how to decipher their environment and will choose a fishing spot according to tide, season, weather, etc. They acquired this field knowledge through the observation of the elders: "it is by going out to sea with the elders that we learn to fish". They scan the surface of the lagoon from the beach, from their boats, or even from the top of a pirogue mast to locate a school of fish or a particular species.

Observation is what every fisher talks about when he or she learns to fish: "First, I look." Fishers are very familiar with the reef and they use various "markers" to ensure good fishing.

- A sea krait swimming at the surface is sign of isolated reefs with fish;
- A flock of seabirds indicates the location of a school of fish;
- Unusual rippling of the water surface reveals the presence of pelagic fish;
- The massive stranding of small crustaceans in Prony Bay indicates the presence of schools of mackerels;
- After a tropical cyclone, large-eye seabreams, short-nose unicornfish and long-nosed emperor readily bite at the line, while Spanish mackerels dive deep into the depths.

"Below the terns there are anchovies, and therefore Spanish mackerels; below the petrels there are large sardines." **(Koumac)**

For many New Caledonians, fishing techniques are learned with the elders. The knowledge of fishing spots is shared by relatives and sometimes new ones are discovered after intensive searches: places where reef fish congregate, "lobster rocks", or "octopus caves", etc. Fishers know where the short-nose unicornfish are and when they are fat. They even observe changes in their behavior at sites regularly visited by fishers. Their observations also attest to the resource depletion or the disappearance of fish schools from sites where they were abundant in the past (rabbitfish, short-nose unicornfish, long-nosed emperors, groupers, etc.)

"There is less fish. Me, when I had the other tiny [tin boat] to myself, alone, I fill the icebox. Now, at five or six, we never fill the icebox." **(Pouebo)**

Box 24

From the knowledge of the elders to GPS

"I fish in relation to places, for fish, for crab, for everything. I use a GPS now... Before, our Elders, they didn't teach us with GPS, we used mountains for landmarks." **(Koné)**
"Before, our Elders, they show us the rocks [sic] but it was secret." **(Koné)**

GPS is an increasingly widespread instrument that is transforming the knowledge of places. It is valued by fishers, especially for those who go far offshore and it is defining new ways of communicating fishing grounds. In Bélep, for example, for young fishers targeting sea cucumbers, GPS makes it easier to explore new areas that had not been visited since their grandfathers with their sailing boats. It is a new tool that challenges the production of knowledge and its transfer to new generations.

The observations that fishers collect (passed on or learned) over years, decades and sometimes even generations, build up a "knowledge", a fine understanding of the reef and of the behavior of the organisms that inhabit it. Today, this knowledge is also of interest to marine biologists and ecologists because it assists them in locating migration corridors, identifying reef fish spawning periods and areas, etc.

Knowing where to fish and being respectful of each other's territories

"There are several of us fishing here. Here at home, among Kanaks, it's forbidden to cut in front of someone else, so we go to small places where there's no one." **(Poum)**

"When professional fishers came to work in the fishing business, it was done quite naturally. We [professional fishers] don't go on the reef flats, because it's dangerous enough to get close to it, but also out of respect for those who don't have boats, those who will walk to cast their nets or fish on the reef. It was done quite naturally: there was no meeting to organize fishing grounds, etc." **(Lifou)**

When you are a fisherman, whether you are Kanak or not, there are a number of implicit "rules" about how to use fishing grounds. The "first on the spot" rule is one of the most common. In addition, while barrier reefs and remote isolated reefs are privileged fishing grounds for boat-owners, especially professional fishers, reef flats and fishing grounds close to residential areas are reserved for subsistence fishers.

Fishers name both species and the places where they can find them. Toponymy thus applies to the seascape. Some islets are taboo and can be surrounded by mists so approaching them can be risky. Places that should not be visited are also named. For example, the small "Peto" Reef ("pillow" in Numéé language) in the south of Ouen Island, in the Southern Lagoon (Grand Lagon Sud) is a taboo reef. The reef is the pillow of the Wakôdô shark, guardian of the island, and must be preserved from any fishing.

Box 25
Taboos on fishing grounds

In New Caledonia, taboos on fishing grounds are numerous and diverse and they always imply a ban on access or removal. They may apply to all inhabitants of the island or only certain tribes or individuals. A clan or person may be entitled to temporarily remove these bans in order to organize, for example, a collective fishing trip for a particular event such as a wedding, investiture of a chief, yam celebration, etc. While the primary function of these bans is social, they also benefit the preservation of marine wildlife.

Tool selection according to location and type of practice

The type of fishing practice generally depends on where people live, their resources, their knowledge, their profession, their duties and so on. It is common for several tools to be taken on board the tiny (tin or light aluminum boat) to be able to adapt to the fish species available at the fishing site, or even to their behavior.

Reef flat fishing aims at collecting shellfish and octopus. While men are not absent from this fishery, it is mainly a fishing practice of women and children.

Angling is often carried out on the soft bottom of the lagoon, at the edge of a fringing reef flat with rising tide, or near isolated reefs for catching species living on the bottom, or close to the bottom, such as large-eye seabreams (Lethrinidae). It is carried out by both men and women.

Spear guns are used by young and old to target the most common reef fish (parrotfish, groupers, etc.) throughout the lagoon, from the coast to the barrier reef, in the passes and outside of the lagoon. Rock and slipper lobsters are caught by hand while free diving or using spear guns for the biggest specimens.

The tide is good, the net is ready to cast. The fisherman is looking for rabbitfish on a reef flat. Goro Bay, Yaté, 2009. © M. Juncker

Bare hand gathering, and free diving is also practiced for the collection of some shellfish such as trochus and giant clams, as well as holothurians (bêche-de-mer) for the Asian market.

Fishing nets, especially the seine and cast-net, are used for gregarious fish species that occur in shallow water (usually one to seven meters deep) such as the short-nose unicornfish *(Naso unicornis)*, rabbitfishes (Siganidae), mullets (Mugilidae) or white fishes (strongspine silver-biddy, milkfish or *Gerres longirostris*). Seines are often reserved for "experienced" fishers; young people usually fish with spear guns, troll or fishing lines, and children often start learning how to fish by hand on the reef flat and later with a fishing line from a boat.

Cast-net fishing, Brosse Islet, Isle of Pines. © P.-A. Pantz

Fishing to exist, trade, feed and sell

"Our field is on the reefs."

These words have been heard in various places in New Caledonia and refer to both current and ancient representations of the role of reefs in the lives of fishers, especially the clans of the sea. Knowing the importance of the field, and particularly the importance of yams for the Melanesians, we understand the value of this statement.

Fishing plays a fundamental role in the organization of Kanak societies. It reinforces the ties between clans through exchanges and is the identity of the fishing and sea clans: it is a duty they have to accomplish for the respect of their chiefdom and the other clans. The product of their fishing is handed out to the chiefdom or shared during customary ceremonies. Fishing is also important in non-Kanak societies, but in different ways. Being able to provide a guest with lobsters or certain large species is rewarding and for religious events, some fishers are relied upon for their catch.

«"I'm trying to keep fish in the freezer because we have people from the [mountain] chain coming by any time to get fish for customs up there." **(Hienghène)**
"Before, since I was a little girl, I used to fish on the reef flat with my parents. To make things better, I took a boat so that I could travel a little further. The first idea was to provide to those in the [mountain] chain: fish and trade with them. Instead of selling, we trade. [...]. They make [give] us what is found [grows] in the range: taros, cassava...." **(Gomen)**
"There's xalaïa, donations for the pastor every first Monday of the month. If you don't have any coins, you bring fish; if you don't have rice or fish, you bring coins. Or yams, cassava, bananas." **(Poum)**

Fisher with a sagai and cast-net. Doueoulou, Lifou. © P.-A. Pantz

Fishing has a special place in the diet and daily life of New Caledonians. It is important to remember that the only sources of animal protein before the introduction of deer and pigs were birds (notou, kagu, etc.), flying foxes (bats) and marine resources. In 2011, a survey of people living in tribes[21] revealed that over half of the families living on customary land practiced fishing: 57 % of households had at least one fishing activity in 2010. A total of 2,730 tons of seafood products were taken from the reefs by the Kanak people living in tribes including lagoon fish, crabs, lobsters, shellfish, octopus, bêche-de-mer. On average, fishing represents 370 kg/year/household, with figures reaching 586 and 572 kg/year/household in Ouvéa and in tribes of the far north (Belep, Pouebo, Ouégoa, Poum and Kaala-Gomen), respectively.

Like in agriculture, seafood products are primarily used for self-consumption and donations (60% self-consumed, 19% donated in 2010) and 21% are sold. In 2010, fishing generated XFP 644 million in revenues for tribal populations. Households in the northern, western and southeastern tribes (Yaté, Thio and Isle of Pines) tend to sell their fish much more than those in the rest of the country. That same year, in addition to fisheries "mainly for subsistence", 656 tons of fish from the lagoon (538 tons in 2015), 2,860 tons of tuna and tuna-like species (2,840 tons in 2015) and 253 tons of sea cucumbers and trochus (192 tons in 2015) were officially taken from the New Caledonian reefs by professional fishers (as declared in the fishing logbooks filed with the provincial authorities). This resulted in sales of XFP 555 million in 2010 (XFP 447 million in 2015) for seafood products coming exclusively from the lagoon and XFP 1,300 million for longline fishery products (XFP 1,200 million in 2015).

"The lagoon is our larder"

«"It's not just about nickel in this country... we cannot eat earth." (Koumac)
"There is no other choice but to value fishing or tourism, if we don't do it, soon there will be no one left in the islands, they will all leave. This is a way to keep people at home."

[21] Survey conducted by the IAC among 1,786 households, or about 12.5% of tribal inhabitants (GUYARD *et al.*, 2013).

Loading of a milkfish or *mïkwaa (Chanos chanos)* net on a decked pirogue in Pwadèwia, St. Joseph Bay, Isle of Pines, 2017. © M. Juncker

Circled by a net and then caught by strong fishers, the milkfish or *mïkwaa (Chanos chanos)* are brought back on board a pirogue, Isle of Pines, 2017. © B. Juncker

Fishing trips ("coups de pêche" in French), are valued by all New Caledonians who are attracted to the sea, as a way of feeding the family, contributing to ceremonies, earning a little money or even earning a larger income. We must remember that, above all, the lagoon is described as a "larder" by many women and men who live by the lagoon, near the reef flats. This term symbolizes both the food, economic and symbolic values attached to the reef and those who experience, know and want to care for it. It shows that, for many reasons, coral reefs are an essential natural and cultural heritage for New Caledonians.

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Chapter 31

Reefs invertebrates: sustainable resources for local populations in New Caledonia?

Pascal Dumas, Marc Léopold and Loïc Bourgine

In New Caledonia, the giant triton *(Charonia tritonis)* is used to gather or warn the inhabitants of a village. © ADCK/CCT/P.-A. Pantz

Octopus, shellfish and crustaceans... the great diversity of reef resources

The use of reef species by Pacific island populations is not new, as evidenced by the abundance and variety of fishing related artifacts (hooks, pirogues, tools, shellfish, etc.) found in the geological strata associated with the settlement of the Lapita populations in the region. Although the diets of coastal populations have diversified considerably since antiquity, these resources are still an essential component of the Pacific islands' food security and a central element of their cultural traditions.

While the diversity of harvestable reef species is high - almost 100 species in a typical South Pacific island about 30 years ago - the range of species that are actually taken from the environment varies widely according to geographical areas and their environmental, economic and cultural context. Studies show that island populations generally collect a large diversity of invertebrates, and that they particularly target bivalve mollusks (giant clams, cardium, oysters, mussels, clams, etc.), gastropods (trochus, green snails, cones, strombus, spider conch, etc.), cephalopods (octopus), crustaceans (crabs, shrimps, rock and slipper lobsters, hermit crabs - including the large coconut crab *Birgus latro*) and echinoderms (sea urchins and, more recently, holothurians). These artisanal practices usually operate at small spatial scales (one or several adjacent reefs, an island, etc.) for subsistence, and have gradually evolved, for some species with high market value, towards commercial fisheries.

Most of the species are harvested primarily for consumption, sometimes after transiting through various traditional channels of exchange or sale. Some others are emblematic and still play a role in the social and cultural practices of the region. These species are, for example, the giant triton (*Charonia tritonis*, Triton's trumpet or "toutoute" in New Caledonia) used as a wind instrument for gathering or warning the inhabitants of a village; cowries or cones used to make seashell currencies; pearl oysters and giant clams used to embellish prestigious objects for customary exchange ceremonies, not to mention the many species used in jewelry or those that end up in craft markets for visitors.

Exploitation of reef resources in New Caledonia

In New Caledonia, as in many other islands in the region, coastal ecosystems - including coral reefs, mangroves and seagrass beds - contribute to food, income and, more importantly, to the self-sufficiency of coastal and island populations. In this respect, the territory benefits from particularly favorable conditions: over 4,500 km^2 of reefs with a high level of structural variability (fringing, intermediate, and barrier reefs - sometimes double or triple -, atoll reefs, etc.). Furthermore, the territory's location at the interface between tropical and temperate zones, means it is responsible for a wide variety of potential ecological niches for benthic species. With nearly 10,000 officially recorded marine invertebrate species, including more than 2,150 marine mollusks, 2,000 arthropods and 250 echinoderms, New Caledonia's coral reef ecosystems are


Coconut crabs *(Birgus latro)*, cooked and ready to eat. © P.-A. Pantz


Green snail *(Turbo marmoratus)*, Vanuatu. © IRD/P. Dumas

recognized as a "hotspot" of global biodiversity. A study carried out by the IRD revealed that over 60 species of macroinvertebrates - mainly mollusks - are harvested by fishers from the fringing reef flats around Nouméa (zone of Grand Nouméa). According to the available statistics, invertebrate catches frequently reach between 150 and 200 tons per year (excluding trochus shells), throughout the territory. However, these values are most certainly underestimated due to the informal and dispersed nature of these activities, particularly recreational and subsistence fishing, which makes them difficult to assess.

The majority of species are traditionally kept for local consumption, including mangrove crabs, lobsters, octopus, giant clams, and the numerous shellfish species collected at low tide such as clams (*Anadara scapha)*, ribbed Venus clams *(Gafrarium Tumidum)*, mussels (*Modiolus auriculatus*), tiger conch (Strombus luhuanus), and other spider conchs *(Lambis* spp.*)*. Others are exported, including holothurians (bêche-de-mer) and trochus, with a cumulative export value ranging between XFP 400 and 500 million/yr in recent years. Scallops *(Ylistrum japonicum)* have recently been added to the list of exports: they are highly sought-after for the quality and delicate flavor of their flesh and 30 tons were exported to the Asian markets in 2016.

Sea cucumber (bêche-de-mer, Holothuria atra), New Caledonia. © IRD/P. Dumas

Opportunistic overexploitation of sea cucumbers: a major challenge

The exploitation of holothurians (sea cucumbers) was developed in New Caledonia exclusively for the export of “bêche-de-mer” or “trepan” (the name of the product once the animal has been eviscerated, boiled and dried) to Asian markets. As in neighboring countries, fishing for sea cucumbers began in the early 19th century with commercial expeditions establishing precarious and temporary installations in isolated fishing areas. However, globalization and the boom in demand from the Chinese market since the 1980s have had a profound and lasting impact on exploitation throughout the Pacific. Many countries have put in place national moratoria following the rapid collapse of catches after a short development period in these fisheries. Sea cucumbers are very easily collected by hand in shallow waters, or by free-diving, and are therefore very vulnerable to fishing. In the absence of effective restrictions, intensive exploitation of spawners generally leads to a depletion of the resource in 10 to 20 years, or even less for high-value species such as the sandfish *(Holothuria scabra)*, white teatfish *(H. fuscogilva)* and black teatfish *(H. whitmaei)*.

Unlike its neighbors, New Caledonia was relatively spared from overexploitation until 2010. Fishing is restricted to less than ten species and is limited to the western and northern lagoons, the coastal reef flats and the barrier reef down to 20 meters (the use of scuba gear or compressors is also prohibited). Catch varies between a few tens and a hundred tons of bêche-de-mer per year and is a source of income for more than 200 professional fishers (export value in 2016: XFP 425 million). However, the country is now facing major market pressure, which threatens the sustainability of these fisheries and requires authorities to rapidly adapt regulations (especially the effective implementation of minimum catch sizes and fishing licenses). A system of co-management by quota was successfully developed by provincial and customary authorities as well as fishers in a pilot project, but its large-scale implementation poses difficulties. Sandfish aquaculture is another development alternative that has been experimented over the last ten years. Restocking trials of this species are underway since 2014, but they produced mixed results. It is not yet possible to consider such operations as a remedy for overexploitation because they are expensive, and their success is uncertain.

The steady exploitation of trochus

Like giant tritons, helmet shells, tiger conchs and other cowries, the trochus *(Tectus niloticus)* is a marine gastropod mollusk found on coral reefs in the Indo-Pacific region. Trochus build fairly large shells (the largest specimens are over 15 cm in diameter), which are highly sought-after for the quality of their nacre or mother-of-pearl layer, exported from the beginning of the 20th century to Europe and Asia for the luxury button industry and artisanal jewelry. Its high value and non-perishable quality (shells can be stored for several months before being sold) make it an attractive source of income for isolated island communities.

As a result of its rapid geographical expansion in the Pacific from translocations carried out in the 1930s and 1940s, growing demand on the world market soon raised serious concerns about resource sustainability. Despite increasingly restrictive fishing regulations and improved measures for restocking from aquaculture, trochus is overfished in the majority of Pacific countries. This generally results in stock decline, which can even lead to local extirpation in some regions.

In New Caledonia, trochus exploitation began in the 1900s and exports soon peaked at around 1,000 tons of shells per year between 1910 and 1920. After a sharp fall in activity during the Second World War, the first regulations were introduced in the 1950s to protect a resource whose vulnerability was detected by scientists. Trochus individuals have a highly heterogeneous spatial distribution: they are not randomly distributed on the reefs but aggregate in very specific and rather accessible "microhabitats" (particularly eroded hard bottoms on reef flats and reef crests with low structural complexity and low coral cover).

Although its rapid growth and early sexual maturity makes it relatively resilient, trochus is particularly vulnerable to overfishing, especially since they move slowly. In New Caledonia, however, the resource does not seem to be threatened in the short term. With a decline in demand for mother-of-pearl in favor of synthetic materials, trochus is no longer actively sought-after: volumes exported in the last 10 years range from 150 to 200 tons per year for a turnover of between XFP 40 and 80 million, far behind that of reef fish catches. In addition to a catch size limit set between 9 and 12 cm to protect the reproductive potential of the species, the management of this resource benefits from the existence of numerous marine reserves distributed throughout the territory.

With diverse status (marine protected areas, sustainable resource management areas, customary reserves, etc.), these protected areas can be considered as refuges for broodstock, and therefore eventually support the regeneration of impoverished populations in the surrounding areas. A recent study indicates that adult trochus populations are twice as dense within the marine protected areas of the Southwestern Lagoon, and that they are made up of specimens 10 to 20% larger, on average, than those observed in the surrounding fished areas.

Very similar results are observed in neighboring Vanuatu, where reserves have very different characteristics (size, regulation, governance regime). In addition to protection and status, the effectiveness of marine reserves to maintain or restore heavily exploited populations mostly depends on the presence of suitable environmental conditions: for trochus and other benthic species that are highly dependent on substratum, resource management cannot be planned independently of habitat characteristics.

Harvesting mangrove crab for the local market

In New Caledonia, as in other Pacific islands, mangrove crab *(Scylla serrata)* is a major resource for the populations living near mangroves. Catches have increased steadily in recent decades to exceed 40,000 tons throughout the entire Pacific region. On the west and north coast of New Caledonia, the mangrove crab fishery gradually evolved from an active subsistence and traditional fishery to a commercial fishery, following the introduction of more sophisticated fishing techniques (such as folding traps) in the early 2000s. Mangrove crab catches doubled in the last 10 years, from about 20 tons (as officially declared) in 2006, to over 40 tons in 2015, with a peak of nearly 80 tons in 2010. However, these figures represent only part of the reality: a study conducted by the IRD revealed the importance of the catch sold in the municipality of Voh, which alone reached nearly 100 tons of crab in 2006.

Due to its socio-cultural and economic importance, the sustainable management of this resource is a real challenge: the first regulation governing the crab fishery dates back to 1963, and already established a minimum catch size and a temporary (two-year) ban on catching soft-shell crabs (i.e., during the molting period[22]). Substantial research efforts on the biology, ecology and prospects for aquaculture of the species in New Caledonia have since led to changes in regulations, which are currently based on four main measures:

– an annual closure of the fishery between December 1st and January 31st, during which any form of capture is strictly prohibited, in order to protect individuals during the peak breeding season of the species;
– a legal catch size of 14 cm (total width of the animal) aimed at limiting fishing pressure on individuals which have not yet spawned;
– a total ban on the consumption or sale of soft-shell crabs, and the marketing of crabs other than whole living crabs (crabmeat is prohibited, with special exceptions);[23]
– a ban on crab traps with a mesh size smaller than 65 mm.

As a result of these measures, the resource does not currently show signs of overexploitation throughout the territory.

While the biology of the species is now well known, some gaps in our knowledge - including the difficulty of observing and capturing juveniles in their natural habitat - still hamper our detailed understanding of how harvesting affects stocks. Some studies also highlight the marked variability in catch rates at small spatial scales (kilometers), given that legal-sized crab densities may vary by more than one order of magnitude between different habitats. From one mangrove to another, fishing can be less productive, particularly in areas where sedimentary conditions, salinity, temperature, vegetation cover, etc., will naturally be less favorable to the species. This highly heterogeneous distribution of the resource has strong socio-economic implications in New Caledonia, where customary land tenure generally prevents fishers from freely selecting their fishing areas. As in other Pacific countries, they depend mainly on traditional access rights rather than on the actual availability of the resource. Even if this practice evolves with the modernization of fishing techniques and the development of on-board fishing, these informal rules largely determine the areas accessible to fishers. These results highlight the importance of a conservation strategy that encompasses habitat, particularly at small spatial scales; they also raise questions about New Caledonia's fishery regulations and the optimal management of such a spatially heterogeneous resource. The congruence between ecological scales (shaping the natural structure of populations) and harvest scales (structuring fishing activities) is thus a strong argument in favor of the spatial management of mud crab fisheries.

[22] *Arrêté du Journal officiel de la Nouvelle-Calédonie,* June 25th 1963.

[23] "Fishing, transportation, marketing, display for sale, sale and purchase of mangrove crabs are prohibited from December 1st to January 31st. Fishing, transportation marketing, display for sale, sale and purchase, possession and consumption of soft-shell crabs and crabs smaller than 14 cm in the largest dimension are prohibited at all times. Only live whole crab may be marketed. The display for commercial purposes of crabmeat in any form whatsoever is prohibited at all times, except exclusively for restaurateurs and caterers, and only in the premises where they carry on their activity, which are certified or approved for hygienic purposes" *(Extract from the North Province Fishery regulations, 2006).*

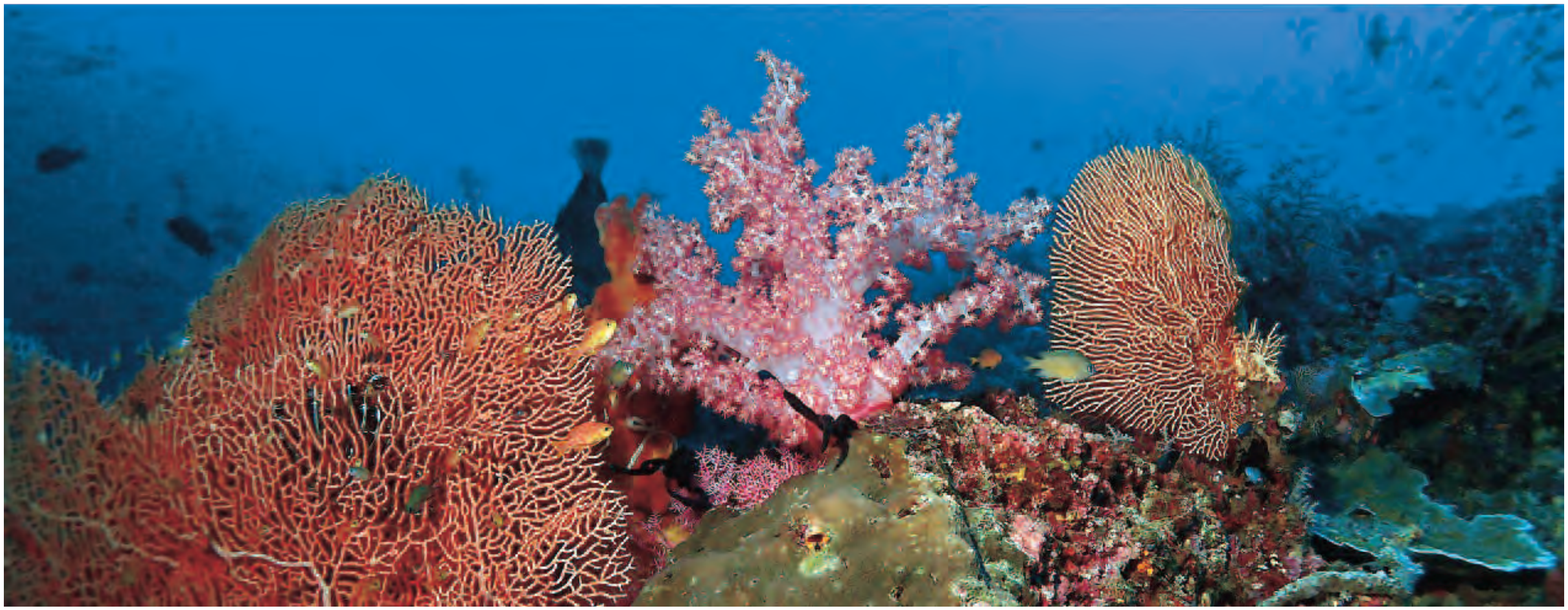
Mud crab or mangrove crab *(Scylla serrata)* ready for sale, New Caledonia. © P.-A. Pantz

While the decline of reef resources is a global issue, it is of particular significance to the islands of the Pacific region. In fact, the vast majority of macrobenthic reef species are of interest to fisheries at some point in their life cycle: their depletion represents a major risk for the economy and the livelihoods of coastal populations, whose dependence on seafood products is generally inversely proportional to the level of economic development. The implementation of a fishery policy for the sustainable management of coastal ecosystems and their resources is a major challenge for New Caledonia, given the current economic context which is deeply affected by the nickel crisis and the political challenges of the future.

Chapter 32

Natural substances: hidden treasures

Sylvain Petek



Gorgonians and alcyonaria are among the organisms tested for biological activities. © IRD/S. Andréfouët

For most people, "natural substances" are closely associated with traditional medicines, ethnopharmacology, herbal medicine and even aromatherapy. This association of ideas comes from multi-century-old knowledge of the uses, mainly of terrestrial plants, in curing various diseases in different communities around the world. Behind this notion, lies a more general interest in molecules synthesized by organisms, particularly those with specific biological and/or therapeutic activities.

Regardless of the organism under consideration, the molecules it produces are generally classified into two groups: those essential to life, known as primary metabolites (amino acids, nucleotide [ADN, RNA...], fatty acids with membrane function, etc.) that are found in very different taxonomic groups of organisms; and those known as secondary which are not involved in fundamental physiological functions, and are generally specific to the type of organism considered (plants, bacteria, fungi, etc.). The latter will be the focus of the present chapter.

From chemical ecology to applications inspired by nature

During evolution, organisms have developed a whole range of secondary metabolites for adapting to the physical (luminosity, temperature, pressure, salinity, etc.) or biological (predation, colonization, infestation, etc.) variations of their environment, and to communicate. Transdisciplinary studies of chemical ecology, involving both chemists and biologists, make it possible to isolate, identify and understand the role of these compounds. Thanks to this work, innovative, nature-inspired and more environmentally friendly solutions can be developed, whether in the realms of human and animal health, agronomy, aquaculture or other technological sectors.

Medicines from the sea

Although the use of terrestrial plants is a very old practice and widespread throughout the world in the various pharmacopoeias, the historical use of marine organisms is mainly known from China and the Far East. The Chinese Pen Ts'ao, published 2,800 B.C., contains a chapter exclusively dedicated to the use of algae for the treatment of gastric ulcers or goiter, for example. Much more recently, the Japanese have used a red alga, called *kaïniso (Digenea simplex)*, containing kainic acid, as an anthelmintic (antiparasitic), which has led to the preparation of a proper drug against *Ascaris*. Outside this geographical area, there is hardly any oral tradition or traditional medicine referring to the use of marine organisms.

It was from the mid-20th century onwards, with the development of new tools for underwater exploration and analysis, and especially from the 1970s, that systematic studies of marine biodiversity for uses in human health really began.

Life appeared in the oceans and they therefore still harbor all existing life forms. Of the 33 main lineages, 12 are exclusively marine and others are essentially marine (sponges or cnidarians [jellyfish], etc. of which there are a few freshwater species) - in other words, there is a whole range of marine biodiversity that is unparalleled in terrestrial and freshwater environments. In addition, seawater contains chemicals such as halogens (chlorine, bromine, iodine, fluorine), sulfur and metals that are not readily available elsewhere. This biological diversity, combined with the chemical specificities of the marine environment and the first encouraging discoveries, gives rise to many hopes for the emergence of a new marine pharmacopoeia.

For instance, the first cephalosporins, a family of antibiotics widely used today, were discovered in Italy in 1948, with the cultivation of *Cephalosporium acremonium*, a microscopic fungus found in lagoon sediments. The family of Arabinosides, with anticancer and antiviral properties, was inspired by isolated compounds of a Caribbean sponge, *Cryptotethya crypta*, in the 1950s.

Faced with this extraordinary biodiversity and without ethnopharmacological knowledge to guide them, the task of researchers is immense. In an attempt to select the most promising organisms, in situ observation of their behavior can provide some information. For example, organisms without physical protection that are not suffering from epibiosis, predation or grazing are likely to have developed a chemical cocktail designed for their defense. To study these organisms, different approaches have been used. Some are rather "systematic" (Fig. 1), without preconceptions as to the biological activity of the organism and with bioassays being carried out on isolated molecules. Others use bioguidance (Fig. 2), which first involves the selection of organisms based on their activity on a biological target (bacteria, enzymes, cancer cells, etc.) and the progressive isolation of the active substance(s) responsible for the observed activity. Each approach has its advantages and disadvantages.

After more than 50 years of research, a true marine chemodiversity has been discovered, with about 29,600 molecules isolated to date, a large part of which has no terrestrial equivalent.

As shown in Figure 3, just over one-third of the compounds are derived from sponges and/or their associated microbiomes. These sessile animals (chap. 13), unable to escape their predators, have developed a “chemical arsenal” for their defense, for colonizing new areas and protecting themselves against pathogens. In addition, sponges belong to a lineage whose compounds provide the widest spectrum of biological activities: antibiotic/antibacterial, antifungal, anticancer, anti-inflammatory, antiviral, antimalarial, immunostimulant, antispasmodic, etc.

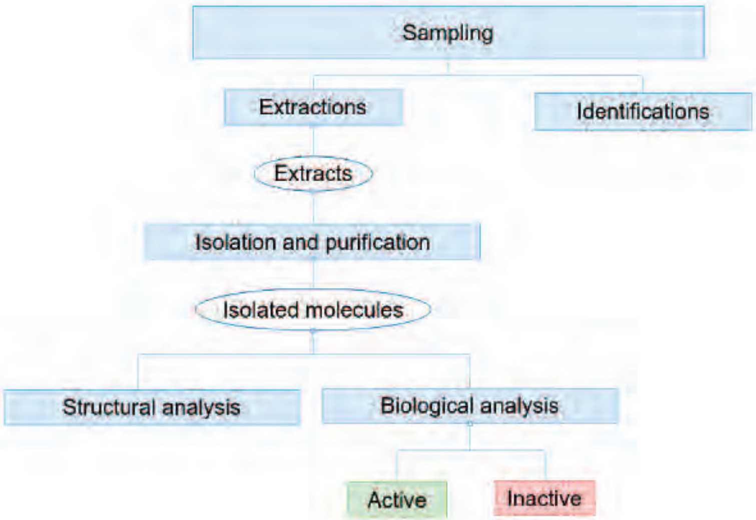


Figure 1: The “systematic” approach. © IRD/S. Petek

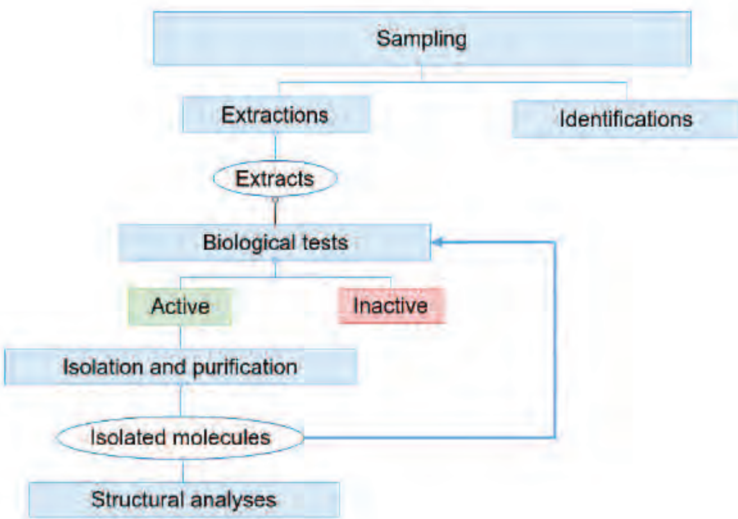


Figure 2: The “bioguided” approach. © IRD/S. Petek

Currently, in addition to cephalosporins (antibiotics, 5th generation since 1964), nine drugs of marine origin (or derivatives) have been placed on the market for anti-cancer, antiviral, analgesic and antiparasitic treatments. Some fifteen other molecules are being used in clinical trial assays. These figures may seem small in terms of the number of molecules discovered, but they are actually relatively significant. This is because, in pharmaceutical research, only one molecule out of every 10,000 will become a drug and it takes an average of 12 years between the discovery of the molecule and its launch on the market.

The valorization of marine natural substances often faces challenges related to resource access, availability and the environmental impact of industrial exploitation. Consequently, their use often involves the development of their synthesis by chemical and/or biotechnological methods or the production of simpler derivatives, where the aim is to keep only those fragments of the molecule necessary for the activity. This can also involve the addition of other functions which will provide complementary qualities in terms of assimilation, stability or target, known as pharmacomodulation. In this context, natural marine substances will be a source of inspiration for the discovery of original bio-active chemical structures rather than a resource as such.

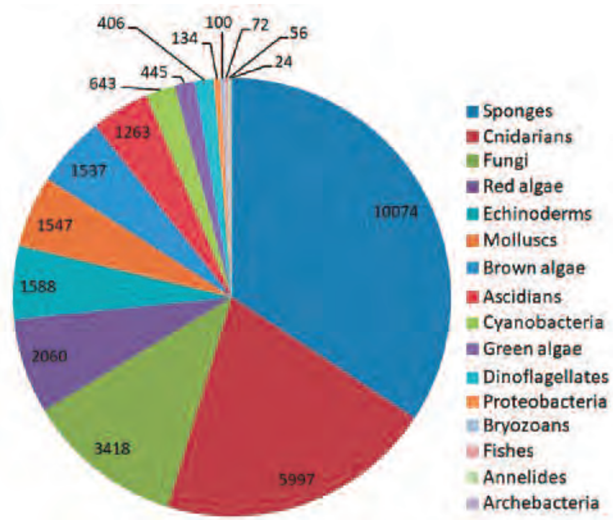


Figure 3: Distribution of molecules discovered by lineage. © IRD/S. Petek

Box 26

Cantharella, a database to capitalize natural substances

Sylvain Petek and Adrien Cheype

When we want to study natural substances[24], whatever their origin, we soon find ourselves confronted with managing a large volume of data of diverse natures and origins:

– sampling sites: country, locality, GPS point, species inventory, environmental/biotope information, etc.;

– taxonomic identification of the sampled organisms, their abundance, physical and genetic characteristics, etc.;

– chemical protocols implemented, molecules identified;

– biological activity assays performed.

In addition, these studies are multidisciplinary and require the support of many specialized collaborators, who are often geographically distant.

In the end, only part of this information will be included in scientific publications and thus permanently recorded. In the long run, therefore, there is a risk that the "raw" data may become unusable or disappear when it could provide historical records and serve as a basis for new projects. In addition, over time, the heterogeneity of paper or computer media, file formats, or the way data is structured make it very difficult to reuse information efficiently.

Cantharella (PETEK and CHEYPE, s.d.), a database dedicated to the study of natural substances has been designed to provide a solution to the various challenges arising from these data, in terms of:

– access and sharing between collaborators or transfer to collectivities;

– analysis and updating;

– long-term sustainability.

This collaborative tool, accessible online and developed from "free" software packages, uses four specialized modules to capitalize all the data from the field collection of organisms through biological assays to identified molecules.

CANTHARELLA
Base de données pharmacochimique
des substances naturelles

In addition, as part of the Access and Benefit-sharing process (ABS, Nagoya Protocol), the tool provides a platform for the transfer of results to communities, who can thus monitor the research that is being done on their biodiversity. For universities or laboratories wishing to use it, the software is made available under a free license (https://forge.codelutin.com/projects/cantharella).

The IRD's instance of Cantharella, operational since 2010, is capitalizing on data from numerous projects, mainly in the Pacific (about 700 sampling sites and 950 species, and over 7,700 bioassay results).

[24] Acknowledgments: IRD funding for Spirales programs (DDUNI) and "Maturation de projets innovants" program (SIV).

Explorations of New Caledonia's marine chemodiversity

In New Caledonia, the first marine bioprospecting studies targeting new molecules of therapeutic interest began in 1976 at ORSTOM with the research program Snom (Substances naturelles d'origine marine). This program was led by Pierre Potier (Institute of chemistry of natural substances, CNRS) and involved researchers and scientific divers from the IRD (ex-ORSTOM) and the taxonomic expertise of MNHN. Over the years, numerous other explorations, studies and research programs have been conducted, which involved several French and international multidisciplinary collaborations (Fig. 4).

A wide diversity of geographical zones, environments and habitats has been explored: from Grande Terre to the Loyalty Islands, the Isle of Pines, remote atolls and reefs (d'Entrecasteaux and Chesterfield), from lagoons to outer slopes of barrier reef, or seamounts (chap. 2).

Currently, out of all lineages, ranging from micro- to macro-organisms, biological analyses and/or activity assays have been carried out on a total of 9,372 species. Extensive pharmacochemical studies on about 50 organisms have isolated and identified more than 350 new bioactive molecules with original structures, including over 100 from sponges.

A few emblematic examples

Girolline, a tiny molecule extracted from *Cymbastella cantharella*, a sponge living on the outer slope of the southern barrier reef, was found to be particularly active during in vitro and in vivo assays on cancer and tumor cells. Without exhibiting major toxicity in mice and

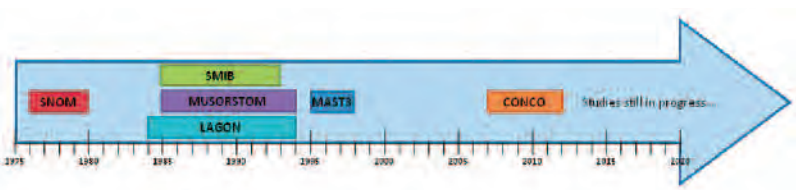
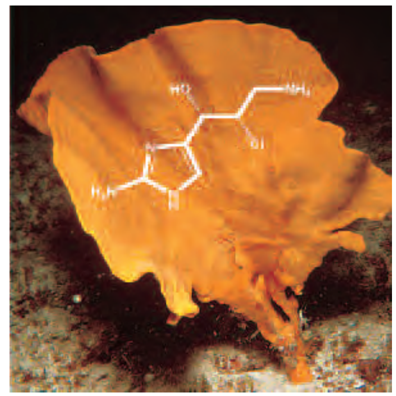
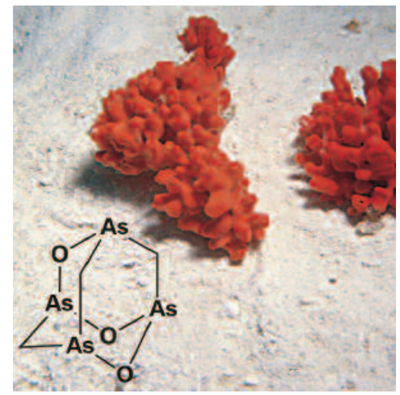


Figure 4: Main bioprospecting and therapeutically oriented research programs. © IRD/S. Petek

Laticauda Laticaudata and the erabutoxin b formula. © IRD/P. Laboute



The sponge *Cymbastella cantharella* and the girolline formula. © IRD/J.-L. Menou



The sponge *Echinochalina bargibanti* and the arsenicin A formula. © IRD/G.Bargibant

dogs, clinical studies were conducted up to phase II with the pharmaceutical company Rhône-Poulenc Rorer (now Sanofi-Aventis), before being interrupted due to side effects on the cardiovascular system. In addition, girolline has demonstrated interesting antiplasmodic activities *in vitro* on four strains of *Plasmodium falciparum*, particularly in synergy with chloroquine, paving the way for new antimalarial strategies.

Arsenicin A, produced by *Echinochalina bargibanti*, a sponge from the eastern lagoon of Grande Terre, is distinguished by its nested polycyclic formula with four arsenic atoms, which is very unusual for an organic molecule of natural origin. It has bactericidal, fungicidal and antiproliferative properties on acute promyelocytic leukemia cells, as well as on pancreatic adenocarcinomas and glioblastomas.

The crinoid *Gymnocrinus richeri* and the gymnochrome B formula. © IRD/P. Laboute

The crinoid *Gymnocrinus richeri*, an echinoderm considered living fossil and sampled at a depth of 520 m on the Norfolk Ridge, led to the discovery of a new family of pigments: the gymnochromes, which have antiviral, anti-HIV and anti-dengue properties.

Poisonous cones, mollusks that paralyze their prey by injecting them with a mixture of neurotoxic peptides, are particularly promising for the discovery of powerful analgesics, such as Prialt® (1,000 times more powerful than morphine). A full research program is dedicated to the study of the genome and venom composition of *Conus consors* from the Chesterfield Reefs.

Lastly, the very emblematic sea kraits, *Laticauda colubrina* and *Laticauda laticaudata*, belonging to the same family as cobras or mambas (Elapidae) produce a particularly potent venom of which the polypeptide erabutoxin b, one of its main components, has been studied for its effects on the neurological system.

After all these years, only part of the pharmacochemical potential of the marine biodiversity of New Caledonia has been extensively studied (sponges, cnidarians, ascidians, etc.). The potential bioactive molecules of other biological groups and species have yet to be explored, rediscovered or valorized using recently developed biological and chemical techniques. Biotechnological developments involving micro-organisms are very promising in various scientific domains, such as microalgae for the production of biofuels or high added-value compounds for cosmetics or nutraceuticals.

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Chapter 33

The lagoon: a natural heritage and recreational space

Charles Gonson, Jocelyne Ferraris, Dominique Pelletier and Isabelle Jollit

Amédée Islet, a very touristic lagoon location. © P.-A. Pantz

Recreational uses: a challenge for coral reef management

"Recreational users" are defined as a group of people who engage in an activity for their leisure only, with no subsistence need or profit motive. These activities are characterized by a diversity of practices and under the influence of population growth and the development of tourism, their number in natural areas is increasing sharply. As is the case in New Caledonia, one of the world's largest lagoons listed as a UNESCO World Heritage Site in 2008, recreational use is intensifying and diversifying in all coastal areas.

Recreational activities such as fishing, scuba diving and water sports play at least two roles:

– an economic role by boosting a pool of activities through tourism or the boating industry;

– a social role in providing goods and services to people.

At the same time, they affect coral reef ecosystems that are already threatened by global climate changes. It is therefore essential to consider recreational uses in the sustainable development of coastal zones, particularly in island environments. Scientific studies have focused on the diversity of recreational activities in marine and coastal environments (diving, boating, water sports) since the year 2000. This research was motivated by the growing need for knowledge and the complexity of the relations between a prolific society and the natural world, on which it depends, which is also a limited resource, and which is particularly fragile in coral reef environments. Research aims at better understanding socio-ecosystems to assist the management of these areas, notably through the establishment of Marine Protected Areas (MPAs). Within these MPAs, which have objectives as diverse as biodiversity conservation and sustainable use, recreational activities are widely practiced. It is therefore essential to improve the understanding of these activities not only just to ensure the protection of ecosystems and the resources that they depend on, but also to anticipate the emergence of conflicts for space occupation and resource exploitation.

However, recreational users are still not well understood. This is mainly due to the difficulty of designing appropriate methodologies and tools that ensure the reliable collection of information, over time, on their number, location and practices. In New Caledonia, research has led to the development of methods for assessing the pressures and impacts of these uses. These methods are adapted to the coral reef environment and allow the acquisition of knowledge useful to the preservation of lagoon ecosystems that are managed by a network of MPAs.

Recreational uses: research for sustainable development

The promotion of the natural heritage of coral ecosystems and their conservation is a real challenge for the sustainable development of New Caledonia. First, the increasing demographics, and then the development of boating and tourism, have led to recreational activities being considered a threat to the sustainable management of fisheries resources and the conservation of reefs. These uses are not well known and are difficult to quantify because of their scattered and informal nature. This is why, since the 1990s, research programs and projects have involved local stakeholders, environmental managers and scientists.

Scientific studies first focused on improving the assessment of pressures and impacts of small-scale coastal fisheries (commercial, subsistence, recreational). In 2005, catches by recreational fishers on motorized boats were estimated at more than 1,100 tons/year in the Southwest Lagoon. Made up mainly of fish and shellfish species, these catches are concentrated on reefs near urban centers (Nouméa and Koné) and in the northern and southern lagoons of Grande Terre. Findings highlighted the importance of studying recreational fishing.

Survey of a recreational fisherman at Pandanus Islet in 2014. © IFREMER/C. Gonson

Cruise ship anchored at Lifou. © IFREMER/D. Pelletier

Conflictual cohabitation between users in the anchorage zone of an islet.
© IFREMER/C. Gonson

Larégnère Islet under heavy traffic. © IFREMER/C. Gonson

Subsequently, because of the issues and costs associated with the complex management of lagoon uses, the substantial development of other activities, such as boating, diving and island excursions raised concerns among public authorities and research organizations. With the improvement of knowledge on coral reef recreational uses, the complexity of the coastal systems under study (the diversity of recreational activities, ecosystems and their connections) is becoming better reflected in research projects. The concept of a socio-ecosystem is increasingly important, including the development of multidisciplinary and spatially explicit approaches.

Recreational activities associated with coral reefs are now better known. This knowledge supports the effectiveness of the management strategies that are implemented for a variety of objectives such as resource management, biodiversity conservation and sustainable use. In the New Caledonian Lagoon, particularly within MPAs and UNESCO World Heritage sites, numerous research programs and management measures (e.g., regulations, awareness-raising) have targeted recreational uses. However, historical knowledge of these uses is limited. In addition, the rapid changes in these uses (e.g., diversification of activities, expansion of tourism), which coincide with global climate change, threaten the sustainable development of New Caledonia's maritime space.

The lagoon under surveillance: an explosion in the number of boats

In the Southwestern Lagoon, close to Nouméa, a large population converges with numerous nautical infrastructures. Promoting the natural heritage associated with coral reefs while protecting ecosystems close to urban centers is a major management challenge for New Caledonia. In this area, studies involving researchers and environmental managers have led to the development of observation protocols and indicators relevant to the monitoring of uses, their impacts and governance issues.

Between 2005 and 2013, nearly 700 field trips and over 2,000 questionnaires were carried out to estimate the number, attendance and spatial and temporal distribution of recreational users, as well as to characterize their practices and opinions regarding the management and ecological state of ecosystems. Today, the methods for observation and the production of indicators have been optimized. Fully operational, they can now be implemented by environmental managers in New Caledonia, such as the provincial authorities and local management committees of UNESCO World Heritage sites.

During this period of less than 10 years (2005 to 2013), the number of boats visiting the reefs and islets around Nouméa more than doubled. These are mainly residents of the Nouméa agglomeration (Grand Nouméa), with at least 10 new boats joining the recreational fleet each week. In addition, the development of taxi-boats as led to an increase in the number of people visiting islets. For example, in 2013, it is estimated that over 10,000 boats and 80,000 people travelled to Maître Islet, and other islets located very close to Nouméa.

The activities are diverse and influence the occupation of the coastline by users in relation to the regulations and to the natural and social characteristics of the areas they use. The development of infrastructures (e.g., Maître Islet) can be used to attract large numbers of visitors, where specific activities (such as kitesurfing) are carried out. Protected natural areas, aimed at the conservation of species and natural habitats, with simple but attractive facilities such as moorings or shelters, are also popular because people expect high environmental standards (e.g., Signal Islet). In contrast, unregulated and often more remote areas tend to be targeted by boaters who want to fish and enjoy quiet islets that are less visited.

Based on the information collected, a simulation model aimed at promoting the adaptive management of lagoon areas, was used to assess the effect of management measures on the evolution of biodiversity and its uses. Results indicate that the development of alternative recreational areas (for example by providing parking lots or navigation buoys and markers) in coastal zones that are less vulnerable to the pressures associated with recreational activities (e.g., sand beaches) could limit the impacts on reefs and islets by draining part of the lagoon's users.

Sustainable recreational uses for a lagoon under pressure

The sustainability of coral ecosystems and their recreational uses depends on several variables, including ecological and social factors: ecological, because ecosystems suffer impacts that depend on their vulnerability to user activities and behavior; social, because the sustainability of uses also depends on whether people are satisfied with their experience of the lagoon. This satisfaction is particularly dependent on their ability to tolerate the presence of other people, in large numbers and in the same space, and their ability to practice their activities.

The distribution of users is increasingly heterogeneous, depending on the area and the time of year or week. Visitor peaks are now more frequent, and the associated pressures are also more intense, impacting very localized areas such as islands and reefs closest to coastal accesses. These pressures result in ecological impacts that alter the state of ecosystems, by the depletion or even extinction of the most sensitive species and habitats, and the modification of fish and invertebrate populations. However, the ecological quality of reef ecosystems also contributes to the sustainability of recreational activities, such as scuba diving or the simple enjoyment of coral reef seascapes. Users are increasingly aware of the impact of their activity on the ecological integrity of their environment. This awareness promotes environmentally friendly practices and thus the sustainability of reef socio-ecosystems. Unfortunately, the biodiversity of coral reefs is vulnerable to any form of human presence, and the state of coral reefs is threatened by the continuous increase in numbers of recreational users.

Beyond ecological sustainability, the intense use of an area can result in conflicts, either in the case of a single activity such as simply relaxing on very busy beaches, or because of the incompatibility between two practices, generally between fishing and water sports, or between boating and swimming, and jet-skiing. Public authorities have a significant role to play in ensuring the cohabitation of users for whom the overcrowding of the visited sites is an important disturbance factor. Strategies for this could include the distribution of different activities over time and space, or the possibility of a "wilderness experience" although this would also increase visitor numbers to a certain extent.

Future research related to development issues

In the areas where it can be assessed in New Caledonia, the level of pressures due to recreational uses may seem relatively low in comparison with other regions of the world. However, it is part of a rapidly changing demographic and tourist context and involves ecosystems that are particularly fragile and vulnerable to climate change (more frequent and intense tropical cyclones, warming of seawater, coral bleaching, etc.). The threats to coral ecosystems and the sustainability of their uses are therefore real and growing. Yet, the real magnitude of the cumulative effects of all these pressures on the state of the ecosystem and its functioning is poorly assessed because of their complexity. This is particularly true in the case of the effects of climate change or in lagoons facing anthropized zones, where the increase in pressures associated with recreational activities coincides with an increase in pressures from land-based sources.

In addition, recreational uses should be monitored in areas where strong demographic or tourist developments are taking place, or are expected, in order to better understand their impacts and evolution. These include the Koné region which has undergone recent economic development or the Loyalty Islands where cruise tourism is booming. The assessment of the ecosystem's state of health must be compared to the pattern of activities in order to identify the most vulnerable areas. This will involve identifying limits to practices based on the vulnerabilities of the surrounding environment. There is also a need to better understand the nature and motivations of users, in order to anticipate changes in their behavior following the introduction of new management measures that may modify their practices (e.g., shifting fishing effort out of the MPAs).

A better understanding of lagoon socio-ecosystems implies the consideration of an appropriate geographical scale. In New Caledonia, due to the mobility of users, their interactions, the connectivity of ecosystems and also the diversity of the structures of environmental management, the entire New Caledonian territory must be taken into account. At this scale, harnessing the knowledge and expertise in a multidisciplinary approach that combines environmental sciences and the human and social sciences - disseminated to decision-makers and civil society - should enhance the anticipation of the environmental and economic consequences of development policies.

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Partie 5

Vulnerable species in a fragile environment

Management, protection and conservation

Coordinator: Eric Vidal

Managing, protecting or conserving coral reefs involves several considerations. Is it about managing an environment, a resource or a territory? Is it to preserve a rare or threatened species or to maintain essential ecological processes? Is it to ensure that everyone continues to live and enjoy the reefs, to fish and observe marine life? Or is it to safeguard the stories and myths that are associated with it and contribute to the identity of each person? Here, the combined views of biologists, anthropologists and environmental managers prove that managing reefs involves the consideration of different knowledge, values and uses, which are essential to recognize, reconcile and engage in dialogue to establish shared rules.

Chapter 34

Managing emblematic species and reef ecosystems

Catherine Sabinot and Éric Vidal

Humpback whale tail *(Megaptera novaeangliae)* belonging to an endangered population that is breeding in New Caledonian waters. © Opérations Cétacés/C. Garrigue

Many biologists who work in New Caledonia have offered to contribute to this book on New Caledonia's coral reefs by presenting the species they are focusing their research on and which, according to them, justify specific management measures.

These chapters will therefore showcase a few species that are of particular interest to scientists in New Caledonia. Some of them describe the knowledge that scientists have accumulated on these animals and tell us how this knowledge can inform or has already guided coral reef management and conservation policies. These species are not only studied because they are emblematic or charismatic. They can be valuable bio-indicators of the state of the ecosystem, or they can be "sentinel" species that can reveal subtle changes in the environment at an early stage. Others play a special role in the ecosystem, and many other species and habitats can rely on them. For example, seabirds form dense colonies that fertilize terrestrial and marine ecosystems with their feces. Some of these charismatic species can also be labelled "flagship species", and the public and users are more inclined to accept restrictions and regulations to guarantee the conditions of their protection.

Research in human and social sciences aimed, among other things, at documenting the views of New Caledonian people on emblematic marine animals, was initiated recently. Some aspects of this are shared in the inset boxes, where the species chosen by biologists can be found; however, the emblematic status of a species is mainly justified by its social and symbolic significance. This reminds us that taking into account the social values of species as well as local and scientific knowledge is always a major challenge when building integrated, and respected, management policies.

In the following pages, the authors will therefore give priority to each "species" itself. However, this is not to lose sight of the challenges (as shown in other chapters of the book) faced by authorities to plan, structure and organize management and conservation policies with an ecosystemic and spatialized vision of the lagoon space which is to be preserved. It is also for this reason that this book has given special importance to the collectivities in charge of the different types of reserves and protected areas.

Box 27

What are the emblematic reef species for New Caledonians?

Camille Fossier, Estienne Rodary, Gilbert David, Espérance Cillauren, Ambre Piémontois and Catherine Sabinot

The ESPAM program is interested in the emblematic species, social acceptance and the sustainability of marine protected areas. In 2017, it began important work on emblematic marine animals for New Caledonians. The objective of this project was to find out which species are the most important for the inhabitants of the island by collecting a list of these species from them, including the reasons for their choices.

A first significant result was the diversity of the species mentioned: out of seven public meetings, 80 species were mentioned. Of these, turtles, sharks and dugongs were the most frequently named, but the species that are fished for food were also important.

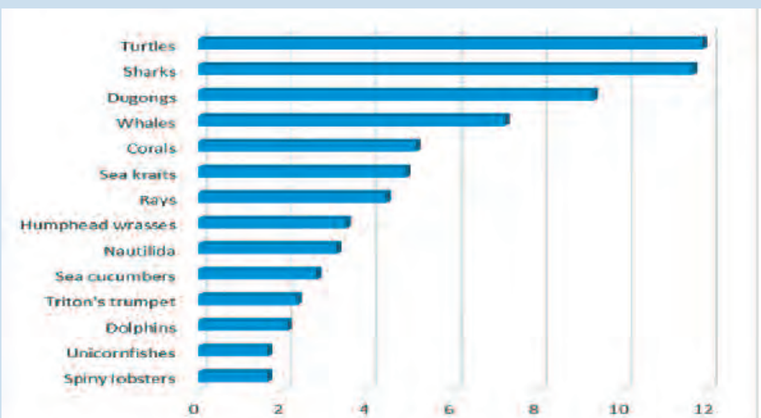


Figure 1: Animals cited by at least 2% of people (number of mentions). It is worth noting the importance of corals, which are selected for their reef-building role. Interviews conducted in 2017 by the authors

A second quite remarkable observation was the reasons why these animals are seen as emblematic. The social and symbolic importance of animals (culture, Kanak totem, etc.) is the most widely mentioned reason, followed by the enjoyment of direct observations. Ecological arguments about the importance of a species, such as its role in ecosystems or its threats, rank third.

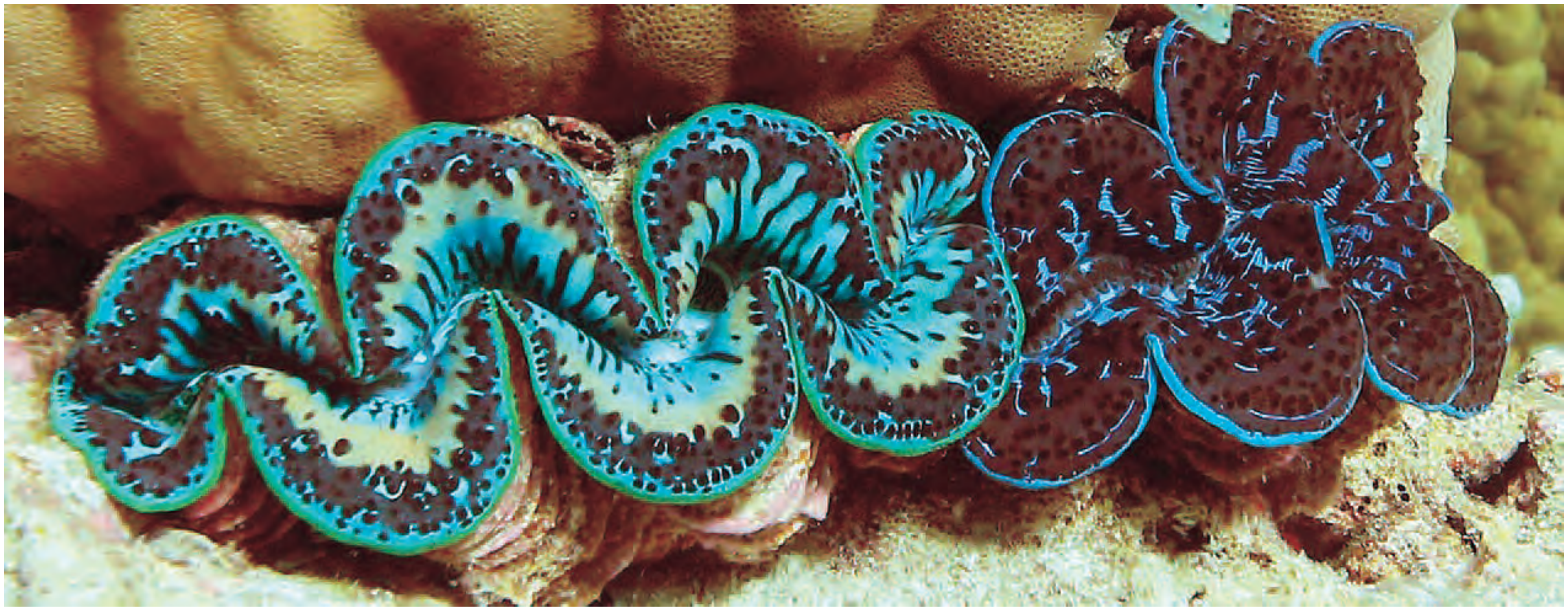
These results may directly impact on conservation policies in the New Caledonian lagoon, which must take into account the social values attached to emblematic species. Policies based solely on ecological criteria are at risk of not meeting people's expectations and therefore not effectively protecting the reefs.

Figure 2: Main reasons given to justify the designation of "emblematic species" (size of words relates to the number of mentions). Interviews conducted in 2017 by the authors

Chapter 35

Giant clams: a resource to preserve

Cécile Fauvelot, Pascal Dumas and Josina Tiavouane



Tridacna maxima is the smallest species of giant clam and the most sough-after in aquariophilia because of the bright colours of its mantle. © IRD/S. Andréfouët

In New Caledonia, as in many Pacific countries, giant clams are a highly sought-after resource. Their exploitation can threaten their availability and even lead to their disappearance. For instance, *Tridacna gigas*, the largest species, once present on the reefs of New Caledonia, is now only found in fossil form. According to the official statistics of the New Caledonian Fisheries Observatory, the official annual catch figures, recorded between 2000 and 2014, are significant and reach up to 9 tons/year for all species. Since 2009, protective measures have been implemented to stop the observed decline in stocks. For example, the fishing of giant clams is regulated in both the northern (article 341-54 of the Environmental Code) and southern (Article 37 of the Environmental Code) provinces: catches are limited to two giant clams per boat and per day for nonprofessional fishing (recreational and subsistence) and five giant clams per boat and per day for professional fishing.

In the Province of the Loyalty Islands, Kanak customary law alone regulates giant clam fishing, no other legislation applies. The absence of statistical data at the species level, however, is currently preventing the accurate assessment of catch rates per species. This is even more true in the case of undeclared subsistence fisheries, where impacts on the resource are not quantified at all. Despite a positive effect (a decrease in catches) since the introduction of these regulations, available data suggest that the densities of giant clams continue to decrease due to increases in fishing pressure linked to the demographic development of the territory.

Tridacna gigas is present throughout the coral triangle as far as the Solomon Islands, but has disappeared from the reefs and lagoons of New Caledonia where fossil shell valves are much sought-after by lapidaries. © IRD/S. Andréfouët

Confronted with the alarming state of the resource and the desire of local communities to keep on consuming giant clams, managers, scientists and local stakeholders must, more than ever, join forces to find innovative solutions. In September 2009, WWF and the Fisheries and Aquaculture Department of the North Province coordinated a restocking operation of the Horse's hoof giant clam, *Hippopus hippopus*, in the two co-managed Marine Protected Areas (MPAs) of Pouébo and Hienghène. In 2012, a genetic study carried out in the Hyabé/LéJao (Pouebo) MPA evaluated the effectiveness of this restocking process and estimated the dispersion range of larvae around the MPA. Coordinated by the IRD, this work revealed that 22% of the giant clams sampled inside the MPA originated from the reproduction of MPA individuals, revealing a high rate of self-recruitment. The study also showed that about a quarter of these "self-recruits" were born from at least one parent issued from the restocking operation, thus proving the effectiveness of this action.

For larval export, the results show that 18% of juveniles sampled on fringing reefs on each side of the MPA are the result of the reproduction of adults located in the MPA, up to about 35 km apart. Re-seeded specimens also participated in exports, with a share of around 30%. Therefore, Horse's hoof giant clam larvae from protected areas, where fishing is regulated, are exported and contribute to the resilience of populations in unprotected areas, emphasizing the importance of these marine protected areas.

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Chapter 36

Rare and endemic fishes, little-known players that must be preserved

Michel Kulbicki, Philippe Borsa, Gérard Mou-Tham, Laurent Vigliola and Laurent Wantiez

This angelfish *(Pygoplites diacanthus)* is rare in New Caledonia except in the lagoon of Ouvéa. Its rarity may be explained by its diet, largely made of sponges, which are toxic to most other fish. © S. Floeter

Endemic and rare species are often a source of curiosity for both neophytes and specialists (scientists or environmental managers). Is this the case for our reef fish species?

First, how do we define endemism and rarity? Endemism refers to species which occur in only one locality. Depending on the definition of locality, there may be many different scales of endemism. In this chapter, we will talk about local endemism, for species with a geographical distribution restricted to an area of about 500 km in radius, and regional endemism, for species with a distribution range of 1,500 km in radius. These scales may seem relatively large compared to terrestrial endemism, which often has very small distribution ranges. This difference in scale is due to the dispersal capacities of reef fish species, which, during their larval stage, can drift with ocean currents over hundreds of kilometers. There are also several ways to be rare:

– rarity of abundance, for which there are very few individuals of the species throughout its entire distribution range;
– rarity of frequency, where the species rarely occurs, but can be locally abundant.

This means that there is a link between rarity and endemism, since one of the definitions of rarity relates to geographical frequency and, consequently, to distribution range.

On the importance of these species

For species to be endemic or rare, it is likely that they have unique biological, genetic or ecological characteristics, which makes them particularly important to diversity. For instance, an endemic species can be expected to be better adapted to local conditions than non-endemic species. Similarly, a species may be rare because its biological or ecological characteristics prevent it from being abundant - for example, large species - and this local rarity is often balanced by a large geographical distribution. In any case, rare species are a source of diversity and as demonstrated in the chapter on the ecological functions of fish, available resources are more efficiently used when diversity increases. This results in more stability and resilience to environmental change, but also more ecosystem services, including the production of higher biomass.

Rare species are difficult to study

A rare species is, by definition, difficult to find and therefore difficult to study. However, sometimes, there is "false rarity" associated with sampling. For example, some species may appear to be rare because of their behavior, such as moray eels which are relatively abundant but live hidden in reef crevices all their life.

Harlequin tuskfish *(Choerodon fasciatus)* are widely distributed in the Pacific Ocean but are rare everywhere. © R. F. Myers

In addition, it is necessary to define thresholds of abundance from which a species is considered rare. In this chapter, we choose a threshold of 10,000 individuals.

Two challenges must be overcome for studying endemic species:
– the definition of the relevant scale, mentioned above;
– the level of knowledge and exploration of fish communities.

An island species can be considered endemic for a long time for the simple reason that the surrounding archipelagos have not yet been properly explored. In the Hawaii Islands, for example, the proportion of endemic species was estimated at about 30% in the 1960s. It decreased to 23% in the 1990s and reached 17% with increasing knowledge of the rest of the Pacific. Conversely, what was once thought to be a single widespread species may turn out to be part of a complex of species. The blue-spotted maskray is a good example: it used to be considered as a single species, but genetics and geographic distributions revealed 11 reproductively isolated, distinct species. Consequently, the rarity or endemism status of a reef fish may be unstable, more than what is observed in the terrestrial environment. This has implications for management policies where a biotope or ecosystem approach will be more appropriate than a species-by-species approach.

Endemic reef fishes, how many and who are they?

The number of reef fish species endemic to New Caledonia is highly debated. If we focus only on properly identified species, there are currently 27 known local or regional endemic species, representing 1.8% of reef fishes.

Endemic New Caledonian species are mostly bottom dwelling, solitary and active only during the day. They mainly belong to syngnathids, a group that includes seahorses (six species), gobies (five species), blennies (four species) and Tripterygiidae, or triplefins (four species). The three latter families are poorly known and it is likely that the status of several species currently recognized as endemic will change in the near future as new knowledge is acquired.

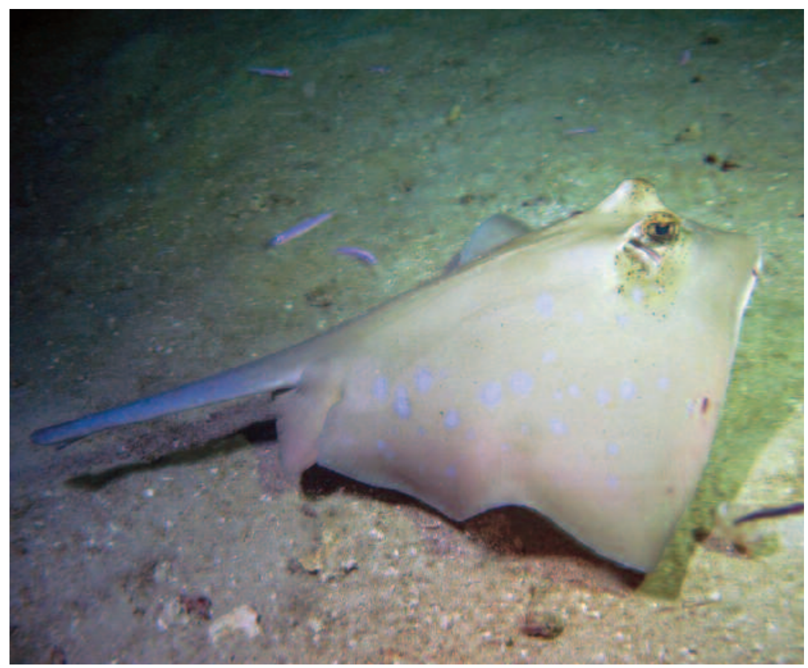
For example a species recently described from New Caledonia and believed to be endemic, the oblong large-eye seabream *Gymnocranius oblongus*, has since been observed in Taiwan. In contrast, one species of the blue-spotted maskray complex (*Neotrygon trigonoides*) may be unique to the Coral Sea region. To our knowledge, none of the species endemic to New Caledonia is abundant.

The next question addresses what can determine the number of endemic species. Specifically, do the number or proportion of endemic species vary from one region to another in the Pacific? And what are the possible factors that cause variation in reef fish endemism? The distribution of Pacific reef fish endemism is very heterogeneous. Regions with high endemism (between 3.8% and 28%) are all located at the periphery of the tropical Pacific. In contrast, the proportion of endemic species in the central tropical Pacific is much lower, with an average of 1.6% of known species. Regions with high endemism, with the exception of Japan, are all characterized by low species richness. In New Caledonia, more than half of the endemic species are considered "local endemic". This dominance of local endemism over regional endemism is observed throughout the periphery of the tropical Pacific, with the exception of Hawaii and Japan. In this respect, New Caledonia differs from its neighboring regions, such as the Great Barrier Reef, the Coral Sea, Vanuatu or the Solomon Islands, where regional endemism prevails.

In reef fish, the underlying causes of the level of endemism are not well known, but the proportion of endemic species increases in isolated archipelagos, especially if islands are small. Two major groups of endemism can be distinguished: sympatric and allopatric endemism. In the first group, species "split" into two or more species as a result of local isolation, a phenomenon that is often difficult to demonstrate (environmental changes, acquisition of behavior in a group of individuals, etc.). In the second group, populations are isolated from each other and evolve separately until they accumulate sufficient genetic differences to become distinct species. The analysis of the distribution of endemic species throughout the Indo-Pacific suggests that the most common group is allopatric endemism. With the succession of glaciations and subsequent warming, followed by retraction and expansion of coral reef regions, it is likely that many populations have been isolated. Depending on their capacity to recolonize from refuge areas, these populations may or may not have produced new, often endemic, species.

How many rare species?

The number of rare species depends on the definition of the level of rarity. Figure 1 shows that the proportion of rare species is very high in New Caledonia: 47% of species for a threshold of one individual per 10,000 and 18% for a threshold of 1/100,000. This ratio changes slightly depending on the environment, with poorly diversified reefs having a smaller proportion of rare species. The proportion of rare species increases with island size: for example, it is higher on Grande Terre than on the Loyalty Islands. This proportion also increases with the number of species in the region: the proportion of rare species in Polynesia is only 14% but in Fiji it reaches 29% (at a rarity threshold of 1/10,000).



New caledonian maskray (*Neotrygon trigonoides*). © J.-L Menou

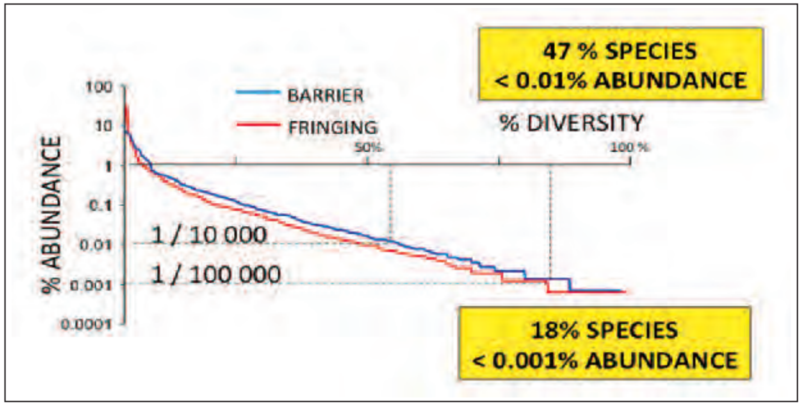


Figure 1: Proportion of rare species on fringing and barrier reefs in New Caledonia. Adapted from JONES, *et al.*, 2002 and MOUILLOT *et al.*, 2013

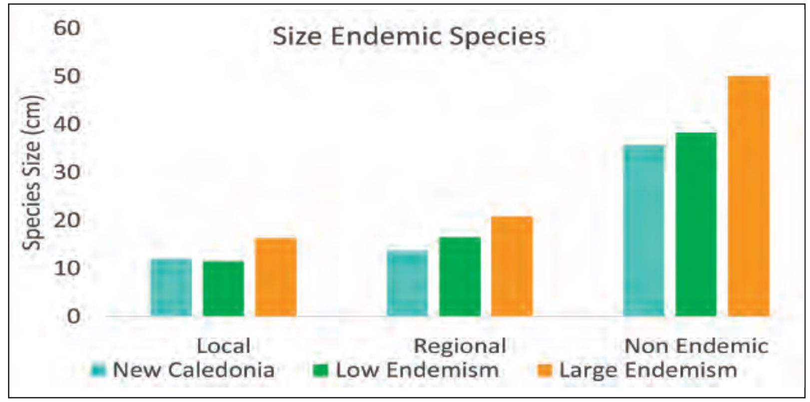


Figure 2: Average size of reef fish species according to their level of endemism (local, regional, non-endemic) and the proportion of endemic species. Regions of low endemism in New Caledonia: < 3.8%; regions of high endemism: > 3.8%.
Adapted from JONES, *et al.*, 2002 and MOUILLOT *et al.*, 2013

Characteristics of endemic and rare species

Endemic species are, on average, three times smaller (Fig. 2) than other species, with local endemic species being slightly smaller than regional endemics. Similarly, regions with high endemism have larger endemic species than regions with low endemism. These size differences are correlated to the remoteness and size of islands: the smaller an island is and the farther away from the central Indo-Pacific region, the more reef fishes are represented by large species. For example, in Hawaii, the numerous endemic species are represented by a large proportion (30%) of species over 30 cm long, whereas in New Caledonia only 8% of species are over this size.

Endemic species have diets that differ from the average (Fig. 3). They are less often piscivorous, herbivorous or sessile invertebrate (mainly corals) feeders than other species. New Caledonia is distinguished by the absence of these three types of diet among its endemic species. In contrast, endemic species in New Caledonia are more frequently omnivorous than in other regions.

Rare species are mostly carnivorous (50% of carnivorous species are rare) or piscivorous (20%) and are mostly (55%) of medium size (8-30 cm). More importantly, the ecological function of rare species is often unique. In other words, each rare species tends to have a very specific ecological function. Its disappearance would therefore lead to the disappearance of its function.

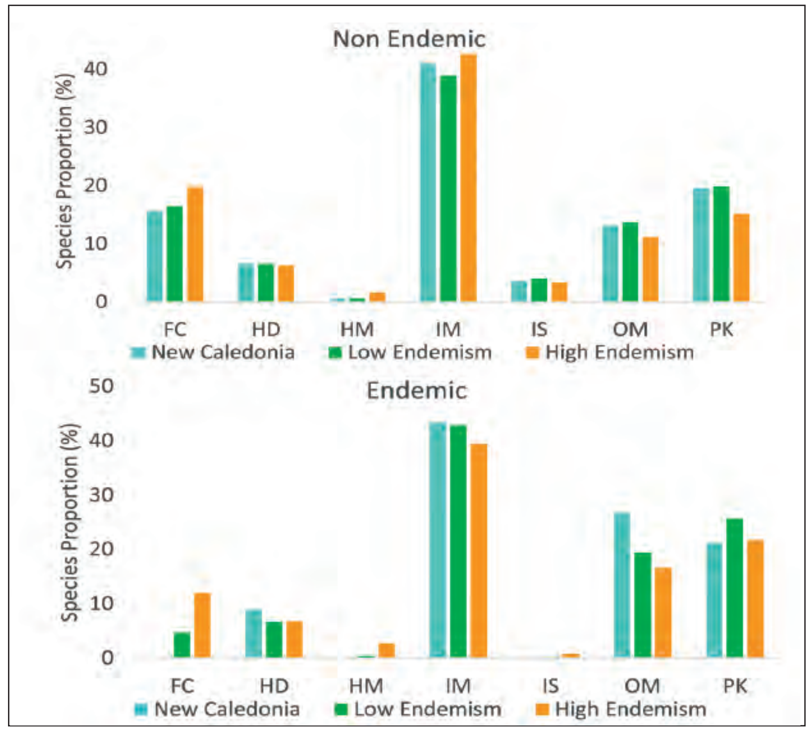


Figure 3: Diet of reef fish species according to their endemism and the level of regional endemism.
FC: Piscivorous; HD: Turf herbivorous; HM: Macroalgae herbivorous; IM: Mobile invertebrate feeders; IS: Sessile invertebrate feeders (corals); OM: Omnivorous; PK: plankton feeders.
Adapted from JONES, *et al.*, 2002 and MOUILLOT *et al.*, 2013

Mandarinfish *(Synchiropus splendidus*) are rare and difficult to observe, they often hide among *Diadema* sea urchins in coastal areas. © R.F. Myer

On the role of endemic and rare species

The role of rare species is still very poorly understood, but their rare ecological functions suggest that, although they are not essential, they contribute significantly to the diversity and thus to the stability and resilience of reef communities. The role of endemic reef fish species in New Caledonia is probably negligible for the functioning of the reef communities because they are never abundant. The situation is different in regions with a high diversity of endemic species (>8%), particularly in the Hawaii Islands and Easter Island, where these fish species represent 30% to 60% of the abundance depending on the island.

Management and conservation

Rare and endemic species are frequently the focus of conservation programs in terrestrial environments because they are often threatened. The same applies to certain marine species, such as the endemic shellfish, dugongs or lobsters off Bourail. The reef fishes that are currently threatened in New Caledonia are all emblematic species (chap. 38), which is not, or almost not, the case for rare or endemic reef fishes. So how and why should we protect them?

How? In New Caledonia, rare or endemic species occupy very diverse habitats. It is therefore difficult to manage these species specifically. For this reason, it is necessary to implement a comprehensive management policy that focuses more on protecting habitats and preserving environmental conditions than on protecting particular species. This is very different from the terrestrial environment, where it is possible to protect targeted species such as kagu, parakeets, crow honeyeater or endemic plants, although habitat conservation, such as dry forest, also protects a range of species, including endemic or rare species.

Why? These species often provide specific ecological functions which lead to an increase in ecosystem services that is often much more important than would be expected given their rarity. Many of these species are particularly beautiful, the angelfish being perhaps the archetype of such a species. A decline in diversity, which most commonly involves these species (Fig. 1), is often a strong signal of disturbance. The analysis of the diversity-abundance curves can provide a prompt detection of the early stages of degradation.

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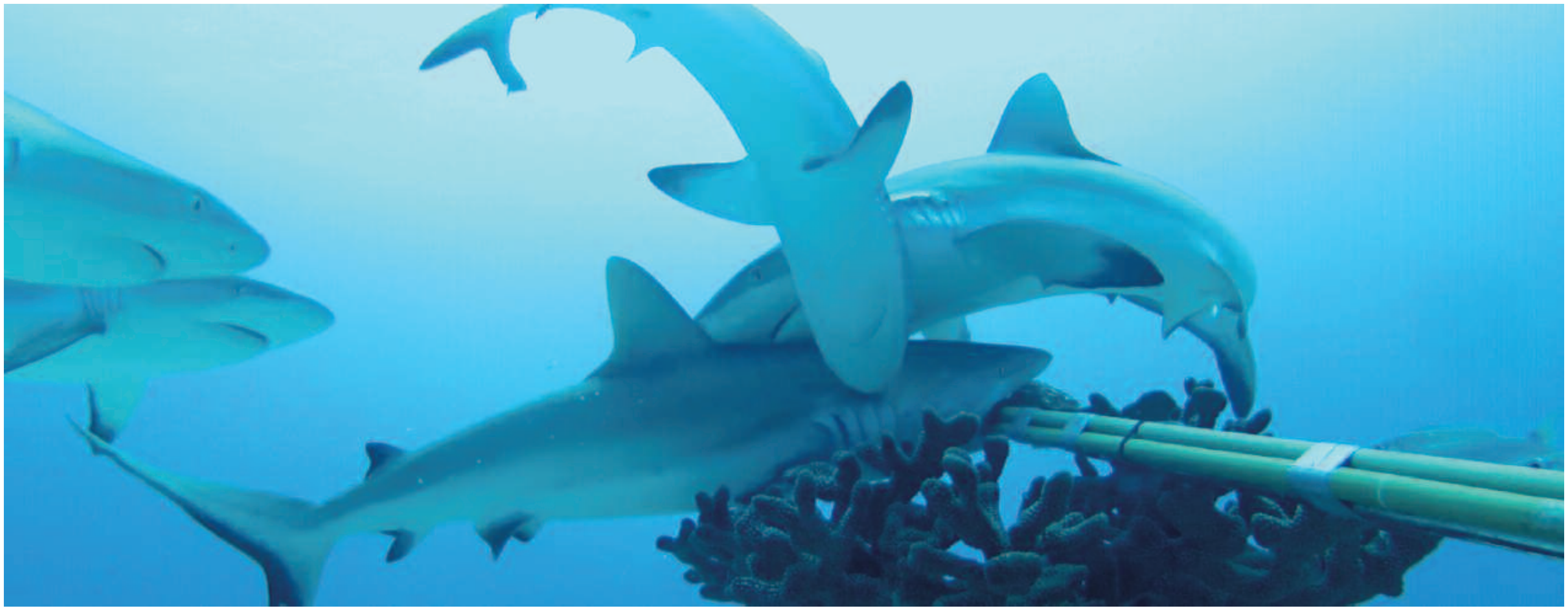
Chapter 37

Where are the sharks?

Laurent Vigliola, Jean-Baptiste Juhel, Laurent Wantiez and Michel Kulbicki



Grey reef sharks recorded by a baited stereo camera at Astrolabe Reef. © IRD/L. Vigliola

Although they are among the most powerful predators of the oceans, sharks are highly vulnerable and many species face a significant risk of extinction throughout the world's oceans. Recent studies show that 97 million sharks are killed each year by fishing and that some populations have declined by 99% (WORM *et al.*, 2013). Unlike other fish that lay millions of eggs every year, sharks can only give birth to a few pups in their lifetime. For example, the grey reef shark, *Carcharhinus amblyrhynchos*, reaches sexual maturity at 10 years of age, at which point females can start giving birth to one to five pups every two years. The gestation period is one year. With such a slow reproductive rate, it will take decades for decimated shark populations to recover.

With a relatively small human population compared to the size of the lagoon, and with no history of industrial shark fishing and a recent formal ban, New Caledonia sharks should have been relatively spared. However, that is not the case. As part of the PRISTINE[25] and APEX[26] projects, we deployed 385 baited camera units and carried out 2,790 underwater dives to sample reef shark communities throughout the New Caledonia Archipelago.

[25] http://pristine.ird.nc
[26] http://apex.ird.nc

Carcharhinus amblyrhynchos (grey reef shark); the behavior of the two animals suggests a mating episode. © M. Juncker

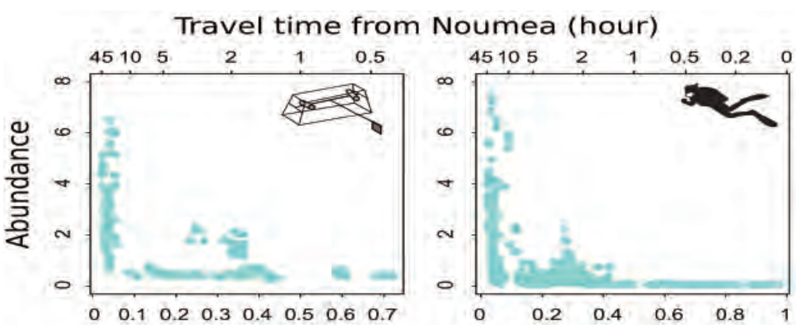


Figure 1: Shark abundance as a function of reef isolation in the New Caledonia Archipelago using baited stereo-camera (left) and visual census by scuba divers (right). Adapted from JUHEL *et al.*, 2018

Our results show that reef sharks are more diverse and abundant in the isolated reefs of the archipelago. There, more than 25 hours away from the capital Nouméa, they are sheltered from most human impacts. However, these emblematic animals have virtually disappeared from reefs close to human populations (JUHEL *et al.*, 2017). The impact is very severe, with a decline of 97% in shark abundance and 94% in species richness in reefs within an hour of Nouméa compared to isolated reefs (Fig. 1).

Many hypotheses could explain this disappearance, the exact causes of which are not identified. For example, the residual effects of historic, illegal or accidental fishing, overfishing of prey, habitat degradation, pollution, or disturbance during reproduction. Whatever the causes, the disappearance of sharks is worrying because, as large predators, sharks have a major structuring role in natural ecosystems (RUPPERT *et al.*, 2017). However, solutions to these problems do exist. Large marine nature reserves (over 200 km^2), where human presence is strictly prohibited, have positive effects on shark abundance and diversity. The creation of this type of reserve (strict nature reserve) requires large areas and some degree of isolation. These conditions are found in the vast southern and northern lagoons in particular, but also in the immense Natural Park of the Coral Sea, where sharks can find an ultimate refuge. With the use of these parks and reserves, New Caledonians still have the opportunity to effectively and sustainably protect sharks occurring on their reefs.

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Chapter 38

Emblematic fish species as flagships of participative ecology?

Michel Kulbicki, Philippe Borsa, Gérard Mou-Tham, Laurent Vigliola and Laurent Wantiez

Reef manta rays *(Manta alfredi)* attract the public's attention because of their size (several meters wide), strange morphology and spectacular behavior. They are the most symbolic of species that promote environmental preservation. © IRD/G.Boussarie

Scientific research is receiving more and more media coverage. This provides ways of communicating the latest knowledge to decision-makers and the public, who can then develop an informed opinion. To reach as many people as possible, the information must be accessible and allow non-experts to understand complex systems such as coral reefs. Emblematic species enable this bridge between science, population and decision making.

To qualify as emblematic, a species has to meet one or more of the following conditions: perform an essential ecological function, be affected by disturbances, have a broad geographical distribution and have the potential to arouse media attention.

In reef fish, three main groups of species can be classified as emblematic. First, very large species such as sharks (chap. 37), large rays, giant groupers, Napoleon wrass or humphead parrotfish. These easy to identify species are all highly sensitive to disturbance, especially fishing, and many of them perform key ecological functions. The second group is made up of small, colorful, and easy to identify species, which are also sensitive to changes in the environment.

Examples include butterflyfish, angelfish and clownfish. The last group also includes species of great local cultural importance, such as short-nose unicornfish *(Naso unicornis)*, emperor red snapper *(Lutjanus sebae)*, emperors *(Lethrinus* spp.*)*, *mïkwaa or* milkfish *(Chanos chanos)* or rabbitfish *(Siganus lineatus)*. These different groups play different roles in our approach to environmental conservation.

The first group is the most mediatized. The spectacular nature of these species makes it is possible to raise public awareness about the ecological and societal challenges related to the maintenance of these species, which contributes to the preservation of their environment. In New Caledonia, it was possible to take measures to preserve the Napoleon wrass *(Cheilinus undulatus)* following an international awareness-raising campaign on this species, whose numbers are threatened in the most populated areas. Another species, which is more economically significant, the humphead parrotfish *(Bolbometopon muricatum)*, is still fished despite its acknowledged key role in the functioning of reefs.

The development of ecotourism has also made possible the in situ observation of species such as sharks, manta rays and giant groupers not far from the most populated zones of the territory. If these species were to experience a decline in numbers, it is likely that populations would be alerted and new protection or management actions would result. However, many of these fish species are concentrated in protected areas and their overall abundance may decrease without significant changes in the protected populations.

The second group is more accessible. It includes, for example, the butterflyfish which can be observed on all the reefs of the country. These fish are very sensitive to changes in their habitat. Butterflyfish are also very strongly linked to corals and this means that they can be used to detect changes in the quality of coral cover over the medium and long term, and they are often proposed as indicators of environmental conditions.

In addition, because of their diversity (34 species in New Caledonia) and because they can be identified easily, they are included in most participative science programs such as the Global Coral Reef Monitoring Network (GCRMN) and the RORC (New Caledonia Coral Reef Observation Network). Participative science has largely demonstrated its potential in terrestrial environments, but the complexity of reef ecosystems makes its application here more difficult.

The last group is relatively difficult to define because its composition is more variable. Most are species of longstanding economic or societal importance. In general, these species are medium to large in size and are an important part of the fish biomass. Before the arrival of Europeans, the capture, keeping or use of these species was often governed by complex rules. Examples include the short-nose unicornfish *(Naso unicornis)* on the island of Tiga, whose fishing was controlled by a set of customary rules, and the *mïkwaa* or milkfish *(Chanos chanos)* which is still ruled by community fisheries in several tribes. Species in this group are not listed anywhere but they are part of the local culture. Local populations would not remain unaffected by a significant decline in the number or size of species such as rabbitfish, large-eye seabream, lyretail grouper or mullet. Although there are ecological indicators based on the density and biomass of some of these species, these are not yet widely used in management strategies. However, the public's reaction to significant changes can lead to decision being made. For instance, the rarefaction of giant groupers *(Epinephelus coioides* and *E. malabaricus)*, followed by their sudden abundance after the discovery of their spawning grounds, generated reactions that led to regulations. Furthermore, the rarefaction of rabbitfish has also led to aquaculture trials.

To date, emblematic reef fish species have no specific status in New Caledonia, but consultations are ongoing. This is an opportunity to better define these species and introduce measures to protect them, to use them as indicators or specifically to preserve their population levels and quality. Most of these species are part of the country's cultural heritage, as are kagus, parakeets, Norfolk pines, kaoris or freshwater prawns. Beyond their preservation, they are an important means of communication and exchange between the public and decision-makers.

Chapter 39

The marine turtles of New Caledonia

Tyffen Read and Richard Farman

The hawksbill sea turtle *(Eretmochelys imbricata)* is in critical danger of extinction. This species is hunted for the quality of the shell scales. © G. Boussarie

Five of the eight marine turtle species recorded worldwide are found in New Caledonia. However, their numbers vary considerably. Leatherback sea turtles (*Dermochelys coriacea*) only transit through exclusive economic zones and observations of the olive ridley sea turtle (*Lepidochelys olivacea*) are anecdotal, and probably due to animals that travel off-track. However, the other three species, the green sea turtle (*Chelonia mydas*), the loggerhead sea turtle (*Caretta caretta*) and the hawksbill sea turtle (*Eretmochelys imbricata*) are frequently observed in the lagoon. Worldwide, the IUCN (International Union for Conservation of Nature) classifies green and hawksbill turtles as endangered, and loggerhead turtles as vulnerable.

Two major rookeries

New Caledonia hosts two of the major rookeries for green and loggerhead turtles in the Southwest Pacific. In terms of importance, these sites are second only to Australia, and the loggerhead breeding site is the only other rookery for this species in the rest of the Pacific islands.

The green turtles of New Caledonia come from several genetic groups, mainly those of the d'Entrecasteaux Reefs (independent), and the Coral Sea, including turtles that lay their eggs on the Chesterfield Atolls, and those of the northern and southern Great

Barrier Reef. However, there is very little connection between these different groups. Females are very faithful to their breeding sites during the same season (a female lays eggs several times during a season), but also between successive seasons. The inter-season gap is estimated at an average of 8.35 ± 3.30 years.

While feeding sites for green turtles can be found throughout the lagoon, particularly on the west coast, rookeries are mainly located in the north of Grande Terre and in the Loyalty Islands. The main exchanges have been documented between feeding sites and rookeries in Australia and New Caledonia, suggesting the existence of migration corridors not only between the two countries, but also within each country.

In fact, 61% of the green turtles in the Southern Lagoon (Grand Lagoon Sud) come from the d'Entrecasteaux Reefs rookery, 24% from Australia and less than 5% from the Chesterfield/Coral Sea area. The number of green turtles feeding in New Caledonia is unknown. It is estimated that there are several thousand females at the rookery of d'Entrecasteaux Reefs, a few hundred more in the rest of the lagoon and a similar number at the Chesterfield site. The size of the Southern Lagoon's population fluctuates considerably with a high prevalence of juveniles (88%) and an absence of adults, which is a concern. This imbalance is due to the high recruitment of new animals, which are easily identified by the color of their plastron.

Turtle population displacements and anthropogenic impact

In this area, it has been estimated that the vital range of a turtle is on average 54 km^2 with, however, a high variability from one area to another and no exchange between areas.

Professional longline fishing has little impact on the populations of green turtles (one catch between 2006 and 2008 and three in 2016). However, fisheries that are authorized by derogation for customary ceremonies have been estimated at about 500 individuals in 2014. A number of animals are also illegally caught, but there is no available estimate of the scale of this.

Loggerhead sea turtle equipped with a transmitter beacon to study the migration of the species between egg-laying and feeding sites. © Aquarium des Lagons

Egg lating of *Chelonia mydas.* © G. Boussarie

At the end of long apneas, the turtles go up to breathe on the surface. *Chelonia mydas.* © G. Boussarie

Loggerhead turtles belong to the Southwest Pacific genetic group. There is very little exchange between the different genetic groups of this species (only five at the global level), which is a major management constraint as conservation efforts have to be applied to all age groups, especially younger individuals, including those caught in the bycatch of South American fisheries. Here again, the exchanges between New Caledonia and Australia have been documented. Females marked at the site of the Roche Percée were tracked all the way to Australia (Moreton Bay, Cape York and the Gulf of Carpentaria) or Papua New Guinea (Trobriand Islands).

As for juveniles, their movements are closely associated with the 19°C isotherm, which they follow to New Zealand where they stay for some time, then cross the Pacific Ocean to the South American coasts before returning to recruit in the region's coastal habitats.

Just as for green turtles, we do not know the number of loggerhead turtles feeding in the New Caledonian Lagoon, although it is estimated that there are about 50 females that visit the main rookery of the Roche Percée in Bourail. It is believed that they are at least as equally distributed on the islets of the Southern Lagoon and there are also some who feed in the north.

Females demonstrate a very high-fidelity rate to their breeding sites during the same season, but also between successive breeding seasons. The interval between seasons is 2.84 ± 1.27 years and the interval between egg laying during the same season is 15.14 ± 1.44 days.

Loggerhead turtles are not fished but egg poaching has been reported at the Roche Percée site (13% of nests were looted). Furthermore, though there was no bycatch by the New Caledonia longline fleet between 2006 and 2008, up to 3,000 individuals are caught annually by Peruvian fisheries, of which 92% are reported to be released alive.

To date, egg laying by hawksbill turtles has never been observed in New Caledonia. It is the least known and probably the least abundant species, even if it is often found in the lagoon (its feeding ground). In addition, an unknown genetic group has been identified at several sites in the region, which could be explained by the existence of another rookery in New Caledonia.

Loggerhead sea turtle *(Caretta caretta)* swiming along the external reef slope. © J.-L. Menou

All marine turtle species are fully protected internationally by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and locally by the environmental codes of the North and South Provinces and by the regulations of the Loyalty Islands Province and New Caledonia. In addition, any catching, disturbance, keeping or destruction of any species is prohibited, as is the destruction of nests, the sale of eggs and marketing of any kind whatsoever.

Given the conservation status of these species (vulnerable or endangered), their heritage value, particularly for local populations, and the importance of New Caledonia for conservation at a regional level, a local action plan is being prepared. The aim is to establish priorities and allocate tasks, to combat, in particular, the effects of climate change that will impact rookeries (coastal erosion, rises in nest temperature, changes in the sex ratio, etc.). In this instance we must, just like the turtle, learn how to get off to a good start. Perseverance leads to success even without the best assets.

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Chapter 40

Seabirds as sentinels of New Caledonian waters

Éric Vidal, Karen Bourgeois and Philippe Borsa

Juvenile masked booby *(Sula dactylatra)* © M. Junker

With several hundred islets scattered like confetti over a vast oceanic and lagoon area, the coral reefs of New Caledonia provide exceptional nesting sites for a diverse and abundant seabird community (chap. 20). Seabirds are one of the world's most threatened animal groups and their risk of extinction is increasing faster than any other bird group. Seabirds are valuable bio-indicators of the direct and indirect impacts associated with human activities, both on land and at sea. This is because most of these species are long-lived and share their existence between their terrestrial breeding colonies (particularly on coral cays) and the sea (for foraging and during inter-nuptial periods). They are major predators positioned at the top of the marine food chain. In addition, because of their sensitivity to environmental changes and disturbances, which affect feeding and breeding sites, environmental managers consider them as "sentinel species", capable of informing on the condition of natural marine and island areas.

They also represent interesting "umbrella species": while the conditions for their sustainable conservation can be met (e.g., MPAs), their high ecological requirements, particularly in terms of habitat quality and surface area, mean that they can, in turn, benefit a wide range of other species, communities and ecosystems. In New Caledonia, the importance and diversity of coastal and island environments, and the quality and size of lagoon and ocean ecosystems, mean that the seabird community is both numerically very large and diverse in terms of species, but also faces major conservation challenges due to the presence of threatened species. Nonetheless, the seabirds of New Caledonia's coral cays face a variety of threats associated directly or indirectly with human activities.

At nesting sites, seabirds are impacted by introduced animal species, including rodents such as the black rat, Polynesian rat or domestic mouse, which prey on eggs and chicks, or invasive ants such as the electric ant which inflict severe stings. Their breeding habitat is also altered by the introduction of different plant species. The seabird community is highly sensitive to disturbances caused by visitors and to the sometimes devastating consequences of tourist developments. Past operations, such as the industrial exploitation of guano on some islands of the d'Entrecasteaux and Chesterfield reefs have also had a lasting negative impact. More recently, new questions have emerged on the possible effect, in the near future, of rising sea levels and more frequent flooding on the availability and quality of seabird breeding grounds on low coral cays. These issues are complex because coral cays and islets are not "passive" geological features. Their evolution over time depends on complex sedimentary and physical processes.

At sea, the threats may seem more diffuse but they are very real. They include changes in the oceanic environment, such as changes in food availability caused by climate change, pollution and biocontamination that particularly affect the physiology of higher predators (heavy metals, pesticides), or even the ingestion of plastic debris or accidental catches by fishing gear. Seabirds have to deal with a dense array of modern threats, the severity of which is still insufficiently documented in New Caledonia and requires further research.

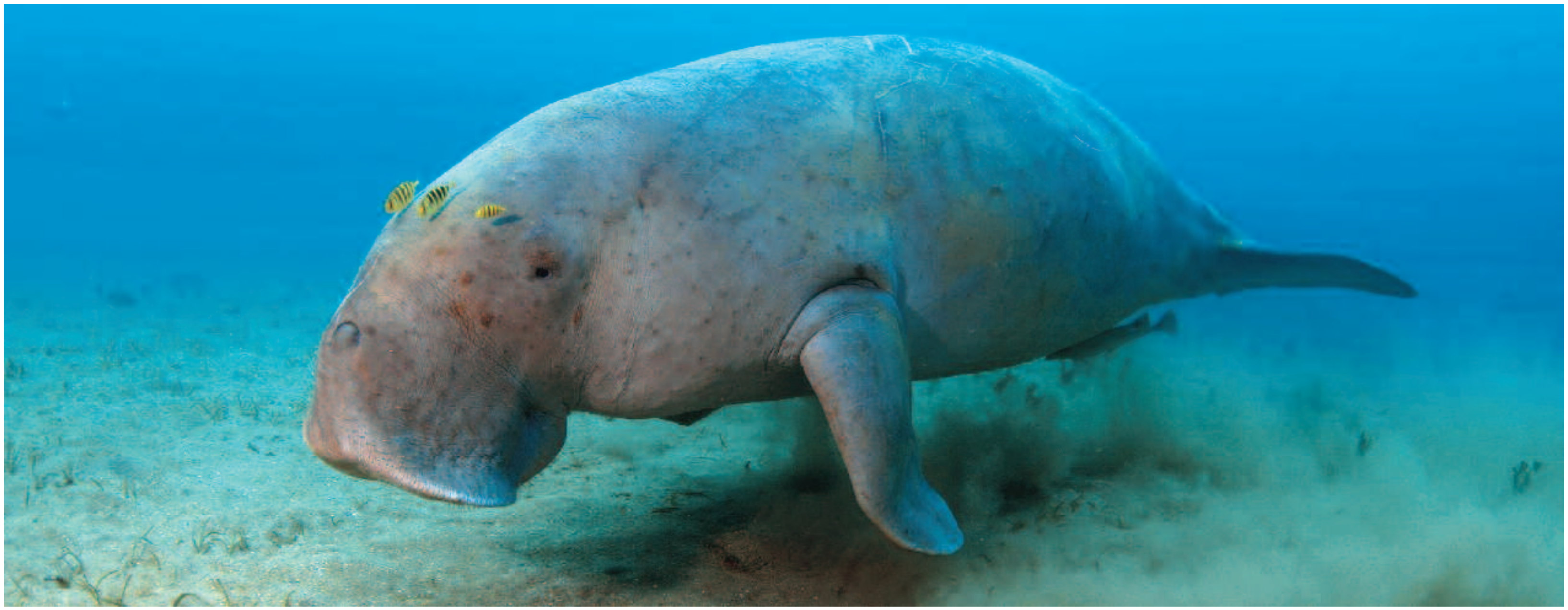
While basic scientific knowledge is being developed for some of New Caledonia's coral reef seabird species, there are still important gaps. Several research programs, recently launched or under development, should be able to fill in these gaps. To name only two: the BIOPELAGOS program, supported by the SPC, IRD and CNRS, is currently aimed at better understanding the use of New Caledonia's oceanic environment by the seabird community. This program combines the monitoring of seabird movements using miniature electronic devices, with the analysis of the characteristics of ocean habitats preferred for foraging and the study of their diet using different methods (regurgitation analysis, determination of nitrogen and carbon stable isotopes, and DNA barcoding of feces). Other scientific programs aim at filling gaps in knowledge about the communities, numbers, reproduction and demographics of seabirds found on some remote islands; to better understand the reproductive biology of different species (many of which have been studied very little); or to clarify the extent of land-based threats such as invasive species or changes in the environment. All these data will contribute to a database implemented by the IRD, which will be made available to environmental managers to improve the sharing of knowledge and data. This should contribute to the sustainable and informed management of the exceptional biological heritage of New Caledonian waters.

Pair of Lesser frigatebird *(Fregata ariel)*. This species is particularly sensitive to human disturbance, which explains why it seeks isolated sites. Mouillage Islets, Chesterfield, April 2017. © IRD/E. Vidal

Chapter 41

Dugongs: endangered lagoon mermaids

Christophe Cleguer and Claire Garrigue



A dugong (*Dugong dugon)* swimming above a diffuse seagrass bed in search of food. © M. Juncker

On the identification of dugongs

With its massive, 3 m long, fusiform and bronze body, its small eyes and broad smile, its lack of dorsal fin, its paddle-shaped pectoral fins and its flattened tail resembling that of cetaceans, dugongs do not go unnoticed in the lagoons of New Caledonia. Also called a "sea cow", the dugong is the only herbivorous mammal that is exclusively marine. From the end of the 18th century, it became the only representative of the Dugongidae family since his cousin the Steller's sea cow was hunted to extinction by humans.

The dugong can be found in shallow coastal areas from East Africa to Vanuatu, through the Middle East and Southeast Asia. In these waters, dugongs find their main larder: the seagrass meadows.

Often found in protected bays, mangrove channels or the leeward coasts of islands, the dugong appears to be a very sedentary animal. However, it makes daily, seasonal, and even random movements of a few dozen to a few hundred kilometers. In New Caledonia, satellite monitoring of a dozen dugongs revealed that they used both the lagoons and the outer zones of the barrier reefs of Grande Terre. Some of them even covered about a hundred kilometers and crossed the administrative borders of New Caledonia's provinces (CLEGUER, 2015).

The dugong reaches its sexual maturity relatively late - between six and 17 years of age. Its gestation and breastfeeding periods are long, between 13 and 15 months and 14 and 18 months, respectively. Its reproductive rate is low (only one young every two to seven years) and is largely influenced by the availability of food resources. As a result of all these characteristics, the dugong is a species that is highly vulnerable to the natural and anthropogenic disturbances of its environment.

Protected by several international laws and listed as a "vulnerable" species on the International Union for Conservation of Nature (IUCN) red list, the dugong has already disappeared from many countries such as Mauritius, the Maldives and Cambodia, and its conservation status remains unknown throughout half of its distribution range. The causes of such vulnerability are multiple and they vary geographically. The most prominent threats include the degradation of seagrass habitats, hunting, accidental capture in fishing nets and collisions with boats. To address these pressures, multiple and diverse conservation and management initiatives are being implemented at the international, regional and local scales.

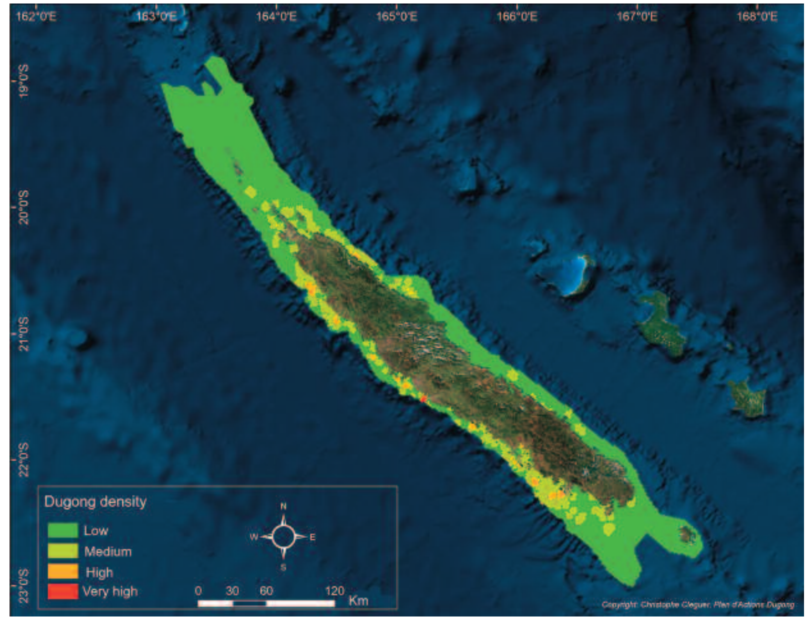


Figure 1: Distribution and density of dugongs around Grande Terre, based on aerial surveys conducted between 2003 and 2012. Adapted from CLEGUER, 2015

Dugongs of the New Caledonian reefs

In New Caledonia, aerial surveys have increased knowledge of the abundance and distribution of dugongs around Grande Terre. Dugongs are mainly distributed on the west and northeast coast of Grande Terre (Fig. 1) and areas of high dugong density are heterogeneously distributed. These hotspots are located in the regions of Nouméa, Ouano, Bourail-Poya, Koumac and Pouebo (Fig. 2). Dugongs are rare in the center of the east coast, as well as in the northern and southern lagoons, probably due to unsuitable habitat.

No aerial surveys have been carried out in the Loyalty Islands, but there are indications that only very few dugongs live there. The most recent observations of dugongs in the Loyalty Islands date back to 2015, when one individual was observed in Lifou and then in Ouvéa, one month apart.

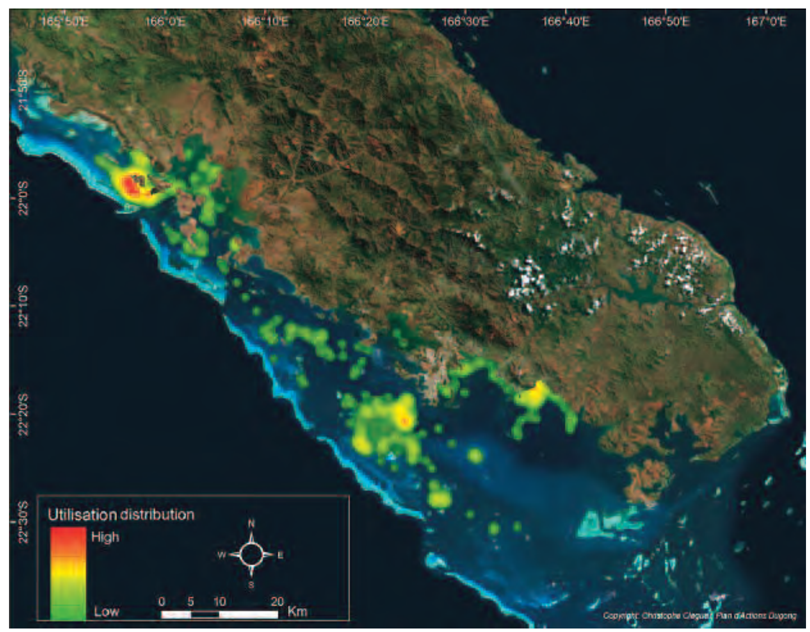


Figure 2: Trajectories of three dugongs equipped with satellite tags in the southwestern region of Grande Terre. Adapted from CLEGUER, 2015. Map © ESRI

Box 28

Dugong: a highly protected species

A dugong in midwater. Several scars from old wounds are visible on the surface of the body and indicate collisions with boats or other watercrafts. © M. Juncker

The dugong is protected by several international laws. The Convention on International Trade in Endangered Species (CITES) of 1973 lists dugongs in its Appendix I, which includes the most threatened species and prohibits "international trade in their specimens". Dugongs are also listed in Annex II of the 1979 Bonn Convention on migratory species of wild animals (CMS), which lists species with "an unfavorable conservation status as well as those that can significantly benefit from international cooperation" (CMS, 2009). A Memorandum of Understanding (MOU) was signed in 2007 on "the conservation and management of dugongs and their habitat throughout their distribution range". The species is also listed as vulnerable to extinction on the red list of the International Union for Conservation of Nature (IUCN).

In New Caledonia, dugong hunting has been banned throughout the territory since 1963. Since 2004, the South Province authorities have completely banned hunting, even for customary events. In the North Province, exemptions may still be granted for specific customary celebrations. However, the number of exemptions granted is low (15 between 1995 and 2004, none since 2004).

The latest population size estimates in 2012 suggest that less than 1,000 individuals are left in the New Caledonian lagoons. This is much lower than the initial estimate of 2,000 dugongs which was made in 2003. Although it is impossible to confirm a decrease in the population, we now know that every individual counts for the survival of the population. This precarious status, confirmed by genetic analyses, results in the fragility and probably low resilience of the dugong population. In other words, each animal removed from the population is a direct threat to the survival of dugongs in New Caledonia.

However, the causes of dugong mortality in New Caledonia are still poorly studied. The recorded strandings and various studies conducted on New Caledonian dugongs over the past decades suggest that poaching, accidental capture in fishing nets and collisions with boats are the main threats.

Conservation

Aware of the urgent need to preserve dugong populations, a technical group involving the three provincial authorities, the government of New Caledonia, the customary senate, the State, WWF-NC and the association Opération cétacés, launched a five-year dugong action plan (PAD, Plan d'actions dugong) led by the French Agency for Biodiversity (AFB) in 2010. One of the first actions taken by the technical group was to launch research projects in order to improve knowledge of the local dugong population. A PhD project was dedicated to studying the temporal variability of dugong abundance and distribution, and their use of the reefs at different spatial and temporal scales in New Caledonia (CLEGUER, 2015). This study also provided inputs for discussions on the conservation strategies for dugong in the territory. An anthropological study combining traditional knowledge and current practices, and focusing on the importance of dugong in New Caledonian society was then undertaken (DUPONT, 2015). In addition, two studies on the population genetics of dugongs were conducted to assess genetic diversity and explore the connectivity between the dugong populations of New Caledonia and neighboring countries (OREMUS *et al.*, 2015).

Results of these scientific studies confirmed the fragility of the New Caledonian dugong population and highlighted the areas where conservation and management measures must be implemented to improve the protection of the species. Some awareness-raising actions have already been taken, such as informing local sea users of the risk of collisions between dugongs and boats or other watercrafts.

A second ongoing action plan (2015-2020) led by the Conservatory for natural landscapes (CEN, Conservatoire des Espaces Naturels) will help to maintain this momentum and tackle other major issues such as dugong poaching and catches in fishing nets. Other actions will follow, such as monitoring the conservation status of the species in New Caledonia, acquiring new knowledge, and maintaining the preservation of the dugongs by awareness-raising, and informing and engaging New Caledonians.

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Chapter 42

Local knowledge to manage and regulate reefs

Catherine Sabinot, Estienne Rodary, Marlène Dégremont, Victor David and Gilbert David

The knowledge of fish passageways is often shared at sea without any cartographic support, but many fishermen know perfectly well how to locate their routes on a map. Vao, Isle of Pines, 2016. © M. Juncker.

New Caledonia is a sparsely populated territory, but its inhabitants are passionate users of the lagoons and reefs. This prompts authorities to implement reef management measures, i.e., to organize and control access and uses. This management is usually carried out by professionals, supported by technical and scientific knowledge which is driven mainly by ecology and biology, and/or following international engagements that involve both ecological and political stakes. In most cases, scientific knowledge is the main driver in creating regulations to maintain reefs and their species in a "good ecological state". However, this management can also be driven by other types of non-scientific knowledge. This local, “vernacular” knowledge, which conveys local values and norms, sometimes called “traditional” knowledge, is owned by different stakeholders and social groups who are users of the reefs. They often are complementary to scientific knowledge and are sometimes linked to sustainable reef management practices. Knowing and taking into account local knowledge can then directly guide reef ecosystem use practices. It can also inform scientific knowledge and involving the various users in the development of common rules promotes efficient management. When these rules become governmental or provincial laws, which are meant to be accepted by everyone, there is more chance that they will be followed by the people of New Caledonia if they are informed by local knowledge. Knowing, informing and recognizing local knowledge is therefore an essential step in the process of building and changing environmental regulations.

The decked pirogue of the Isle of Pines allows to move discretely to catch fish. It still exists today thanks to a few elders who passed on their knowledge to their children, both on how to build the pirogue, and also to locate schools of fish and cast the net. © M. Juncker

Local ecological knowledge is based on a regular experience of the environment

"When the whales arrive, their breath looks like smoke. It reminds us of how to burn the field for its preparation. They clap with their fins, like when you plant the yam." (Grand Sud). The arrival of the whales informs locals of the time to plant yams.

"When the *iiletch* tree is flowering or when oulek reeds are blossoming, it means that the dawas [*Naso unicornis*] are fat. When the *wiitch* tree makes fruits, it means that the oysters are full." (Hienghène). The blossoming and fruiting of terrestrial plants indicates the favorable season for fishing and the harvesting of certain fish and seafood.

Local ecological knowledge is empirical knowledge, linked to practices and to an "engagement" with the environmental elements. Corals, passes, fish, sharks and many other animals of the lagoon are known and recounted from generation to generation. In the Kanak world, this knowledge relates to the world of elders as well as food, social or economic resources. It is acquired through the experience of each person and is therefore constantly renewed through regular, often daily, interactions. This experience includes practices and observations of the environment that guide fishing practices and trips on the lagoon.

Box 29

Participative customary management works

Luen Iopué, Maël Imirizaldu and Sophie Katrawi

Yeega and Dohimen Marine Protected Areas in Hyehen commune. From DDEE-SMRA, Province Nord.

In New Caledonia, the four authorities (government and island, North and South Provinces) have jurisdiction over environmental management, which leads them to work closely with customary authorities. These stakeholders often play a central role in the co-management of maritime areas.

Even if they do not physically occupy the entire space (whether marine or terrestrial), communities maintain a special bond with it. This link can be the result of alliances, the supply of essential resources or simply a mythical one. It is a true bond that inspires the symbolic identity of the Kanak people, translates into a socialization of space and different lifestyles and is conveyed by legends, myths and practices.

The particular links that Kanak people have with the marine and terrestrial environments have been further described by various studies. In the Nouméa Accord and the preamble of the Organic Law, special attention is given to the integration of these cultural characteristics into the management of maritime areas.

The result of this is the participative management of New Caledonian sites. For instance, UNESCO requires the involvement of local communities in the management of World Heritage sites. In New Caledonia, the participation and involvement of customary communities has been pivotal.

This customary participative management must take into account several factors for the best possible implementation of the practices in the field. To quote the words of customary communities, “the souls of the elders watch over people and the implementation of their actions”.

This requires the respect of a number of practices related to the Kanak culture. It is often described as “making a custom offering” (“faire la coutume”), but these few words cover several realities. A “custom offering” (“geste coutumier”) is required as an introduction before establishing any action in a given place. This offering involves introducing oneself (showing one's face), bending down before asking to speak in order to express a request or to give responses, without offending the elders, and offering a gift related to this request (e.g., a yam, mat, etc.). It is the start of everything that is undertaken in the customary world.

Customary participative management also integrates a connection to space and time. Beyond the physical differences (land and sea, surface and contents), Kanak people consider their land as a whole (fauna, flora, biotope), from the crest line to the reefs, or even beyond the horizon line (d'Entrecasteaux Reefs are part of the Dau Ar/Belep chiefdom). This is why reefs often have vernacular names. Customary communities therefore have to include this reality in their management policy, and this is what the three provinces and the government of New Caledonia are trying to do.

However, the timeframe is often longer than usual. In a management framework, it is often necessary to adopt strategic orientations and actions to be implemented, which do not require the support of the majority but do need the consensus of all the families and/or clans involved. In doing so, the proposal must encompass all the "paths of alliance" or structures kinship for the decision to be taken. This speech journey is sometimes long, but it is necessary and in practice, solutions are found to facilitate it.

Traditional Kanak hut, tribe of Grand Atéou. © P.-A. Pantz

On New Caledonian sites, customary participative management works well. Communities ensure that customary aspects are taken into account in the management and implementation of actions, as is done in Australia, to some extent.

The New Caledonian management committees, in which customary communities are strongly represented, are the formalization of this consideration. In these committees, customary communities become important management stakeholders and they are recognized as such. Management committees meet every two years under the auspices of the Conservatory of Natural Areas (CEN: Conservatoire d'espaces naturels) to review the management of UNESCO World Heritage sites.

In addition, the customary senate has a representative on the CEN board of directors, a representative on the managment committee of the Marine Park of the Coral Sea and in other institutions dealing with environmental issues: the environmental advisory council (CCE: conseil consultatif de l’environnement), the economic, social and environmental council (CESE: conseil économique, social et environnemental), the area councils, and the youth councils.

Preparing a custom offering, Isle of Pines. © P.-A. Pant

Knowledge that builds culture and rules

A customary reserve is an area closed to fishing on a temporary basis. With flexible spatial and temporal boundaries, it can be opened occasionally during customary or religious events. Access to the reserve may be dependent on kinship and a customary reserve is generally associated with a tribe, according to the logic of a territorial continuity between land and sea (box. 29).

Unlike a customary reserve, a taboo site is permanent. Access to a taboo site implies the observation of a number of rules, such as requesting permission from the tribe or associated clan and making a custom offering as a sign of respect for the ancestors or entities that populate the site. These places are named and have a history known to the knowledge "owner" and, hence, the site.

Those who have lived alongside the reefs for a long time have developed particularly precise knowledge of the reefs, knowledge that is an integral part of their history and culture. For Kanak people, as for other communities in the territory, this ecological knowledge is both the support and cement of their cultures. It is the basis of social relationships and pathways, links between individuals and between groups. It is linked to formal and informal rules for sharing territories and resources. These rules, and the customs associated with them, have a social function and can have beneficial consequences on the ecosystem, such as ensuring the good condition of a habitat or certain species of the lagoon.

Integrating local knowledge into lagoon management

As part of the inscription of the New Caledonian lagoons on the UNESCO's World Heritage List, several management committees have been set up, bringing together all socio-economic and institutional stakeholders, as well as representatives of local populations.

If the green sea turtle *Chelonia mydas* is fully protected in New Caledonia, it is still possible to obtain exceptional hunting permits for customary ceremonies. This system of derogations has been set up to take into account the specificities of Kanak culture. Depending on the provinces, it may still be subject to adjustments and consultations with the customary senate, customary areas and populations, in order to refine the standards if it produces local misunderstandings or presents implementation difficulties.

For the Environmental Code of the Loyalty Islands Province, developed using a participative approach, co-construction of environmental rules is a pivotal aspect of the law. The aim is to reconcile customary practices and legal regulations stemming from the national "biodiversity law" of 2016 and international objectives. The provincial authorities can now delegate the power of managing the maritime zones that are within their area of influence to the customary authorities, thus ensuring that endogenous law is taken into account.

These examples show that, in New Caledonia, there are many instances where local knowledge meets official initiatives for the management of reef areas: hybrid management areas where MPAs (marine protected areas) overlap with customary reserves or taboo sites; the consideration of fishing practices to define the level of protection of the most socially emblematic species; and so on. This plurality ensures compliance with management measures by formalizing customary practices that are not necessarily known to all users.

This is very important because, in Kanak societies, the social and political organization is part of a territorial relationship that includes both land and sea. Customary areas extend from inland (from the peaks of the mountain chain on Grande Terre) to the reef and further offshore. The reefs, islets and remote islands are "marked" by names that testify of their appropriation, as well as of ancient practices that are still present in oral tradition.

Faced with the hybridity of areas and the plurality of customary functions and logics mentioned above, the law has to adjust for better environmental protection, as seen in the Loyalty Islands Province.

Engaging knowledge dialogue

In New Caledonia, social science's study of the relationships between societies and their environments (and thus of how they "manage" the areas called "reef ecosystems" by scientists) is often interdisciplinary (involving not only anthropologists, geographers, socio-economists, jurists but also ecologists and biologists) and in direct contact with users and keepers of the local knowledge. This overlap between different forms of knowledge produces useful results for the implementation of informed negotiations between inhabitants and decision-makers, without which it would be difficult to conceive appropriate, accepted, acceptable and sustainable natural resource governance policies.

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Chapter 43

Towards planned management of reserves in New Caledonia

Laurent Wantiez, Emmanuel Coutures, Maël Imirizaldu, Michel Kulbicki and Laurent Vigliola

Juvenile Napoleon fish *(Cheilinus undulatus)*. This species, classified as endangered by the IUCN, is found in protected sites. © IRD/S. Andréfouët

Coral reefs are one of the most threatened ecosystems on the planet. They are confronted with the combined effects of global climate change (warming, sea level rise, ocean acidification) and local environmental changes linked to local human activities (growing demographics, fishing, pollution, habitat degradation). These pressures add to natural disturbances (tropical cyclones, acanthaster outbreaks, etc.), whose destructive dynamics are amplified by the environmental changes induced by human populations. The conservation of this ecosystem and the preservation of the resources and services it provides have therefore become major challenges, which often involve controlling the exploitation of resources (species, their size, fishing gear and harvesting season) or establishing marine protected areas (MPAs).

New Caledonia hosts the world's largest lagoon around the main island, Grande Terre (19,385 km^2), the second largest barrier reef (1,600 km long) after the Australian Great Barrier Reef, and one third of the world's most isolated and preserved reefs. Therefore, their environmental protection is fundamental at both local and global levels.

In New Caledonia, the implementation of protective measures has been gradual and pragmatic. It was carried out concomitantly to the increase in anthropogenic pressures and the observation of the first impacts, particularly the decline in resources (fishing) and the direct or indirect degradation of the reef and lagoon environments (from mining and urbanization). The implementation of the first protective measures in the 1970s followed a "wise pragmatism" approach, responding to a determination for action despite the lack of knowledge. The New Caledonian coral ecosystems would probably not be as healthy today if this pragmatism had not triggered and fueled local conservation policies. With time and the acquisition of new knowledge on the dynamics of systems, these policies gradually evolved towards a truly planned management strategy.

The natural protected area is one of the most commonly used protection tools in New Caledonia. It complements resource regulations through the protection of biodiversity within its environment. This type of protection is familiar to the New Caledonian people because it involves the use of various historical forms of "customary/traditional reserves", which are common in Oceania. These customary reserves are now being gradually integrated into "contemporary" marine protected areas. The success of this tool lies in the relative simplicity of its management and its proven effect on protected resources, particularly on harvested species.

The "reserve" tool in New Caledonia

The first protective measures were implemented by confronting the conservation objective (the reserve as a "larder") with expert analysis.

The first significant action was the creation of the Merlet Reserve in 1970 (box. 30). This initiative can be commended for several reasons. First, it was established at a time when the conservation of New Caledonian reefs was not a priority. Second, it is large (173 km^2) and benefits from the maximum level of protection (strict nature reserve). Lastly, its protection level has been maintained until today with increased surveillance facilities and regular monitoring of its health status.

The second milestone was the creation of the reserves of the “Grand Nouméa Park” ("Parc du Grand Nouméa"), formerly known as the “South Lagoon Park” ("Parc du lagoon sud"). These protected areas are regulated marine reserves where access is permitted, but any harvesting is prohibited. The origin of this awareness was the impact of fishing on coral reef resources near Nouméa, where the density of users and the resulting boating pressure are the highest. The initiative involved two phases. The Amédée lighthouse and Maître Islet have been protected since 1981 and four other islets since 1989 (Bailly, Canard, Larégnère and Signal). The year 1990 marked the real beginning of conservation programs with the launch of the first surveillance vessel, the Isabelle. At the same time, and since 1994, regular monitoring (every four years) of the evolution of these reefs has been undertaken to quantify the success of these actions. Their status then evolved into Sustainable Resource Management Areas (SRMAs) or nature reserves, according to the uses and possible economic activities that developed there. Seasonal reserves were also set up to protect fish aggregation sites for spawning, such as the Dumbéa Pass or Grand Port in Prony Bay. However, some inefficient initiatives were discontinued, including the rotating reserve of the three barrier reefs facing Nouméa (Mbéré, Aboré and Kué), where each reef was successively protected for three years.

Although the first regulatory tools for the protection of natural areas were set up around the capital, this type of protection has always been employed by indigenous populations in their so-called "customary reserves" (box. 29). The creation of these protected community areas is linked to the original perception of the clans of the sea that the lagoon is their property. Their main vocation is to protect "their own" resources, particularly so that they are available during major customary ceremonies or special community events. This is probably why the Northern Lagoon (Grand Lagon Nord) is one of the most exceptional reef formations in the territory today. Over the last decade, this customary protection, which also has a subsistence objective (food and artisanal fisheries), has evolved towards an acceptance of the need to adapt and integrate into the rules of common law (regulated protection). The associated objectives have evolved from the protection of resources ("larder") to the conservation of ecosystems for economic valorization (ecotourism). This evolution has led to the creation of the Pweevo and Hyehen reserves on the northeast coast and discussions are under way on the creation of a reserve around Ouvéa Island (Uvea/Iaai).

The strict nature reserve of Merlet. © P.-A. Pantz

Box 30

The Merlet Reserve, the jewel of the South Province

Emmanuel Coutures

Located between the Sarcelle and Havannah passes, the strict nature reserve, Yves Merlet, created in 1970, is a sanctuary for both the terrestrial and marine flora and fauna of the Southern Lagoon. This maritime space of 17,200 ha, which includes the islets of Améré and Kié, was already covered by customary management when it was formalized by a palaver transcript between the Goro chiefdom and the territorial office of the merchant marine.

Now integrated into the provincial marine park of the Grand Lagon Sud (part of the property inscribed on UNESCO's World Heritage List), the "Merlet Reserve" aims at maintaining the wild state of a reef and lagoon area with a minimum of anthropogenic activity.

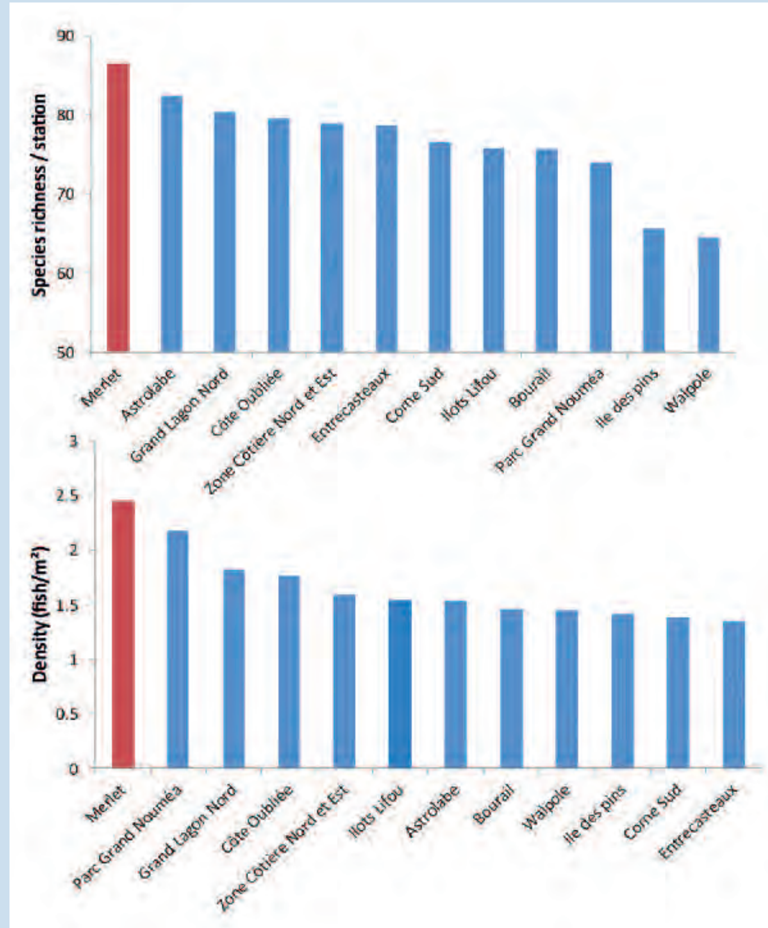
The level of protection of this sanctuary has increased over time: the derogations for the organization of customary fisheries (*mïkwaa* or milkfish *Chanos chanos* and green sea turtles), which are still provided for in the South Province Environmental Code, have not been implemented for nearly 10 years.

The reserve is subject to specific management measures. Authorizations to enter the Merlet Reserve for scientific purposes (collection of samples) are increasingly rare and constrained.

Due to its status and the diversity of its coral communities, the Merlet Reserve was chosen as a site for monitoring the Grand Lagon Sud Marine Park. Between 2008 (initial state) and 2013, the monitoring revealed a very healthy ecosystem with no significant anthropogenic impact (WANTIEZ *et al.*, 2013). It hosts the largest diversity (more than 100 species/site) and density (more than 2.3 fish/m^2) of reef fish measured as part of the New Caledonia reef monitoring. Giant clams are also very frequently observed (95% of sites) and numerous (4.9 individuals/250 m^2), and the trochus are relatively large (9.7 cm on average). Emblematic species are common, including sea turtles and Napoleon fish.

Rangers carry out between one and five inspections of the Merlet Reserve per month, either by day or night, and only record five to six offences per year.

Over time, the Merlet Reserve has become the reference point in discussions relating to the environmental and societal importance of areas with enhanced protection from human pressures. It is both a source of pride for all New Caledonians and a treasure pampered and fiercely protected by the South Province.



Number of species by site and fish density at major coral sites monitored in New Caledonia between 2012 and 2014. © UNC/L. Wantiez

Reference

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Box 31

What is the reef in the eyes of the children of New Caledonia?

Jocelyne Ferraris, Georgeta Stoica, Catherine Sabinot, Pascale Chabanet, Stéphanie M. Carrière, Claire Levacher and Marlène Dégremont

Influence of the socio-cultural and environmental context on the perception of coral reefs (after using the MARECO case).
A: Yaté, "Wadiana waterfall". © J.-B. Agourere
B: Nouméa, "The coral reef". © M. Meray

Drawings before (left) and after (right) the use of the MARECO case, "The reef in our hands", by Marie-Louise, eight years old, Isidore Noell school. © M. L. Xowi

In 2016, about 80 children from five primary schools in Nouméa (Boyer, Isidore Noell), the east coast (Thio and Yaté) and the mountain chain (Coula) participated in an interdisciplinary research program on the perception of coral reefs. This program was led by a team of natural and social science researchers. Its aims were to assess the knowledge, practices and perceptions related to coral reefs in children aged between six and eight years old and to develop a method to evaluate the impact of an awareness campaign on reef vulnerability in four French regions (New Caledonia, Mayotte, Reunion Island and Pyrénées-Orientales).

Exploring the coral reef ecosystem is fun!

Coral reef drawings were collected before and after the use of a "The reef in our hands" kit containing three educational games whose objective was to communicate scientific concepts on biodiversity, disturbances, uses and management methods of the coral reef ecosystem. A total of 1,300 drawings and interviews conducted in the field, were analyzed using a grid listing and coding of the depicted elements, in order to compare the coral reef perceptions of the 20 primary school classes involved in the program.

When science meets education

The analysis reveals a great diversity of perceptions among children according to socio-cultural profiles, but also between urban, rural and coastal environments. This emphasizes that relationships with nature or the environment vary from one school to another, depending on direct and indirect experiences of the reef. Using the MARECO case results in an improved understanding of reef biodiversity. The immersion of scientists in the school environment also improves understandings of academic and empirical knowledge and their plasticity in different contexts, as well as how they are transferred, in order to maintain, disseminate and improve them.

Modernity is marked by the gradual transition from the "wise pragmatism" of the beginnings to planned management, including the adoption of an Environmental Code by all provinces. Two major initiatives also reflect the growing and recent awareness of protection and the stakes involved in conservation: the inscription of the "Lagoons of New Caledonia" on the World Heritage List in 2008 (15,743 km^2; chap. 46) and the creation of the Natural Park of the Coral Sea in 2014 (1,291,000 km^2; box. 5). These two major initiatives commit New Caledonia to long-term responsibility for conservation. They will only be successful if they are supported by a strong and well-established management policy, as well as the implementation of appropriate resources and coherent governance.

The success of pragmatic management

The success of the pragmatic use of the "reserve" tool in New Caledonia is based on a series of decision-making processes:

– setting realistic objectives;

– the choice of a suitable strategy and tool based on available knowledge;

– regular assessment of the outcomes to enable informed decision making and regular adaptation of management strategies and objectives.

It is now recognized that well positioned and monitored marine reserves have many positive effects on protected communities. These effects have been checked and demonstrated on numerous occasions in New Caledonia.

In the reserves of the Grand Nouméa Park, fish communities developed very rapidly after the implementation of monitoring measures and reached spectacular levels in just four years. The number of edible fish species increased by 67%, their density by 160% and biomass by 246% (WANTIEZ *et al.*, 1997) (Fig. 1). At the same time, the number of species and biomass at unprotected sites did not change and the density increase was twice as low. Since 1994, changes in the protected fish populations have been mainly the result of natural causes (Fig. 1). They develop when environmental conditions are favorable and are particularly affected by disturbances (tropical cyclones). The global oceanographic climate (El Niño/La Niña) also seems to affect these communities.

Another typical example is the lobster populations in the Ouano Reserve. None were observed in the reserve and adjacent monitored unprotected areas before the reserve was created and for seven years after monitoring began. From 2014 onwards, lobsters became frequent in the Ouano Reserve (over 50% of sites) while they are still absent from unprotected areas, although favorable habitats are available (WANTIEZ *et al.*, 2015). Thanks to these protected areas, the emblematic Napoleon fish has also returned.

The protected areas thus allow protected communities to develop. In the long term, they also have an "overflow" effect, with specimens moving from the protected area to adjacent unprotected areas, a phenomenon which was documented in the Grand Nouméa Park for commercial fish species (coral trouts, groupers, parrotfish) (CHATEAU and WANTIEZ, 2009). These effects have probably also occurred in all other protected areas of the territory, for which no pre-protection monitoring data exist.

The limits of New Caledonia's reserves

Marine reserves are an effective tool. However, like any tool, they have their limitations and cannot solve all problems on their own. Marine reserves must evolve with knowledge and adapt to contemporary environmental and societal challenges.

The monitoring of protected reefs in New Caledonia revealed that reserves could do nothing to protect against major meteorological events (e.g., tropical cyclones). These events have an immediate and devastating effect on coral habitats and their associated species. A tropical cyclone can destroy years of protection efforts. For example, in 2003, the tropical cyclone Erica had immediate and significant destructive impacts on the entire ecosystem of the Grand Nouméa Park, resulting in a complete change of community structure. This was still significant in the medium term (two years) (WANTIEZ *et al.*, 2006) and complete restoration occurred only in the long term (10 years) (WANTIEZ *et al.*, 2014). When the ecosystem is particularly vulnerable, the time required for restoration is dependent on the absence of further disturbance during the process. Hence, reefs recovered in Nouméa, but not in Ouano, where strong westerly swells in 2008 and 2009 destroyed the first signs of coral habitat recovery (WANTIEZ *et al.*, 2015).

In addition, protecting an area leads to the geographical transfer of the fishing effort, which increases in unprotected areas as a result. In New Caledonia, this happens in a context where the pressure exerted on reefs (fishing and non-extractive uses) is increasing. If too many reefs are protected in a densely populated area, the effects on coral reefs, as a whole, may be more negative than positive. It is necessary to optimize the balance between protected and unprotected areas according to the population and to provide the necessary means to control catches. An alternative to this would also be to develop non-extractive economic activities in order to reconcile economic development and environmental protection. However, non-extractive uses also need to be regulated to minimize their environmental impact. For example, a reserve where all harvesting is prohibited but access is allowed, attracts people who come to observe healthy reef communities (e.g., large fish). These areas can then attract a population that exceeds their carrying capacity. This is very obvious on sunny weekends when large numbers of boats aggregate in the reserves of the Grand Nouméa Park.

When properly designed and monitored, marine protected areas are often presented as the ideal tool for conservation. However, despite effective protection, this tool does not allow the coral ecosystem to recover all the characteristics of a system devoid of any negative impact (D'AGATA *et al.*, 2016). This is well illustrated in New Caledonia by the Merlet Reserve, whose results do not reach those of the most remote reefs (d'Entrecasteaux, Astrolabe, Pétrie, Chesterfield, etc.). The most significant differences are in the case of large predators such as sharks (JUHEL *et al.*, 2018), as well as species with high commercial value such as giant clams and sea cucumbers.

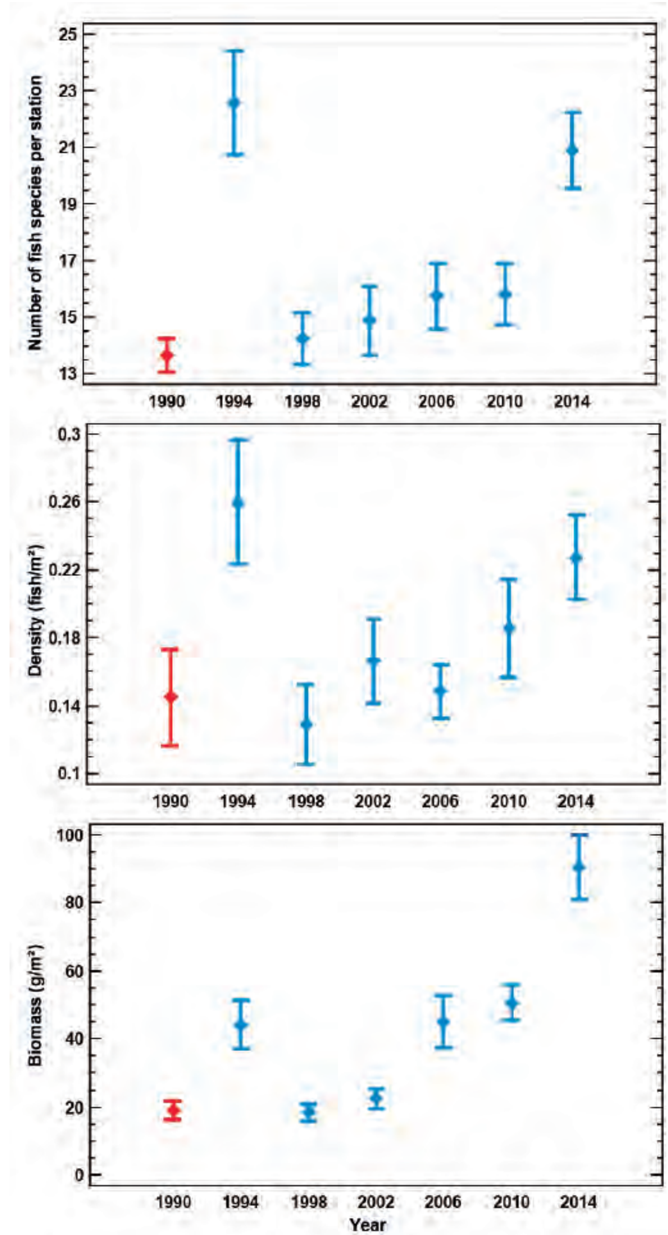
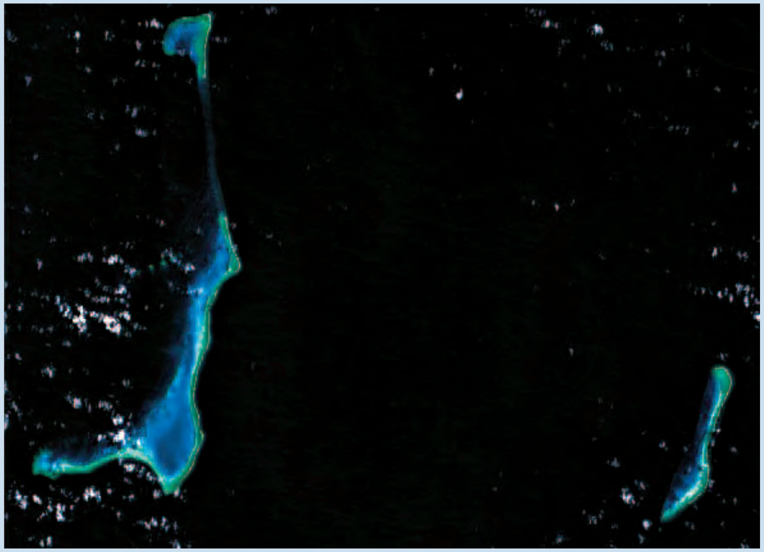


Figure 1: Variations (± standard error) in total species richness, site species richness, density and biomass of commercial fish species in the five reserves of the Grand Nouméa Park, before (in red) and after (blue) the implementation of monitoring actions. Adapted from WANTIEZ *et al.*, 2014

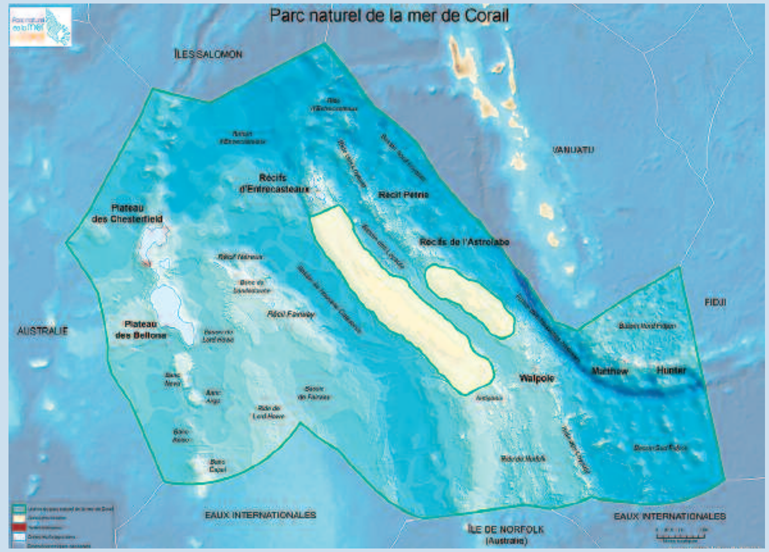
Box 32

Isolated reefs will soon be highly protected

Marie-Hélène Merlini and Julie-Anne Kerandel



Satellite view of Astrolabe reefs (Sentinelle 2 image, march 15th 2018)



Natural Park of the Coral Sea. © Gouvernement de la N.C/DAM-NC/SPE

Only 1.5% of the world's reefs are considered "untouched" by any human impact. The Natural Park of the Coral Sea hosts 30% of these reefs.

Pétrie and Astrolabe: exceptional reefs

The reefs of the natural park that have already been studied are among the richest in the world and described as pristine by the scientific community. The Pétrie and Astrolabe reefs, for example, host one of the highest reef fish biomass in the world and rank higher than the largest marine reserve in the Chagos Islands (Indian Ocean). Chesterfield and d'Entrecasteaux reefs also surpassed Kingman Reef, which used to be the global reference point for "virgin" sites in the Pacific. These comparative studies ("PRISTINES" and "PRISTINES SEAS" projects), carried out in 2012 and 2013, provided an understanding of the value of regulating access to the most remote areas of ecological interest.

D'Entrecasteaux, a challenge for protecting biodiversity

Since April 23rd 2013, the government of New Caledonia has clearly stated its intention to protect the environmental jewels of its maritime space by establishing a protected area in the atolls of d'Entrecasteaux, the first natural reserve in the waters under its jurisdiction. The Le Leizour Islet and the vegetated part of the

Surprise Islet are classified as a strict nature reserve. All other emerging zones, waters and seabed included within the protected area of the d'Entrecasteaux Atolls are classified as nature reserves. Across the protected area, activities related to professional fishing are prohibited and access to the area is restricted.

Turning isolated reefs into sanctuaries, one of the first management priorities

One year later, on April 23rd 2014, the Natural Park of the Coral Sea was created, confirming the energy for conservation and the protection of all reefs, even those far removed from the New Caledonian maritime space. Although it is recognized that the remoteness of coral reefs forms a natural protection, planning a management strategy is an absolute necessity. In the management plan of the Natural Park of the Coral Sea, the first objective, dedicated to natural and cultural heritage, is to "protect ecosystems and their connectivity", and particularly to "protect remote reefs". This objective requires a high level of protection for remarkable areas (pristine reefs). By mid-2018, all “pristine” reefs (Chesterfield-Bellona and Petrie-Astrolabe) will be protected by the government.

Maintaining the life cycle

A high level of protection would help the conservation of ecosystems. For example, these reefs are used as breeding and feeding grounds by reef and tiger sharks. It is also likely that large predatory sharks use the Chesterfield-Bellona zone as a stopover for annual migrations between New Zealand and the tropical zone. Coral reefs are unique ecosystems essential to the life cycle of species, and to ensure the safety of an abundant and balanced marine life. Establishing regulations and providing the necessary means for their implementation is a visionary and responsible long-term strategy.

Today, conservation measures mainly target coral reefs, which represent the country's emblematic marine ecosystem. This approach has its limitations because it does not take into account the entire reef and lagoon environment, which functions as a connected network of fragmented ecosystems. Reef conservation therefore requires the consideration of wider geographical scales and even the entire seascape. The "informed management" process, which is being gradually adopted in New Caledonia, will have to consider this constraint and significant efforts will have to be dedicated to the protection of mangroves, seagrass meadows and lagoon soft bottoms, which are poorly taken into account today. The situation is similar for seamounts, located at the interface between remote reefs and those closer to Grande Terre, as well as deep and coastal, and pelagic and reef ecosystems.

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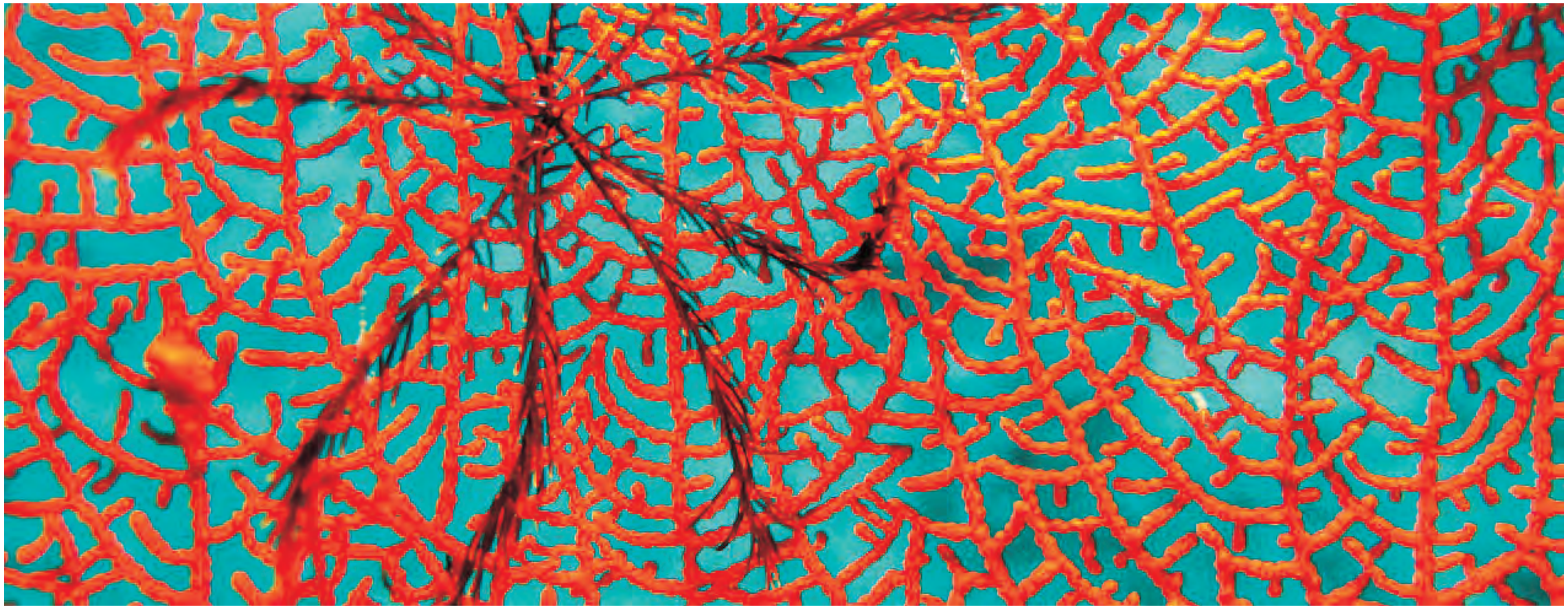
Chapter 44

The challenges of modelling coral reef ecosystems

Morgan Mangeas, Antoine Wickel, Jean-Brice Herrenschmidt, Catherine Sabinot, Pierre-Yves Le Meur, Laurent Vigliola and Gilbert David



Gorgonian and feather stars, east coast, 2012. © IRD/J. L. Menou

Coral reef ecosystems are complex and their health relies on a balance between the composition of the associated fauna and flora, and the environment. When they are healthy, coral reefs perform many functions that translate into "ecosystem services". They contribute to the well-being of local communities and participate in coastal economic development. Coral reefs support recreational and tourism activities, produce biomass that contributes to economic development and food security through fishing, and provide other services such as protection from wave action and carbon sequestration. These ecosystems also have high symbolic and identity values, and their cultural and heritage aspects are essential at local, national and international levels.

Modelling (box. 33) coral reef ecosystems and the pressures they are exposed to, as well as the interactions with human populations and the links to ecosystem services, is, therefore, a real challenge. The stakes are high: modelling coral reef ecosystems provides a better understanding of the internal and external rules by which they are governed, as well as a detailed analysis of the relationships between the fundamental elements they consist of. Modelling can also estimate the responses of the coral reef ecosystem to different scenarios of future environmental and human pressure. In addition, by including control variables in the model it is possible to determine which combination of actions can be effective for ecosystem stabilization and to avoid major degradation.

Box 33

What is modelling?

Modelling involves defining a set of equations or rules intended to describe a phenomenon and its dependencies in a reproducible and simulated way. A model is used to predict the response of a system to known stresses. Modelling generally requires a calibration phase, which involves estimating a set of parameters so that the model's response is close to what would be expected by experts or reproduces past observations.

There are several types of models and a distinction can be made between "mechanistic" and "statistical" approaches. The mechanistic approach equates the biological, ecological or physical mechanisms that induce the dynamics of the studied phenomenon. The statistical approach builds on the data available to determine a function capable of "approximating" the interactions between the variable to be explained (the phenomenon) and the explanatory variables (the factors that influence the dynamics).

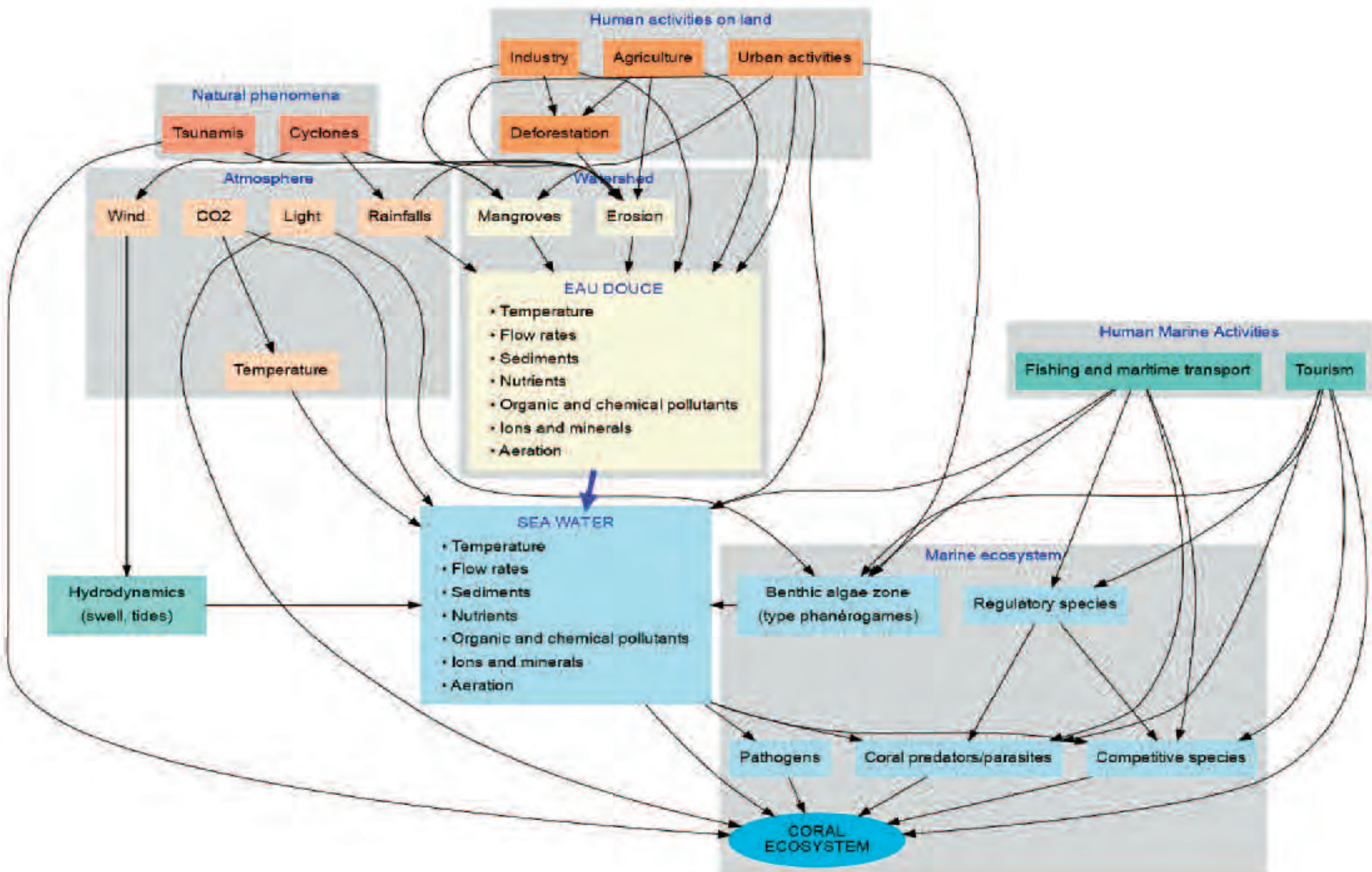


Figure 1: Relationship between the main stressors of the coral reef ecosystem, their potential impacts and the indicators used for assessing the state of the environment. Arrows describe the known relationships between these different elements. © IRD/M. Mangeas

As is often the case with complex ecosystems, the modeler is confronted with spatial and temporal scale issues. Some pressures can be occasional, such as an industrial chemical spill in the lagoon, which massively disrupts the coral reef ecosystem in the very short term. Others can act over several decades, such as the slow rise in seawater temperatures (+0.7°C on average since 1990), which strains the adaptive capacity of the flora and fauna of coral reefs. Similarly, at the spatial level, modelling processes limited to coral colonies will require detailed and highly localized information, which is not available at the scale of a reef of several square kilometers. Model design therefore depends on the nature of the phenomenon under study and the spatial and temporal scales of the relevant and available data. Lastly, a problem-oriented model always represents a compromise between complexity, robustness and the ability to simulate observations

Pressures and impacts

The Knowledge Representation Model of pressures (ICRI, 2016) that impact the health of a coral reef ecosystem (Fig. 1) is the first step in a modelling process. However, there are still many grey areas around abiotic (physico-chemical conditions) and biotic (species interactions) factors that maintain coral systems in a healthy state. This makes it difficult to translate them into equations. Although they are necessary to statistically estimate the relationships between the various components of the ecosystem, there are very few datasets that simultaneously characterize the state of the environment and the health of the coral reef ecosystem.

It becomes even more complex when the health of the coral reef ecosystem is linked to socio-economic factors and coral reef-induced services (Fig. 2). We observe that, if the health of the coral reef ecosystem deteriorates, ecosystem services are affected and users are likely to act accordingly (fewer tourists, fewer fish, recreational activities are less attractive, etc.). If this happens, users will exert pressure on public authorities to implement protective measures. This therefore gives rise to the hypothesis of a dynamic system, structured by a feedback loop and self-regulation between users and the coral reef ecosystem.

This complex issue was recently addressed as part of the CORAIL research project, funded by the European program BEST and conducted in New Caledonia and French Polynesia, between 2013 and 2016. Research institutes, organizations and consulting agencies involved in this project worked in collaboration with local decision-makers and stakeholders to apprehend and co-construct methodological developments and public policy tools for the management of coral reef ecosystems. The study sites were the southern region (Grand Sud) and Hienghène for New Caledonia, and Opunohu and Moorea in French Polynesia.

Bayesian networks

A Bayesian network (KJAERULFF and MADSEN, 2007) is a probabilistic graphical model, representing random variables in the form of an acyclic oriented graph. Its networked architecture transcribes almost directly the models of knowledge representation such as those described in Figures 1 and 2. The cause-effect relationships between variables are not deterministic in this type of modelling, but probabilistic. Thus, the observation of a cause or several causes does not systematically lead to the effect or effects that it triggers, but only modifies the probability of observing them. Bayesian networks are particularly interesting because they simultaneously take into account the a priori knowledge of experts and the information contained in the data. Bayesian networks are mainly used for risk analysis and to support decision-making. Mathematically, the states of variables representing nodes in the Bayesian network are assessed using conditional probability calculation techniques and the Bayesian theorem (box. 34).

For example, a simplified Bayesian network can model interactions between coral reef ecosystems, induced ecosystem services, human pressures and natural disturbances (Fig. 3). Although this model has been successfully tested in other parts of the world, its application in New Caledonia is difficult due to a lack of data. However, one of the advantages of Bayesian networks is that a model can be built based on expert knowledge. It was possible to calibrate a model for targeted areas of New Caledonia using the knowledge of researchers,

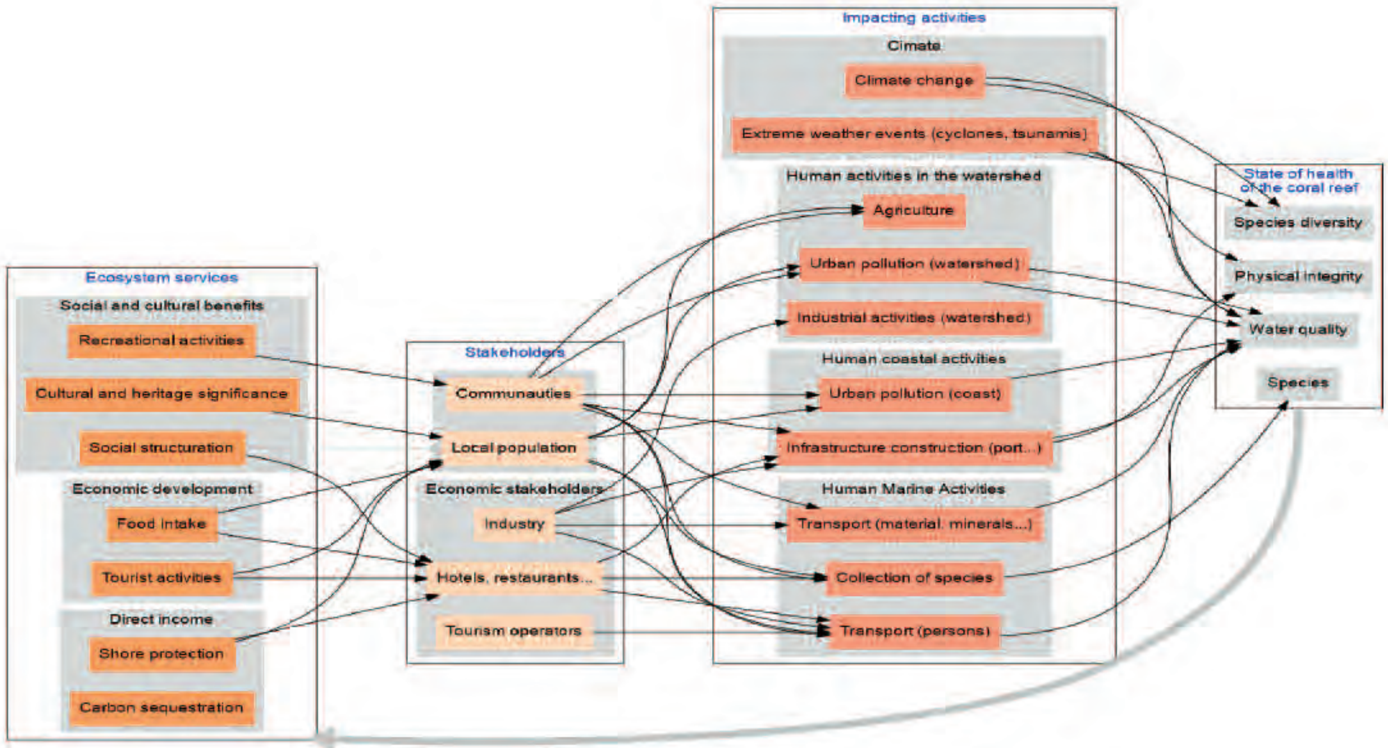


Figure 2: Interactions between users, ecosystem services, pressures on the coral reef ecosystem and potential impacts. The arrows describe the known relationships between these different elements. © IRD/M. Mangeas

inhabitants, lagoon users and stakeholders involved in environmental management.

Feedback modelling would require the use of a more complex model such as a Dynamic Bayesian Model (DBN). However, this simplified approach identified the main trends and proposed scenarios that can then be used to guide the management of coral reef ecosystems in the study area.

Study site

Yaté is a municipality of New Caledonia located in the south of Grande Terre, 80 km from Nouméa (Fig. 4). Its surface area is significant (ranked the 15th largest municipality of France) given the small number of inhabitants (less than 2,000). The population mainly inhabits the narrow coastline where traditional fishing is practiced on the reefs facing the municipality. However, since 2009, one of the world's largest nickel mining plants has been built and is operated by the Brazilian mining operator Vale. The lagoon and coral reefs of the municipality are subject to several forms of pressure yet still thriving, but the population has largely abandoned fishing for mining jobs. The situation in New Caledonia is a typical example of multi-stakeholder negotiations involving diverse issues (environmental risks, mining industries, food uses, etc.). Negotiations on environmental management and the offsetting of mining impacts are very active, sometimes conflicting and often mediatized. The available socio-economic data are provided by the ISEE (Institute of Statistics and Economic Studies of New Caledonia), spatial data by the geographical portal of New Caledonia (www.georep.nc) and biological data by l'OEIL (Environment Observatory in New Caledonia, www.oeil.nc).

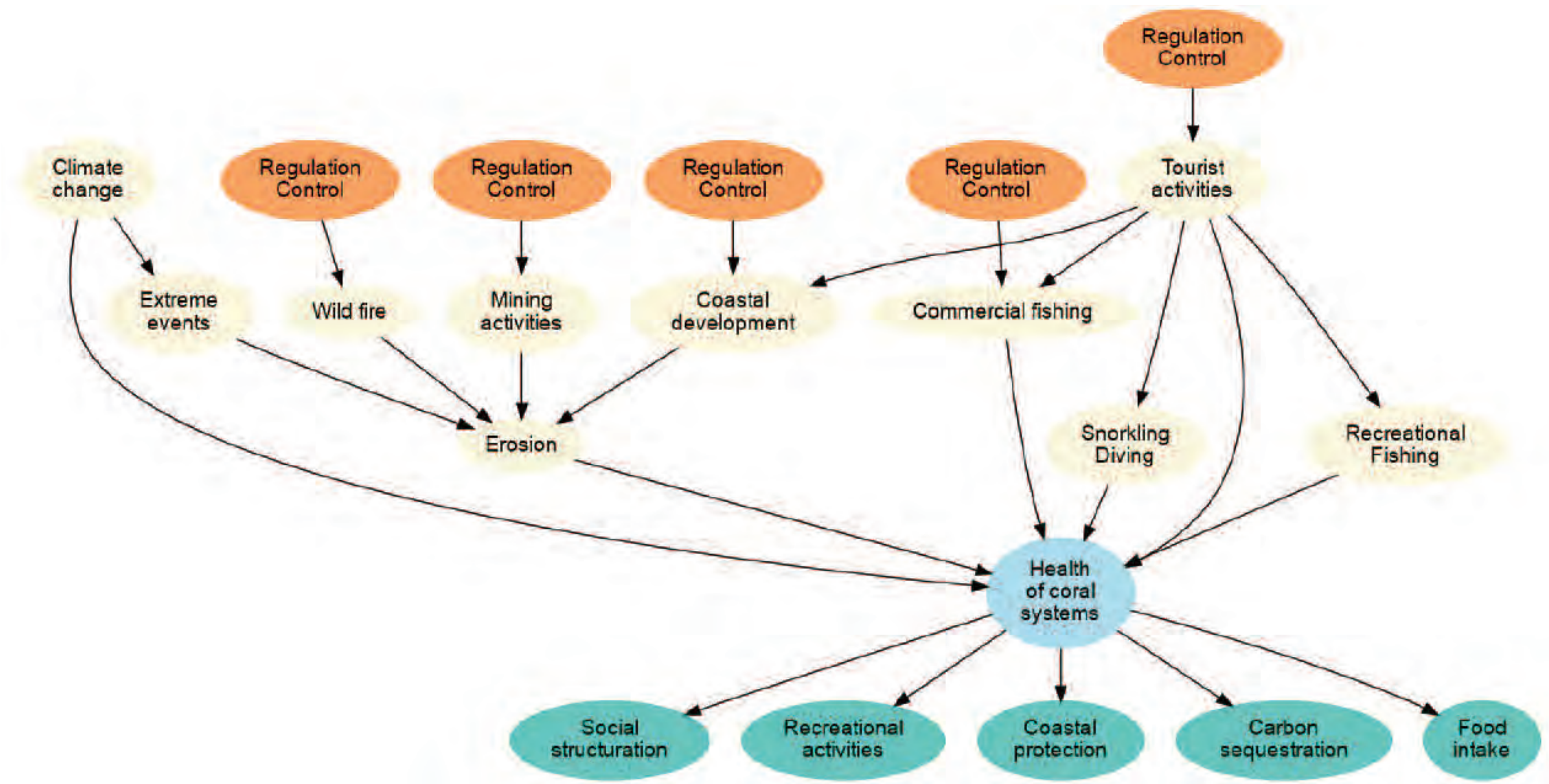
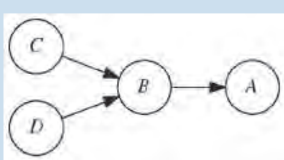


Figure 3: A simplified Bayesian network. © IRD/M. Mangeas

Box 34

The Bayesian theorem



Suppose that each of the four variables A, B, C, D evolves in a set of three states: "strong", "medium", "weak". Conditional probabilities are written as:
P(A = "strong" | B = "weak")

This literally means: probability that A is in the "strong" state, knowing that B is in the "weak" state. In a Bayesian network, if all the conditional probabilities associated with the relationships are known, either by statistical estimation or via an expert opinion, it is possible to calculate the probability that one of the variables is in a certain state according to the known states of the other variables. For example, it is possible to calculate by domino effect P(A = "strong" |C = "strong" and D = "medium") even if the state of B is unknown.

Note that it is possible to estimate the probability of a variable being in a certain state, even if it is a cause and the consequence is known. For example, P(B = "weak" |A = "strong") is calculated using the famous Bayes theorem that calculates P(B|A) from P(A|B), P(A) and P(B):
P(B|A) = P(A|B)P(B)/P(A).

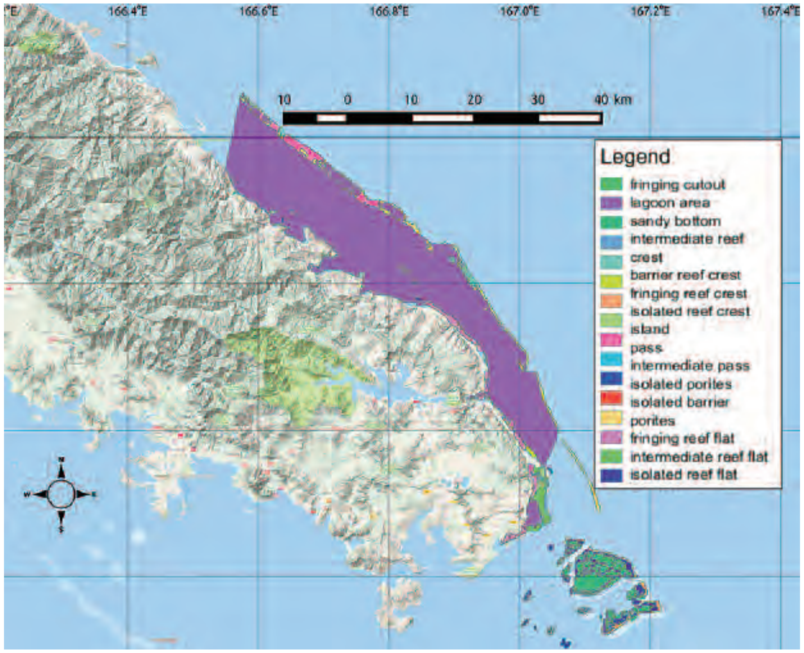


Figure 4: Study sites in the south of Grande Terre, New Caledonia. © IRD/M. Mangeas

The scenarios studied using modelling

The simplified Bayesian network was calibrated to provide satisfactory answers regarding the needs and the current state of health of the coral reefs in the municipality of Yaté. The various pressures were also assessed and the impacts estimated by experts. The aim is to use the model to provide trends for four specific configurations. The four scenarios, which correspond to contrasting but possible situations in this region, are as follows:

– 1: Current scenario: reef and ecosystem services under the human and natural pressures of recent years;
– 2: Establishment of a strict nature reserve in the intertidal and subtidal zone of the lagoon of the municipality of Yaté corresponding to the IUCN protection level I.a.;
– 3: Closure of the Vale plant: mining activity is interrupted, resulting in the dismissal of employees who have to move to new jobs;
– 4: Population growth in the surrounding villages (strong urbanization): massive influx of population into the area.

The coral reefs in the municipality of Yaté are currently considered to be in good health (scenario 1), particularly far from residential areas where the population is sparse. This indicates that regular human and industrial activities in the area have had little impact on the ecosystem to date. However, this does not take into account the possible occasional pollution that could be caused by an industrial spill; such as a malfunction of the nearby marine outfall, which drains the water coming out of the metallurgical plant from the port of Prony into the Havannah Channel. This outfall raises the majority of concerns regarding potential impacts on the ecosystems of the Yaté lagoon.

The resulting model projections for coral reef ecosystem health and recreational activities are shown in Fig. 5. In the case of scenario 2, the IUCN's protection level I.a. requires a ban on all harvesting in the area and the model predicts that ecosystem health will improve. In the event of plant closure (scenario 3), the model predicts that the ecosystem will deteriorate due to inhabitants returning to a more marine-oriented subsistence lifestyle. Lastly, in the event of accelerated urbanization of the area (scenario 4), the high recreational use of the lagoon, coastal development and pollution linked to a high density of inhabitants could have a significant impact on the reefs in the area. On the basis of the available data, the model therefore suggests that a significant increase in attendance would have a stronger impact than the current "ordinary" mining activities (excluding pollution events caused by industrial spill). However, this model was adjusted based on very fragmented data, particularly regarding the indirect and long-term environmental impacts of the mine and plant on all components of the coral reef ecosystem.

One of the major advantages of modelling is the possibility to analyze all situations resulting from the factors used in the model. It is possible to test scenarios combining the "establishment of a reserve" and "plant closure" or "plant closure" with "heavy urbanization". With Bayesian networks it is also possible to identify the most likely cause of an improvement or degradation of the ecosystem, depending on the area and the intensity of the event.

Modelling coral reef ecosystems and the pressures to which they are exposed is highly complex. Societal changes are particularly difficult to apprehend, much more than direct measurable impacts, and just as much

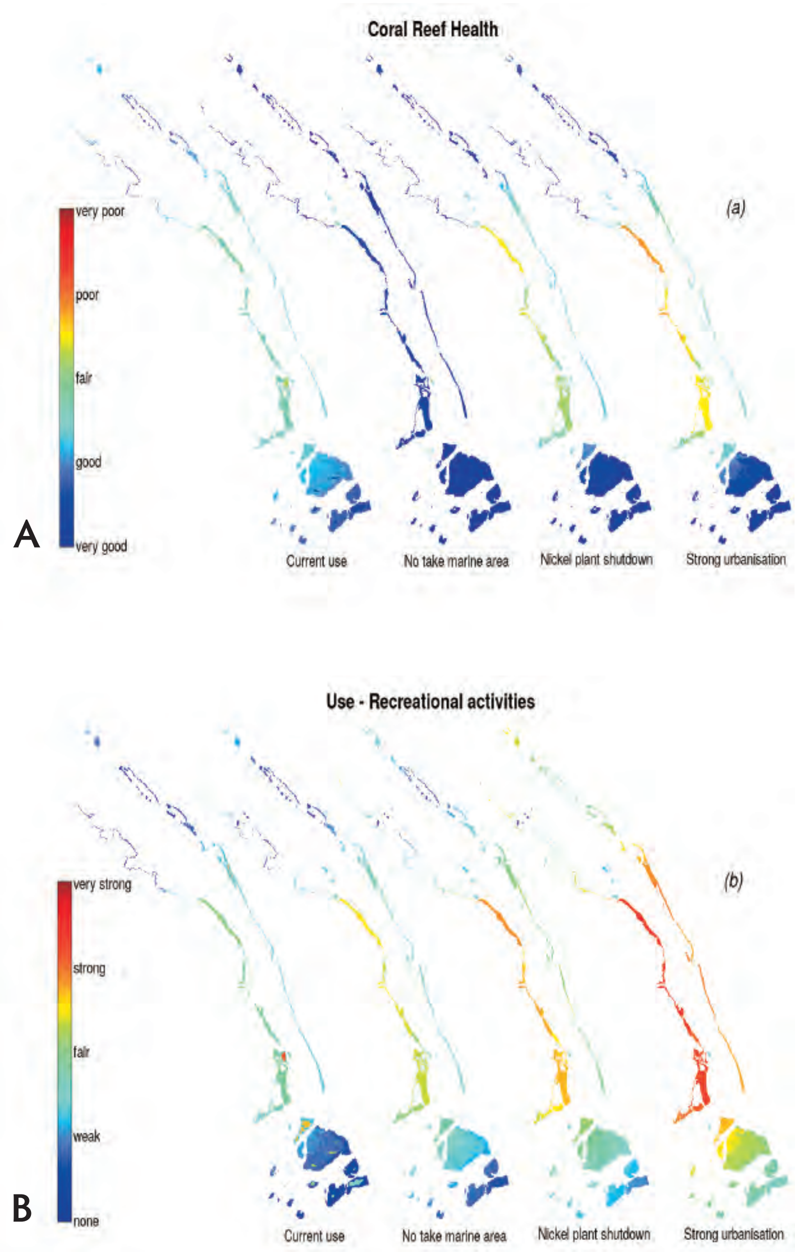


Figure 5: Municipality of Yaté, spatial assessment and evolution under the three scenarios studied.
A: Spatial assessment of coral reef ecosystem health.
B: Spatial assessment of recreational activities in the lagoon. © IRD/M. Mangeas

Mining processing plant, Vale, Prony. © P.-A. Pantz

as indirect impacts with their multitude of interactions between species and environmental variables. In the absence of a series of observations that are sufficiently long and accurate, modelling is highly dependent on expert knowledge. It also requires a multidisciplinary approach to determine the biological, societal and environmental interactions that influence the state of coral reefs and determine their ability to produce ecosystem services. In the case of the municipality of Yaté, because of the uncertainties surrounding the results, modelling is more suited as a tool for consultation and analysis than for prediction. In addition, modelling is not an end in itself; for it to be useful, it must become a user-friendly and efficient management tool so that stakeholders and decision-makers can use it in concerted decision-making processes.

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Chapter 45

The law applicable to coral reefs of New Caledonia

Victor David

Southern Province protected area, Larégnère Islet. © IRD-ENS/T. Berr

The reader may be surprised to discover that there is no specific law applicable to coral reefs in New Caledonia! In fact, unlike other ecosystems and despite their importance (several points of view have been widely developed in this book) and their extreme vulnerability to natural threats and anthropogenic pressures, with only a few exceptions there is no binding law related to coral reefs ("sea rainforests") at an international, national, regional or New Caledonian level. Before proceeding further, it is important to clarify the concepts of hard law and soft law.

Hard law refers to binding legal texts. In the context of international law, hard law includes international treaties or agreements, as well as international customary law, which create binding obligations and rights for parties (states) and other international entities. Failure to comply with these obligations may result in the prosecution of the party before international courts.

Soft law refers to rules that are neither strictly binding in nature nor completely devoid of legal meaning. In the context of international law, soft law refers to agreements that establish guidelines, political declarations, action plans, strategies, guides to good practice or codes of conduct that set standards. However, they are not directly applicable and their non-compliance may not result in any prosecution or punishment.

Soft law rules

Over the past 50 years however, numerous programs and actions have been implemented for the conservation and direct or indirect management of coral reefs. These legal initiatives fall under the definition of soft law. They have been implemented, in terms of binding law, through the following legal mechanisms:

– most often, the legal procedure of protected areas and particularly marine protected areas (MPAs);
– legal rules on protected species and the protection of "marine biodiversity" in general;
– legal rules on fisheries management and the prevention of overfishing;
– rules for the prevention, control and remediation of marine pollution;
– rules for the control of invasive alien species;
– rules for the protection of "common heritage" or "World Heritage";
– rules intended to promote tourism.

Since the Paris Agreement on climate and taking into account the impacts of global warming and ocean acidification, legal measures to combat and mitigate these impacts can also be used to protect corals.

International soft law texts that can be mobilized

Several soft law texts are applicable in New Caledonia and can be mobilized to protect coral reefs here.

At the international level, France signs and ratifies treaties, agreements and conventions. Not all agreements signed by France are automatically applicable in New Caledonia. The protection of biodiversity was devolved to New Caledonia and its provinces in 1988, and it is therefore necessary to ensure that international agreements are applicable to the area. These protections include the following agreements, which can be used for the conservation and management of coral reefs:

– the MAB program, Biosphere Reserves (UNESCO, 1971);
– the Ramsar Convention on Wetlands (1971);
– the Convention on the Protection of the World Cultural and Natural Heritage (UNESCO, 1972);
– the United Nations Convention on the Law of the Sea (Unclos, 1982);
– the Convention on Biodiversity (1992);
– the International Convention for the Control and Management of Ships' Ballast Water and Sediments (2004);
– Aichi Biodiversity Targets (2010);
– the International Coral Reef Initiative (ICRI). ICRI is defined as "an informal partnership between nations and organizations working to preserve coral reefs and related ecosystems around the world". While the ICRI is an informal group whose decisions are not binding on its members, its actions have been instrumental in continuing to highlight the overall importance of coral reefs and associated ecosystems for environmental sustainability, food security and social and cultural well-being;
– The UN Agenda 2030, particularly Objective 14 and its seven sub-objectives;
– the Paris Agreement on climate (2015).

National texts favorable to coral reefs

At the national level, considering only the most recent texts, it is also important to mention the n° 2016-1087 Act for the restoration of biodiversity, nature and landscapes. Article 113 of the Act states that "to stop the loss of biodiversity in overseas France and preserve its role in promoting the adaptation of the territories to climate change, the State shall set the following objectives, with the support of its public institutions under its supervision and in consultation with the relevant local authorities":

1. Develop and implement a program of action at the scale of the territory to protect 55,000 hectares of mangroves by 2020;
2. Develop an action plan contributing to the protection of 75% of coral reefs in the French overseas territories by 2021, within the framework of the French coral reefs initiative and on the basis of an assessment of the state of health of coral reefs and associated ecosystems carried out every five years.

While Article 113, which comes under soft law, has not been made directly applicable in New Caledonia, the State may act with New Caledonia and its provinces - through its research establishments, IFRECOR and the French Agency for Biodiversity (AFB). It can also be assumed that funding requested by the New Caledonian authorities from the State for the protection of mangroves and coral reefs in the archipelago will be granted under Article 113.

Regional agreements that can be implemented in New Caledonia

Environment Program (SPREP) and the Pacific Islands Forum. The agreements and action programs of these regional organizations can be implemented in New Caledonia.

To date, there is no legally binding coral reef legislation at the regional level. In January 2018, on the occasion of the launch of the third IYOR (International Year of the Reefs), from the available solutions, Fiji chose the Ramsar Convention on Wetlands to protect their Great Barrier Reef (Cakaulevu). In this convention, wetlands have a fairly broad definition and can include coral reefs.

Soft law documents have existed for a long time and allow the adoption of action plans for reefs. The first of such documents was the Apia Convention on the Protection of Nature in the South Pacific (1976), which was approved by France in 1988 and has been in force since 1990. It focuses on broad environmental protection with incentives for the creation of conservation areas to protect "representative samples of natural ecosystems".

Following this, in 1986, the Convention for the Protection of Natural Resources and Environment of the South Pacific Region, known as the "SPREP (or Nouméa) Convention", included the South Pacific in the Regional Seas Program of UNEP (United Nations Environment Program), which was itself launched in the early 1970s. Control measures - against pollution sources, in particular - provide actions which support coral reefs, even if they are not mentioned in the Convention.

Interestingly, SPREP declared a double Year of the Reefs (2018-2019) to promote the protection of coral reefs among its member states.

The legal texts of New Caledonia

In the legal order of New Caledonia, there are several texts pertaining indirectly or directly to the coral reefs of the archipelago.

With respect to the general provisions, reference should be made to the amended Organic New Caledonia Act 99-209, which allocates jurisdiction between the State, New Caledonia and its provinces. The protection of biodiversity falls within the normative jurisdiction of each of the three provinces, hence the existence of three environmental codes that apply within their geographical boundaries. The maritime zone outside one of the provinces but within the limits of the Exclusive Economic Zone (EEZ) falls within the jurisdiction of New Caledonia. Coral reefs located in the public maritime domain of a province fall under provincial jurisdiction and those located in the EEZ currently fall under the protection and management rules adopted by New Caledonia. This means that there may be four different protection regimes in existence (even if there are also informal or formal mechanisms and space for consultation and harmonization, such as the Conservatory of Natural Areas). As well as these different regimes of formal law, endogenous law (customary rules) also plays an important role regarding the management of maritime spaces, as part of customary land tenure, which may involve the inclusion of protected areas under endogenous law. Their effective consideration by the entire population requires a formalization that only the Loyalty Islands Province has formally accepted, initially in the form of the "Ouvéa Joint Declaration" co-signed by the customary and provincial authorities in 2007 and later in its Environmental Code in 2016.

At the level of New Caledonia's maritime zones, the protection of reefs may be carried out within the categories of marine protected areas provided for in the 2011 51/CP decision. In accordance with this decision, the decree of April 23rd 2014 was adopted for the creation of the natural marine park known as the Natural Park of the Coral Sea. However, by early February 2018, no practical rules had yet been adopted for the specific protection of coral reefs. As part of its expertise in foreign trade, New Caledonia also acts for the protection of corals and, since 2009, has imposed a ban on coral exports.

Finally, the jurisdiction (shared with the State) over external relations at the scale of the Pacific region provides the possibility of signing bilateral and multilateral agreements on the protection of coral reefs. The provinces are involved in the legal protection of coral reefs through the various provisions of their respective environmental codes (protected areas, protected species, actions against pollution, etc.).

Among the measures that specifically target corals and fall under binding law, mention should be made of the provisions of Title III of Book 2 of the South Province Environmental Code, which are dedicated to the conservation of "ecosystems of heritage interest", including coral reefs over 100 m^2.

As we can see, it is either rare or impossible to find binding legal texts imposing enforceable rights and obligations specific to coral reefs. This is particularly worrying when we know that protection, especially through the protected areas mechanism, is not always satisfactory (chap. 43), and neither are the actions taken to combat pollution. The 3rd International Year of the Reefs should be used to study the feasibility of an international convention on coral reefs, including necessary regional, national and local variations, with binding provisions to protect them more effectively. The recognition of the legal status of the ocean and elements of marine biodiversity - such as coral reefs, which would thus be granted rights of their own would be a real step forward.

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Chapter 46

New Caledonian reefs and lagoons on the UNESCO World Heritage List

Myriam Marcon

N'dué Islet, Southern Lagoon. © P.-A. Pantz

International recognition as a catalyst for action and cohesion

"The lagoons of New Caledonia: reef diversity and associated ecosystems" joined the prestigious World Heritage List in 2008. Thanks to strong support from the French Coral Reef Initiative (IFRECOR), New Caledonian stakeholders joined forces and submitted a collective application.

Since then, efforts and commitments around the protection of reefs, a major element of the inscribed sites, have multiplied. While there was only one management committee at the time of nomination, there are now 13 management committees looking after the heritage property. Representing the local populations (customary, institutional, economic, tourist, educational, educational and associative sectors, etc.), these committees design and implement management plans for the various sites included in the list, the main purpose of which is to maintain their integrity. Over the past 10 years, ten management plans have been implemented.

Networking for more efficiency

The CEN (Conservatoire d' espaces naturels), which is responsible for coordinating the management of the New Caledonian World Heritage property, provides a platform of exchange between

Boat Pass, Northern Lagoon © P.-A. Pantz

managers. Since its creation, the CEN has worked towards the production of networking tools: e.g., the management committee forum, training courses and promoting experience sharing. The aim is to strengthen the skills of management committees and increase the effectiveness of their actions.

Various communication and awareness-raising tools developed by the CEN promote the World Heritage Convention and encourage good practice. Examples include “My name is lagoons”, a video aimed at raising awareness among tourists, or the exhibition "Les gardiens du trésor" (“Guardians of the treasure”). All tools are made available to the New Caledonian stakeholders involved in managing this heritage.

Inscription on the World Heritage List also allows stakeholders in New Caledonia, to benefit from the experiences of other marine site managers around the world. The conferences organized by the World Heritage Center represent extremely rich opportunities for exchanges, particularly regarding global issues, such as climate change, cruise tourism, etc.

IFRECOR, which has been coordinated locally by the CEN since 2016, is an additional platform for engaging in discussions and actions to protect reefs and associated ecosystems.

A jewel in the Pacific

Since the World Heritage listing, increased attention is being paid to the lagoons and reefs of New Caledonia. Populations, institutions, associations, and researchers are increasingly aware of the importance of this jewel, which is now recognized worldwide.

Epilogue

In New Caledonia, the sea does not separate men; it creates a link between them

Didier Poidyaliwane, member of the government in charge of customary affairs, ecology, sustainable development, relations with the customary Senate and customary councils, customary lands.

Totems of St. Maurice, Isle of Pines. © P.A. Pantz

This book reminds us that New Caledonia is an exceptional maritime space, which includes a developed coastline, large lagoons and coral reefs with first-class biodiversity. It also shows us that the coral ecosystem results from permanent interactions between the sea and the land, and that, over time, demographic growth together with the development of human activities have generated transformations that have left a number of marks. Despite an environment that is generally still well preserved, New Caledonia is not immune to the social and economic evolution of the world with both positive and negative effects on the marine environment.

As noted throughout the chapters, this extraordinary ecosystem of great wealth and diversity is complex, fragile and vulnerable. Processes of adaptation and resilience are complex, and research on the resilience of coral communities to environmental and climatic changes is still in its infancy. The book emphasizes in particular the unique site of Bouraké, where corals and mangroves are able to live in conditions close to those predicted for the end of this century. This exceptional natural observatory will help scientists to better understand the adaptive capacities of corals and will provide natural-scale data for predictive models that are currently based solely on laboratory measurements, thereby reducing uncertainties about future projections and scenarios.

For New Caledonians, the coral ecosystem represents a fundamental and vital natural and cultural heritage: it nourishes people in all its meanings and participates fully in the construction of the codes of functioning of societies and their identities. The ecological continuum, known in the Kanak culture and promoted by scientists throughout the book, has been shaped over millennia as a balance between nature and people. This continuum is not broken by death since many "taboo" or "cemetery" areas of the spirits of the dead are located in the lagoon around Grande Terre and the Loyalty Islands.

Rules for the sharing and protection of territories, which have long been established, codified and mapped by clans and tribal groups, coexist and sometimes overlap with institutional rules for the management of areas.

The knowledge of populations in relation to nature and that of scientists must meet future challenges to co-produce standards that are better adapted to ecological and sociocultural issues.

Through their beauty and diversity, the seascapes offer fertile ground for new initiatives with a promising future for the harmonious development of New Caledonia. Therefore, maintaining them in good ecological condition is key to the success of these initiatives. The services in charge of environmental management have been aware of this challenge for the last two decades and have established a network of marine protected areas supported by regulations governing iconic and threatened species as well as activities within those areas. Accession to the World Heritage label for more than half of the reef and lagoon areas surrounding Grande Terre marked a shift in conservation action, with the establishment of management committees in each of the protected areas. After 10 years of existence, 13 management committees and several associations federated around the communities, the government and the Natural Areas Conservatory act for the protection of these lagoons and reefs. The Government of New Caledonia wished to go further by creating the Natural Park of the Coral Sea in April 2014, which encompasses the entire New Caledonian exclusive economic zone and represents one of the most extensive marine protected areas on the planet. The recent approval of a management plan and the various decrees that will result from it will regulate activities within this area. The sanctuarization of the isolated reefs of the very large Chesterfield-Bellona plateau to the west of Grande Terre and the reefs of Pétrie and Astrolabe to the east, should limit the impacts of human activities on these exceptional and preserved environments.

However, the most difficult challenge will undoubtedly be to develop sustainable and responsible uses that respect both nature and people. A number of chapters in this book have shown that tourism and leisure activities, which are essential for the country's economy and its exposure to the world, can impact on the coral reef ecosystems, either through the construction of infrastructure or through activities in the lagoon.

Biological diversity in general, and that associated with coral reefs in particular, represents a major asset for the development of New Caledonia. There is still a great deal to discover and understand in this area extending from the abyss, colonized by deep corals, to the clear waters of the lagoons which shelter a multitude of reef-building corals. This ecosystem, that is both an intangible heritage and a source of knowledge, myths, legends and rituals, requires a precise inventory of traditional knowledge to be made, before the knowledge disappears with the Elders.

The writings collected in this book bear witness both to research efforts and to exchanges between various disciplines that the lagoon has been able to bring together, for creating better understanding and contributing to the preservation of this common heritage. The Natural Park of the Coral Sea, blooming with life and a source of bio-inspiration and challenge for the territory and its links, is now part of New Caledonia's ambitious policy of conservation and sustainable use of ocean space. It places our small Pacific archipelago in the large global group of maritime nations.

Glossary

Accretion : Creation and growth of a calcareous organism (corals, algae) or a structure (reef).

Allochthonous: Originating from another place.

Anthropic: Refers to anything caused directly or indirectly by the action of man.

Attendance: Level of use measured as a number or density of users.

Autochthonous: Native to this place.

Beachrocks: This beach sandstone is a sedimentary rock that forms in the nearshore zone by rapidly cementing sand, shells or coral debris on a beach, parallel to the shoreline, in the wave breaking or intertidal zone.

Benthic: Characterizes organisms and processes that inhabit or happen on the ocean floor.

Bioaccumulation of metals: The ability of corals (or other organisms) to absorb and concentrate metals in the various parts of their structure (e.g, animal tissue, *Symbiodinium* and skeleton).

Biocenosis: Or "community", it corresponds to all living organisms (animals, plants, microorganisms, etc.) established in the same environment or biotope.

Biodetritic: Refers to sediments made up of bioclasts and debris from living organisms, such as coral and shellfish skeletons, and brought mechanically to a site.

Biodiversity inventory: The listing of species encountered in a particular environment.

Biomes: Vast biogeographical region extending under the same climate (e.g., coral reefs).

Biota: All living organisms (flora, fauna and fungi as well as micro-organisms...) present in a habitat (natural, semi-natural), particular biotope, place or region.

Boating: Activity practiced for recreational activities with nautical crafts (sailboats, motor boats, boats).

BOLD: Barcoding of life data systems, a DNA barcode and analysis database of all living organisms hosted by the University of Guelph in Canada.

Cambrian: Older of the six Paleozoic geological periods, extending from 541 to 485.4 million years ago.

Cays: Small islands of sand or coral.

Creek: Small stream that dries out during drought.

Diazotrophic: An organism capable of (indirectly) producing protein substances from the gaseous nitrogen (N2) present in the atmosphere and the environment.

DNA: Deoxyribonucleic acid, universal carrier of genetic information in living organisms, transmitted from one generation to the next by reproduction.

Echinoderm: A lineage of marine animals occurring at all depths in the ocean, which includes starfish, sea urchins, sea cucumbers, crinoids and brittle stars.

Ecological resilience: The ability of an ecosystem, habitat, population or species to return to normal functioning and development after significant environmental disturbance.

Enzyme: Protein with catalytic properties, capable of accelerating the transformation of compounds.

Eocene: Geological period from 56.0 to 33.9 million years ago, marked by the emergence of the first modern mammals and a massive extinction of species.

Eutrophication: Imbalance of the environment caused by an increase in nitrogen and phosphorus concentrations.

Food Chain: A series of food relationships between organisms (each consumer eats a prey or non-living resource that comes before it).

Geomorphology: Study of the evolution of shapes and reliefs of the earth's surface and the causes of it.

Grand Nouméa: Agglomeration grouping the municipalities of Nouméa, Dumbéa, Païta and Mont-Dore.

Heterotrophy: The need for an organism to feed solely on the organic matter that makes up or has formed other organisms.

Holocene: Geological period extending over the last 10,000 years and last Quaternary period.

Ichthyofauna: Part of the fish fauna.

Indicator: A measure of a phenomenon or effect, depending on the observation protocol and calculation method used.

Isotope: Atom of the same element that contains an identical number of protons but a different number of neutrons.

Klippe: Part of a nappe or thrust sheets isolated from the rest by erosion.

Long-lived: Refers to an animal whose lifespan persists in a sustainable way.

Mantle: Part of the globe between the crust and the nucleus.

Marine Protected Area (MPA): Maritime and/or coastal area delimited in space and time, aiming at the protection of the natural environment, and where practices are specifically regulated.

Mesozoic: Geological era, formerly known as the secondary era, extending from 252 to 66 million years ago.

Miocene: Geological period ranging from 23 to 5.3 million years ago.

Mitochondria: Organelle present in all cells of living organisms called eukaryotes, which have a cell nucleus.

Neutraceutical: Refers to a food product sold as a tablet or other pharmaceutical formulation with positive health effects.

Nudibranch: Marine animals belonging to molluscs (sea slugs), without a shell and with bare gills.

Observation protocol: Field data acquisition method.

Oligocene: Geological period extending from 33.9 to 23.03 million years ago, characterized by the rare appearance of new mammals.

Paleozoic: Geological era, also known as the primary era, which lasted nearly 300 million years from 542 to 251 million years ago.

Participatory management: Mode of management involving all interested parties.

Pediveliger: A larval stage of development with the appearance of a foot with which the larva will fix to a substratum.

Pelagic: Refers to organisms and processes that inhabit or happen in the water column and not to the bottom.

Peridotite: Magmatic rock composed mainly of crystals of olivine and pyroxene, which makes up most of the earth's upper mantle.

Phanerogam: Plant with flowers and seeds.

Quaternary: Most recent geological period on the geological time scale, which began 2.6 million years ago.

Recreational use: Activities carried out for the sole pleasure of users, not for profit or subsistence.

Saltmarshes: Herbaceous or floodable zone developing near a mangrove.

Seamount: Coral construction rising from the bottom of the lagoon towards the surface.

Seine: Very long single fishing mesh net.

Socio-ecosystem: Systems integrating social and environmental aspects and their interrelationships.

Strict reserve: A fully protected natural territory, where no activity is permitted in order to conserve and manage outstanding or threatened natural resources.

Symbiodinium: Microalgae living within coral tissues and capable of photosynthesis, commonly known as zooxanthellae.

Symbiont: Organism living with another of a different species, one of which often provides vital benefits to the other.

Trochophore: Larval phase in some invertebrates (molluscs) characterized by a top shape.

Trophic network: Set of food chains that connect organisms and which circulates matter and energy through an ecosystem. Living organisms can belong to several food chains and different levels depending on the food chain.

Typology: Method of classification into relatively homogeneous groups distinguished from each other by their characteristics.

Ultramafic (or ultrabasic): Refers to very low-silica magmatic rocks (less than 45%) containing more than 90% iron and magnesium-rich minerals.

Veliger: Larval stage of molluscs derived from trochophore larvae.

Zooplankton-feeder: Organism that feeds on micro-organisms which form the zooplankton.

Zooxanthella: Unicellular algae, belonging to the genus *Symbiodinium*, living in symbiosis with various marine invertebrates such as corals, giant clams and with many species of sea anemones and jellyfish.

Acronyms

ABS: Access and benefit-sharing
ACNC: Alis Current of New Caledonia
AFB: French Agency for Biodiversity
AVNIR-2: Advanced Visible and Near Infrared Radiometer type 2
BOLD: Barcoding of life datasystems
CCE: Environmental Advisory Council
CDOM: Colored dissolved organic matter
CEN: Conservatory of natural areas (Conservatoire des espaces naturels, France)
CESE: Economic, Social and Environmental Advisory Council
CITES: Convention on International Trade of Endangered Species
CMS: Convention on the Conservation of Migratory Species of Wild Animals
CNRS: National Center for Scientific Research (France)
CRIOBE: Island Research Center and Environment Observatory (France)
DBN: Dynamic Bayesian Network
DDUNI: Department for the development of innovative digital uses (IRD)
DENV: Department of Environment of the South Province of New Caledonia
DFA: Department of Land and Development (New Caledonia)
DHW: Degree Heating Week
DIMENC: Department of Industry, Mining and Energy of New Caledonia
DIN: Dissolved inorganic nitrogen
DITTT: Department of Infrastructure, Topography and Land Transport (New Caledonia)
DNA: Deoxyribonucleic Acid
DON: Dissolved organic nitrogen
DTSI: Department of Information Technology and Services (New Caledonia)
EAC: East Australian Current
ECC: East Caledonian current
EEZ: Exclusive Economic Zone
ENSO: El Niño-Southern Oscillation
EPHE: Ecole Pratique des Hautes Etudes (France)
ESPAM: Emblematic species, social acceptance and sustainability of marine protected areas (research project funded by the Fondation de France, coordinated by C. Sabinot)
GBIF: Global Biodiversity Information Facility
GCRMN: Global Coral Reef Monitoring Network
GOPS: South Pacific Integrated Observatory for Environment and Terrestrial and Marine Biodiversity
ICRI: International Coral Reef Initiative
IFRECOR: The French Initiative for Coral Reefs
INPN: The National Inventory of Natural Heritage (France)
IPCC: Intergovernmental Panel on Climate Change
IRD: National Research Institute for Sustainable Development (France)
IRENav: Naval School Research Institute (France)
ISEE: Institute of Statistics and Economic Studies of New Caledonia
IUCN: International Union for Conservation of Nature
IYOR: International Year of the Reefs
JAXA: Japan Aerospace Exploration Agency
MNHN: National Museum of Natural History (France)
MODIS: Moderate Resolution Imaging Spectroradiometer
MOM: Overseas Ministry (France)
MOU: Memorandum Of Understanding
MPAs: Marine Protected Areas
NASA: National Aeronautics and Space Administration
NCJ: North Caledonian Jet
NDD: Nitrogen derived from diazotrophy
NOAA: National Oceanic and Atmospheric Administration (United States)
OBLIC: New Caledonia Coastal Observatory
OEIL: Environment Observatory in New Caledonia
OREANET: Oceania Regional Acanthaster Network
ORSTOM: Office de la Recherche Scientifique et Technique Outre-Mer (now IRD).
PAD: Dugong Action Plan
PLD: Pelagic larval duration
POM: Particular organic matter
RORC: New Caledonia Coral Reef Observation Network
SCJ: South Caledonian Jet
SEC: South Equatorial Current
SIV: Innovation and Development Department (IRD)
SMIB: Natural Substances of Biological Interest (research project)
SNOM: Natural Substances of Marine Origin (research project)
SPC: The Pacific Community (founded as the South Pacific Commission)
SPN: Natural Heritage Division
SPREP: Secretariat of the Pacific Regional Environment Program
SRMAs: Sustainable Resource Management Areas
SST: Sea surface temperature
STCC: Subtropical Countercurrent
TAXREF: Taxonomic Register (France)
UMS: Mixed Service Unit
UN: United Nations
UNC: University of New Caledonia
UNEP: United Nations Environment Program
UNESCO: The United Nations Educational, Scientific and Cultural Organization
VAHINE: Variability of Vertical and Trophic Transfer of Diazotroph-derived Nitrogen in the South West Pacific (research project)
WWF: World Wide Fund for Nature

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With 40,000 km² of reefs and lagoons and more than 15,000 species, New Caledonia harbors the second largest coral reef in the world. At a time when coral reefs are among the most threatened ecosystems on the planet; faced with human activities, global warming and ocean acidification; it is now imperative to preserve this exceptional environmental and cultural heritage site, which has been inscribed on the UNESCO World Heritage List.

Bringing together researchers from various disciplines (natural sciences, humanities and social sciences) and conservation stakeholders, this book features the most advanced knowledge on New Caledonian reefs and lagoons. It provides an understanding of the extraordinary diversity of these environments in connection with the history of the marine environment, as well as the complexity of the relationships between the various organisms that make them up. It also emphasizes how these ecosystems provide people with essential resources that serve as some of the foundations of the Kanak culture. Lastly, the resilience of these highly vulnerable environments to global environmental change is questioned and the measures implemented to protect them are presented.

Abundantly illustrated and written in a style accessible to all, this book is intended for any reader interested in this place's exceptional heritage. Beyond that, it will raise awareness among the general public about the challenges involved in conserving biodiversity, the environment and cultures.

Claude E. Payri is Research Director at the French National Research Institute for Sustainable Development (IRD). Her work focuses on coral reefs, and marine and island ecosystems in the Indo-Pacific.

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