OUR SHARED OCEAN

Science in the Global South for a sustainable world

IRD Éditions

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Children fishing on a reef flat in Reao, French Polynesia. © IRD/S. Andréfouët

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Preface

VALÉRIE VERDIER

CEO of the French National Research Institute for Sustainable Development

The ocean is a reserve of biodiversity; it regulates the climate and provides a wealth of resources. It is one of our most precious common assets, and is essential to the balance of the planet and the well-being of humankind. As the ocean comes under increasing pressure, its preservation has become a crucial priority, calling for an international response in which science must play a leading role.

IRD has long placed the ocean at the heart of its scientific strategy. More than 350 researchers at the Institute are currently involved in around thirty programmes in the Atlantic and Pacific tropical regions, the Indian Ocean and the Mediterranean. Our primary objective is to produce cutting-edge knowledge that is a source of innovation and can help all those involved to develop sustainable solutions for preserving the oceans. We have made this commitment with more than a hundred institutions around the world through an ethical and equitable scientific partnership, embodied in a number of international joint laboratories and international research networks. As part of this approach, we are also determined to strengthen research capacity in countries of the Global South in the field of ocean science. Every year, our researchers supervise dozens of student theses and we support young research teams, helping to consolidate skills at a local level.

This book has been published on the occasion of the Third United Nations Ocean Conference, jointly organised by France and Costa Rica, in Nice. It highlights the major advances in research by IRD and its partners in our knowledge of ocean ecosystems and our understanding of the complex issues at stake, especially societal ones. This research draws on a wide range of disciplines, from life and earth sciences to human and social sciences, to provide a better understanding of the complex interactions between societies and their marine environment. We take an interdisciplinary approach, which is essential if we are to design adaptation strategies that take account of specific local contexts and the needs of countries in the Global South, in order to preserve and sustainably manage the ocean, given the many threats it faces: global warming, acidification, deoxygenation and rising sea levels, marine biodiversity loss, depletion of fish stocks, multiple forms of pollution including plastic, and coastal erosion... to name but a few.

I sincerely hope that 2025, the year of the Third United Nations Ocean Conference, will be a decisive turning point in the world's commitment to preserving the oceans. The future of the oceans, and therefore of our planet, depends on our collective ability to understand, anticipate and take action together. Our Institute works at the forefront of international action, and is strategically placed to contribute to the definition of ambitious and sustainable public policies, based on the knowledge generated by our research. Our commitment is not limited to a compartmentalised scientific approach, but is part of an ongoing dialogue with all those involved in the preservation and management of the ocean: local institutions, communities, NGOs, the private sector, etc. Only by taking into account needs and uses, mobilising local knowledge and involving the populations concerned can we develop sustainable and equitable solutions. Together with these stakeholders, we are working on strategies to ensure the sustainability and resilience of the fragile but vital ocean ecosystem. By sharing research data, raising awareness and training academic and non-academic stakeholders, we are also committed to ensuring that scientific advances can be translated into tangible action to preserve marine ecosystems.

This book is an invitation to explore the ocean's many facets through the prism of science, and to think together about the challenges and solutions for protecting it in a rapidly changing world. We are proud to be a key player in this process. Driven by a commitment based on scientific cooperation with the countries of the Global South, our ambition is to use science as a lever for action and to play an active part in implementing solutions to ensure that the ocean is protected and managed sustainably for future generations.

Introduction

Our Shared Ocean

The ocean, covering more than two-thirds of the planet, is an essential part of life on Earth. Its interaction with the climate, its extraordinary biodiversity and its many resources, feeding more than three billion people around the world, make it one of humanity's most precious shared assets. The vast expanses of ocean are both fascinating and frightening, yet their power of attraction is unrivalled: almost 40% of the world's population live less than 100 km from the coast, and most of the world's megacities are located on the ocean's shores. However, the ocean and its shores face many pressures and threats. They are heavily impacted by climate change, highly coveted and overexploited. In the current context of global change, gaining a better understanding of ocean and coastal areas and their interdependence with society has become an absolute priority, as reflected in the launch of the United Nations Decade of Ocean Science for Sustainable Development (2021-2030).

Given the ecological, economic and social challenges it faces, the ocean is undoubtedly the most complex but also the most fragile ecosystem. These challenges are particularly acute in the tropical zone, because of the unique characteristics of the ocean in this part of the world, its role in regulating the global climate, its distinctive biodiversity, and the essential resources it provides for the societies of the Global South, which are among the most vulnerable on the planet. The coastal populations of the tropical and Mediterranean areas depend heavily on the ocean for their livelihood (aquaculture, fishing, tourism, etc.) and are exposed to its uncertainties (surges, storms, erosion, tsunamis, etc.). These populations are an integral part of the coastal and marine ecosystems with which they interact; we therefore refer to "oceanic socio-ecosystems". The pressure caused by human activities including overfishing, industrialisation, deforestation, uncontrolled urbanisation, poor management of waste, soils, rivers and coastlines immediately affects the functioning and health of coastal areas and oceans, from the shore to the open sea, with a series of major impacts, including destruction of habitats and ecosystems, depletion of resources, and pollution. Coastal and oceanic socio-ecosystems are particularly vulnerable to natural climatic hazards,

whether extreme events such as cyclones and heat waves, or el Niño episodes. Climate change adds to and accentuates these threats: rising sea levels, disruption of the water cycle and intensification of extreme events (severe rainfall, floods, droughts), warming and acidification of waters affecting environments, particularly coral reefs, and fish stocks.

In view of these major challenges, IRD has placed the ocean, in all its facets, at the heart of its scientific strategy. Through research carried out with its partners, IRD studies oceanic socio-ecosystems, taking into account the complexity of their various facets, functions, interactions, dynamics and scales. This research focuses on a number of crucial issues, including climate impacts, regulation and protection against risks, preservation of biodiversity, access to resources, heritage and identity issues, sovereignty and food security. It supports the many local and global initiatives aimed at preserving and sustainably managing these areas and their resources. To help design and develop these policies and action programmes, and to guarantee and evaluate their relevance and effectiveness, there is a focus on interdisciplinary approaches (in which scientists from different disciplines work together) and transdisciplinary approaches (which reach beyond the scientific sphere to the various stakeholders involved in the issues studied): local authorities, governing bodies, sponsors and political institutions, NGOs, the private sector, etc.). This type of approach is essential, on the one hand, for understanding the complex interactions within oceanic socio-ecosystems, in the light of their many forms and uses, and, on the other hand, for developing strategies with the various stakeholders to promote the sustainability of these socio-ecosystems and equity in the way their resources are shared.

A long-term commitment

Ocean research at IRD has undergone profound changes in recent years in response to increasingly pressing challenges. It began as exploratory research, with the aim of understanding how the ocean operates, how it interacts with the atmosphere and the continents, and its biodiversity, using single and then multidisciplinary approaches. It then gradually evolved to focus more on the

human and social aspects, with the aim of understanding how people who live in close contact with the ocean and its shores are adapting to the profound changes that are taking place.

The Institute launched its first research projects in the tropical areas of the Pacific, Atlantic and Indian Oceans shortly after it was founded, following the Second World War, with the opening of oceanographic research centres in New Caledonia and French Polynesia, in French Guiana and on the coasts of Madagascar and West Africa. This geographical presence, particularly in the French overseas territories, made the Institute and the many institutions working alongside it pioneers in the study of the tropical oceans. From 1945 to the mid-1960s, inventories were the main focus. At the time, it was important to discover the vast expanses of ocean that were sometimes virtually untouched by scientific investigation, with a few studies on fisheries for economic purposes, as the colonies had to be developed! These early studies were mainly concerned with describing the biological workings of the ocean environment, with research on the different levels of the food chain and on the benthic and pelagic species living in coastal regions. Physical oceanography was not overlooked, with research into the seasonal and interannual hydroclimatic variations (winds, currents, water temperature and salinity) typical of tropical ocean ecosystems. Along with independence, fundamental research continued, but in the 1960s and 1970s studies were increasingly aimed at supporting the economic development of the newly independent states and overseas territories. This period saw the rapid growth of research into the variability of fishery resources (especially tropical tuna) and, subsequently, into the socioeconomics of fisheries, with studies on small-scale fishing in particular, for which IRD played a pioneering role in tropical ocean zones. In connection with the theory of plate tectonics, which was in full swing at the time, innovative work was also carried out on the Pacific seabed, the seismic risks it could generate and its potential mineral resources.

From the 1980s onwards, IRD's research became an integral part of major international programmes and drew on ocean observation networks collecting data at the surface or at depth from both merchant ships and fixed buoys. This was particularly the case in the tropical Atlantic (PIRATA network) and in the Pacific (TAO network), where these measurement systems led to an intensification of research into interactions between the ocean and the

atmosphere. Coupled with the satellite observation that was developing at the time, the data collected on location over nearly fifty years led to crucial advances in our knowledge of the ocean's role in the global climate, particularly in the Pacific, where the main El Niño and La Niña mechanisms were deciphered, having major consequences in tropical regions. In this ocean, like in the tropical Atlantic, these results helped refine climate forecasting models and improve our understanding of the climate upheavals that the recently created Intergovernmental Panel on Climate Change was beginning to warn of.

At the end of the 1980s, and especially following the Earth Summit in Rio (1992), the conservation of tropical ocean ecosystems became a major research focus for IRD and its partners. For example, studies on coral reefs, which gave a better understanding of how the lagoons of New Caledonia and French Polynesia work, provided fertile ground for new research into how they have changed as a result of climate change, particularly over the last ten thousand years, and into the impact of human activities on these environments, which are home to exceptional but highly vulnerable biodiversity. Similarly, research into fisheries resources was firmly focused on sustainable fisheries management. This is the case, for example, for tuna fishing, as illustrated by the studies on FADs (fish aggregating devices), analysing not only their attractiveness to tuna but also their negative impact on these large pelagic fish and on the environment, prompting more judicious use of this method of capture.

While in the early days of the Institute, physical oceanographers and biologists rarely worked together, over time their research has gradually taken on a multidisciplinary approach. In this respect, the studies on upwellings of rich and fertile cold waters that are ideal for fishing, were pioneering. These studies, carried out from the late 1970s, led to a better understanding of the interactions between variations in fish stocks and fluctuations in coastal upwellings, showing that there are optimal environmental conditions, common to all upwelling zones worldwide, which ensure the maintenance of fish populations and have a major impact on the fishing economy. From the 2000s onwards, bridges between different disciplines began to multiply: physicists, biologists, chemists, geologists and ecologists, combining field measurements, space observations and modelling, sharing methods and tools, set out together to study the ocean, now considered as a complex system driven

by ocean dynamics, atmospheric forcing, and biological and biogeochemical interactions. Not forgetting researchers in the humanities and social sciences, an increasing number of whom look at the complex dynamics between the ocean and human societies. Research into the dynamics and biodiversity of the ocean environment is now complemented by studies into the various ways in which the ocean is used, inhabited and understood, and by an analysis of the full complexity of marine and coastal socio-ecosystems. When this research is conducted within the framework of the sustainability sciences, it is fuelled by inter- and transdisciplinary approaches involving a range of stakeholders, with the aim of identifying and developing practical and sustainable solutions to improve the resilience of marine socio-ecosystems.

The ocean central to our climate

Climate variability and change are now the focus of ocean research carried out by IRD and its partners in tropical and Mediterranean regions. To understand the climate and its main mechanisms, we need to observe, model and decipher the complex links between the ocean and the atmosphere. And these links, such as the El Niño phenomenon, the most famous example, are particularly important in tropical oceans.

The ocean's power to regulate the world's climate is now being disrupted by global warming. Warming, acidification, deoxygenation and rising sea levels are the most worrying consequences. "What are the impacts of these disturbances in tropical ocean regions?" This is one of the major issues currently being studied by IRD scientists and their partners. Their modelling work shows, for example, that the strongest El Niño episodes will become increasingly frequent and intense. The challenge today is to anticipate the consequences of such upheavals on a regional scale: how will winds, precipitation regime, currents, upwellings and sea levels be affected? This is a prerequisite for estimating how these regional events are likely to affect the global climate.

In the Pacific, the knowledge acquired over the last few decades is beginning to facilitate the forecasting of El Niño episodes several seasons in advance,

as well as comparable forms of climatic anomalies in other tropical regions, such as the Indian Ocean Dipole. These advances hold great promise for the management of ocean ecosystems and the sustainable development of societies in the Global South, which are particularly affected by climate change. In the South Pacific, for example, a regional programme has recently been launched. It is unique in that it combines climate projections with analyses of how people feel and how local knowledge is changing as they cope with extreme events. This knowledge will be made available to local and national authorities in small island territories (New Caledonia, French Polynesia, Wallis and Futuna and Vanuatu) with a view to developing strategies for adapting to climate change.

Ocean and coastal environments under pressure

Over the last century, the oceans have suffered more than just the effects of climate change. On top of these have come the impacts of the unbridled growth of human activities and the uncontrolled development of coastal regions, which have been particularly damaging to the balance and biodiversity of marine and coastal socio-ecosystems. Making the right political decisions to protect ocean ecosystems requires an understanding of the state of biodiversity. Understanding its dynamics in relation to current upheavals is necessary to assess the capacity for adaptation of living organisms, from microorganisms (particularly plankton) to large pelagic species. In the Atlantic, Pacific and Indian Oceans, as well as in the Mediterranean, IRD researchers and their partners are working on this front, exploring shoreline environments (sandy coasts, lagoons, mangroves, deltas and estuaries), coastal environments (continental shelf) and deep-sea environments. Their research is a race against time, as ocean environments, under the effects of intense pressure from a variety of sources, change very quickly, sometimes before they have even been defined. But observing and monitoring entire populations or ecosystems in the ocean is a difficult task. The most recent research calls on a range of complementary disciplines (ecology, evolution, genetics, etc.) and observations carried out at different spatial and temporal scales and at different levels of organisation of living organisms, from the gene to the ecosystem.

This research draws on a wide range of exploration methods and tools. An innovative methodology combining observations provided by acoustic sounders, statistical models and numerical modelling has recently revealed a reduction in the biomass of pelagic fauna of between 3% and 22%, depending on the situation. New approaches such as the study of environmental DNA, the use of undersea optical telecommunication cables for continuous data collection, and the use of artificial intelligence are opening up immense prospects, pushing back the limits of ocean observation.

Marine pollution is now reaching alarming levels. From plastics, whether microparticles or those forming their own continents, to heavy metals, hydrocarbons, chemical compounds, rubbish and invasive organisms... the ocean receives an abundance of pollution. These massive inputs of artificial elements and the abnormal proliferation of living organisms (algae, jellyfish, starfish, etc.) disrupt the functioning and productivity of ecosystems and pose a threat to human health. The coastal countries of the Global South are particularly at risk from these disturbances, due to intense economic and industrial development, undersized or non-existent waste management systems and often insufficient environmental regulations. Researchers are taking an integrated approach to marine pollution, characterising the products at fault, how they are transported and transformed, and their impact on the trophic chain. Such an approach is indispensable if we are to understand its origins and mechanisms of action, evaluate strategies to reduce its impact, and regulate emissions from the main sources, whether industrial, domestic or agricultural.

Scientists are working particularly hard to understand how coral reefs work and to optimise their preservation. Coral reefs are ecosystems that boast exceptional biodiversity, which is essential for coastal populations, and act as natural protective shields against flooding, but they are also the most threatened ecosystems in the tropical ocean. Warming and acidification of waters, mining and organic pollution of lagoons, pressure from invasive species and an increase in destructive climatic events are causing bleaching of coral reefs and their gradual death. In fact, 20% of these ecosystems, which are home to a quarter of the world's marine biodiversity, have already disappeared. Research is currently focusing on discovering how corals adapt to new environmental conditions and identifying possible ways of helping them to do so. These studies have revealed unexpected capacities for recovery or adaptation: some corals are resistant to acidic conditions, suggesting that they

are mobilising ancestral genetic resources to adapt, while others have had their growth or their ability to resist bleaching stimulated by metals such as nickel and manganese. Although it still raises many questions, this research is opening up promising avenues for restoring the most threatened reefs and for shaping the coral reef ecosystems of the future.

Anthropogenic pressure is also affecting the suitability of coastal regions for human habitation. Much of humanity has developed in deltas, where the alluvial deposits carried by rivers have made the land particularly fertile, encouraging intense agricultural activity. Population density in the major Asian deltas, such as the Ganges, Mekong and Red Rivers, is among the highest on the planet, exceeding 1,000 inhabitants per square kilometre. These delta regions are the product of a delicate balance between the action of the sea, which is constantly encroaching on them, and sedimentary fluvial inputs. But this balance has now been disrupted, and those living in the delta regions are seeing their coastlines retreat, their arable land become salinised or disappear, and their towns subjected to ever-increasing flooding, under the influence of a series of factors: reduced sediment supply due to the construction of dams on rivers, the often illegal dredging of sand for the construction of megacities, the weight of cities that are sinking due to their vertiginous skyscrapers and increased pumping of groundwater, hydrological variability induced by climatic phenomena such as El Niño, to which we can add the rise in sea level induced by climate change. To gain a better understanding of this problem, identify its main causes and propose solutions, scientists are working to define how these complex hydrosedimentary systems operate, to understand the interactions between ocean and river dynamics and their responses to the various factors of variability, both natural and man-made, on different spatial and temporal scales.

Towards a new form of ocean governance

Today, the ocean provides food for humankind at the cost of overexploitation, which is of great concern both for the health of marine and coastal ecosystems and for the future of the people who rely on them. The steady

increase in demand for seafood products since the end of the Second World War generated a prodigious boom in world fishing - production increased 5-fold between 1950 and the end of the 20th century - with a major impact on resources: Currently, a third of stocks (fish, crustaceans and molluscs) are overexploited and more than half are fished to capacity, leaving little scope for expansion of fisheries. Since 2000, there has been a decline in catches in temperate waters and coastal upwelling zones, and to a lesser extent in tropical waters. Aquaculture has stepped in to meet consumer demand, but its considerable expansion comes with a host of problems, particularly environmental: more than two-thirds of the world's aquaculture production comes from species fed on formulated feeds which often contain fishmeal, exacerbating overfishing. Fishing and aquaculture are two sectors that have a major impact on marine ecosystems. To be sustainable, they must be developed within the framework of an ecosystemic approach that integrates ecological, social and economic aspects, so as to ensure food security and the development of the sector while preserving the integrity and resilience of the ecosystems involved. These challenges are particularly important in the Global South, where fishing and aquaculture are essential resources in terms of food and employment: more than 95% of the 58 million fishers and fish farmers in the world live in Asia or Africa.

Against this background, scientific knowledge is essential. For several decades, IRD and its partners have been running major programmes on fisheries in the tropical ocean. In the Atlantic and Indian Oceans, observatories collect biological and fisheries data on large pelagic fish caught by industrial and semi-industrial tropical fisheries (seine net, pole-and-line and longline) and make them available to public authorities, regional fisheries organisations, experts and scientists. This work aims to promote more sustainable fishing practices, in particular by studying the environmental impacts of certain fishing techniques and helping to develop solutions to reduce them. Studies are also being carried out into how much fish can be caught while allowing stocks to replenish, with the aim of making recommendations on fishing quotas and restoring balance to the marine ecosystem. Small-scale fishing is at the heart of this research, combining biological and social sciences, given its vital importance to food security and the income it generates in the countries of the Global South. In Senegal, for example, this sector provides 75% of West Africa's animal protein consumption and represents a significant proportion of GDP. In Senegal, studies have shown that small-scale fisheries are highly

resilient despite the scarcity of resources and strong competition from industrial fleets. More sustainable management of ocean ecosystems also means focusing on aquaculture. Here again, scientists are working to promote sustainable production models that guarantee food safety, ensure better nutritional quality of aquatic foods and reduce the impact of aquaculture farms.

Whether it is a question of sustainably managing fisheries resources, protecting marine biodiversity or strengthening the resilience of coastal socio-ecosystems, the countries of the Global South do not always have the same resources as wealthier nations, either for implementing policies to adapt to global change or for resisting the economic pressure exerted by operators with little regard for environmental issues. So how can research contribute to a new form of ocean governance? For each marine or coastal socio-ecosystem under consideration, scientists recommend that solutions must take an integrated view of all the mechanisms and stakeholders involved and interacting in its operation, as well as its specific features, otherwise the results may be ineffective or even counter-productive. In the South-West Indian Ocean, one of the richest regions in the world in terms of biodiversity and where small-scale fishing is central to the way of life, transdisciplinary research illustrates this approach. Here, researchers are seeking to define scenarios that could balance the conservation of biodiversity and the sustainability of fishing through sustainable and equitable management methods that take into account the specific nature of local socio-ecosystems and their capacity to adapt. Working closely with local stakeholders and drawing on observatories, they are studying how spatially-based management measures, and in particular marine protected areas, can be effective tools for restoring biodiversity, while ensuring the resilience of fisheries.

Implementing conservation or adaptation policies requires closer collaboration between scientists and the various stakeholders (decision-makers, managers, fishermen, consumers, etc.) to debate the issues and develop possible solutions together. In a number of coastal countries in East Africa and the Indian Ocean islands, emphasis is being placed on improving the dialogue between scientists and decision-makers and taking greater account of local knowledge in the development of conservation policies. This involves investing in the creation of forums for multi-stakeholder dialogue on coastal and ocean management issues, training local experts to advise decision-making bodies, and educating local populations and raising their awareness of the vulnerable nature of marine environments. In addition to coastal regions, the deep seabed is also the subject of exploration campaigns that take into account the relationship between local

populations and this largely unknown environment. The objective is to work with political, economic and community stakeholders to propose management tools to deal with the pressures affecting the deep seabed, such as climate change and the potential risks of future exploitation of its biological or mineral resources. This research highlights the need for long-term work to establish genuine dialogue built on trust, identify the needs of stakeholders, build solid local skills and thus ensure the sustainability of initiatives.

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The complex challenges facing coastal and marine socio-ecosystems call for close collaboration between scientific disciplines, and must draw on solid fundamental knowledge that is constantly evolving. It also requires dialogue between scientists and all those involved in the functioning and management of these environments, particularly at local level. This interdisciplinary and participatory approach is essential if we are to develop sustainable, context-specific strategies that can be adopted at all levels of society. It demands a high level of commitment and involvement, and must be a long-term process. Differences in vocabulary, priorities and scales sometimes hinder dialogue between disciplines, especially when these disciplines are far removed from each other: while such dialogue is increasingly well-established between physicists and biologists, it is less so between modelling physicists and anthropologists in the field. Furthermore, actions involving researchers outside the scientific sphere, which have been emerging over the last decade or two, have yet to be fully developed and invented. In particular, this means sharing research findings as widely as possible, both within the scientific community and with decision-makers, civil society, the business world and the general public.

The ocean, a source of life and a driver of climate, is facing unprecedented challenges. Meeting sustainable development objectives for the ocean is a collective responsibility that requires universal commitment. Scientific research in particular plays a crucial role in preserving this vital ecosystem. The only way to shape a future in which the ocean is preserved as a common asset is through transdisciplinary, open and shared research. This awareness of the environmental and social urgency facing marine socio-ecosystems is particularly acute in the academic community, and is motivating an ever-growing number of scientists to follow this path. IRD is fully committed to this approach, promoting action-oriented research that enables the co-construction of solutions that combine local knowledge with research, are accessible to countries in the Global South and respect the balance of ecosystems.

PART 1

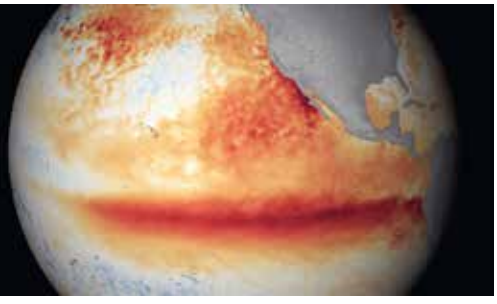
EVOLVING ENVIRONMENTS

Squall in the lagoon in Tahiti, French Polynesia.

© IRD/P. Marmey

El Niño in the spotlight

El Niño is a major driver of climate variability in the Intertropical Zone. It modifies rainfall, impacts productivity in certain ocean areas and influences cyclone formation, with major consequences for local populations. Understanding this phenomenon better is a high-priority scientific objective.



Ocean surface temperatures during an El Niño event in November 2015.

In the 1980s, meteorologists were adamant that it would never be possible to forecast the weather beyond one or two weeks. Ten years later, climatologists demonstrated the opposite by being able to predict certain climate anomalies several seasons in advance.

This required greater understanding of a phenomenon about which very little was known at the time: El Niño. Achieving this hard-won objective involved observing and collecting a vast amount of data using merchant ships, oceanographic campaigns, satellites and networks of instrumented buoys (such as the TAO buoys, positioned in the Equatorial Pacific since the 1990s).

These observations have gradually revealed the secrets of El Niño, a major climate phenomenon linked to interactions between the ocean and the atmosphere. Normally, in the Pacific, the trade winds blow from east to west, generating upwelling of deep, cold, nutrient-rich waters near the South American coast, and warmer waters favouring heavy rainfall on the other side of the basin. But when El Niño occurs, the trade winds weaken, leading to droughts in Australia and Southeast Asia, abnormally warm waters with low productivity in Peru, and tropical cyclones in French Polynesia.

In the late 1990s, major advances were made in our understanding of the ocean-atmosphere interactions that cause El Niño events and the oceanic processes that put an end to them. However, many questions remain unanswered. How can this phenomenon be translated into simple mathematical models? What are the key differences between extreme El Niño events, with devastating impacts, and more moderate episodes, limited to the central Pacific? These are crucial issues, because most of the Intergovernmental Panel on Climate Change (IPCC) models predict that extreme El Niño events will double by 2080, with major consequences for societies that are vulnerable to exceptional climate events.

PARTNERS

Centre for Advanced Studies in Arid Zones, Chile

Geophysical Institute of Peru

University of Hawai'i, USA

University of French Polynesia, France

Yale University, USA

••• Research over many years has made it possible to gain a better understanding of the multiple facets of El Niño, but many questions remain unanswered •••

Flooding is one of the consequences of El Niño events, Porto Alegre, Brazil.

"El Niño events cause drought in the Amazon basin and Northeast Brazil, as well as flooding in the south of the country. The socioeconomic consequences for Brazil are considerable, ranging from water and energy shortages to crop losses. Research into El Niño has improved forecasting of extreme events, helping to mitigate their impact on Brazil's water, food and energy security."

Regina Rodrigues, Federal University of Santa Catarina, Brazil

PIRATA, the observatory in the Tropical Atlantic

Tropical oceans play a key role in the Earth's climate mechanics, and require constant monitoring and dedicated instrumentation if they are to be understood.

© IRD/B. Bourlès

PIRATA buoy being launched into the Atlantic Ocean.

In 1960, very little was known about tropical ocean circulations... until currents were measured at various depths in the Equatorial Pacific from Nouméa, revealing the existence of unsuspected undercurrents and countercurrents. At the same time, the United States were turning their attention to the Tropical North Atlantic, source of hurricanes that ravage the Caribbean and its coasts.

In 1974, France and the United States decided to join forces to identify the circulation of the Equatorial Atlantic and understand how heat from the ocean was transmitted to the atmosphere. Water samples were taken from the first 500 metres of depth during the GATE campaign, followed by the FOCAL/SEQUAL programme in 1982-1983. The consortium showed the influence of ocean temperatures on the African monsoons and rainfall in Brazil.

In 1997, the United States, France and Brazil went even further by setting up a network of weather and ocean buoys in the Tropical Atlantic, called PIRATA (Prediction and Research Moored Array in the Tropical Atlantic). Since 2006, this network has been made up of 18 buoys, which have to be replaced every year. They measure surface meteorological and oceanographic parameters at depths of up to 500 m in real time. France maintains six of these buoys and three moorings

"The PIRATA programme's success is the result of sustained international commitment and scientific cooperation, a willingness to evolve in line with research and monitoring needs, and a desire to share data with the scientific community and operational centres. The observational system continues to develop in order to meet a growing set of research priorities and operational and climate challenges."

Hervé Giordani, Météo-France

© IRD/J. Lido

Weather and ocean buoy for the PIRATA campaign.

that measure the current between the surface and 300 m depth along the Equator. Though maintenance is expensive (€5-6 million per year in total, including €1.5 million for France), it is absolutely necessary to maintain the quality of weather forecasts. But that is not all this network provides...

••• A network of scientific buoys allows scientists to understand and monitor the Tropical Atlantic •••

Over the last 27 years, and thanks to solid collaboration with partners in the Global South, Brazil, West Africa and South Africa, PIRATA has made it possible to understand the link between cooling waters in the Gulf of Guinea and the onset of African monsoons in the boreal summer, as well as the influence of freshwater from the Amazon and the Congo on ocean-atmosphere heat exchanges. PIRATA also provides essential data for understanding the influence of small-scale (diurnal) variability on air-sea exchanges, validating satellite measurements and feeding weather and climate models.

PARTNERS

NOAA Pacific Marine Environmental Laboratory, USA

National Institute for Space Research, Brazil

Federal University of Pernambuco, Brazil

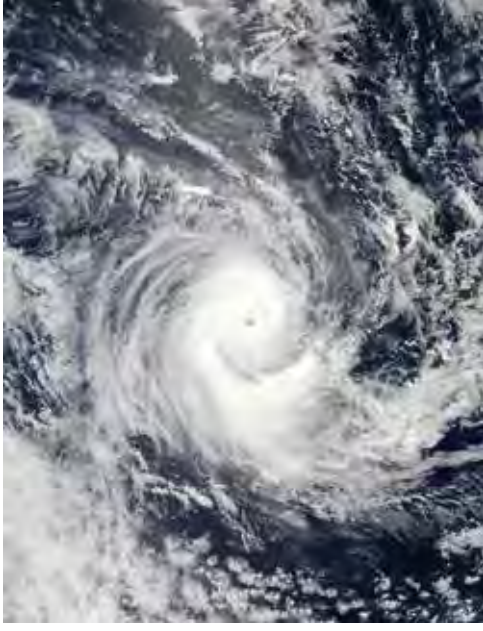
Helmholtz Centre for Ocean Research Kiel, Germany

Météo-France, France

French Oceanographic Fleet, France

Extreme waves and tropical cyclones

Tropical cyclones are among the most devastating natural disasters, and the flooding they cause is responsible for over 90% of the human and material losses observed during these events.



© Nasa/GSFC/J. Descloitres

Cyclone Erica, which passed through New Caledonia on 13 and 14 March 2003.

Climate change is causing global sea levels to rise, threatening certain Pacific islands such as the Kiribati and Tuvalu archipelagos. Under these conditions, the danger and impact caused by cyclones (including rainfall), which the Intergovernmental Panel on Climate Change (IPCC) has already predicted will become increasingly intense, are likely to exacerbate the coastal vulnerability of these already fragile nations. It is therefore important to study and model the extreme waves and water levels that these storms generate.

Tools that simulate the generation and propagation of cyclone waves show that, during cyclones, the height of waves approaching the coast can increase by 35-50% on average in tropical regions, and by up to 100% in the North Pacific. Even more astonishing is the fact that, through the long-distance propagation of cyclone waves, these same tropical storms can have an impact on distant regions such as the Equatorial Pacific, where such cyclones never occur.

••• Tropical storms increase the vulnerability of low-lying islands •••

Research on a smaller scale has made it possible to draw up risk maps for the occurrence of cyclone waves along the coast of New Caledonia, as well as for coastal flooding in densely populated areas, where 70% of extreme water levels are due to tropical cyclone waves. These extreme waves, which can reach over a jaw-dropping 7 m, are predicted to hit the reefs every 100 years.

Lastly, for the lagoons of New Caledonia, data from several past tropical cyclones and virtual cyclone ensembles have been used to model the rise in sea levels along the coast, with surges of over 2 m

PARTNERS

French Research Institute for Exploitation of the Sea (Ifremer), France

French Geological Survey (BRGM), France

University of La Rochelle, France

Météo-France, New Caledonia

UMR Entropie (IRD, université de La Réunion, CNRS, Ifremer, université de la Nouvelle-Calédonie), France

Bourail Town Hall, New Caledonia, France

Touho Town Hall, New Caledonia, France

Directorate of Industry, Mines and Energy, New Caledonia (DIMENC), France

Ouvéa Town Hall, New Caledonia, France

in narrow lagoons, especially in certain very densely urbanised sites. These extreme events can occur every 50 years.

The protective role of natural coastal ecosystems, such as mangroves and especially reefs, has been highlighted. However, these physical barriers are submerged during the most powerful cyclones, causing major flooding. In a climate change context, and in the most likely scenario, this flood risk would result in flooded areas doubling. The detailed mapping of surges in all New Caledonia's lagoons will eventually be used by public authorities to establish planning documents and climate change adaptation plans.

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Mangroves protect the coast from cyclones, New Caledonia.

The variability of upwellings

Upwelling systems are areas where cold, nutrient-rich water rises, which contains high numbers of fish and is important for fisheries. But their productivity varies from year to year. Where do these fluctuations come from?

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Fishing off the coast of Peru.

PARTNERS

Marine Institute of Peru

Cheikh Anta Diop University, Dakar, Senegal

Assane Seck University, Ziguinchor, Senegal

Of all the upwellings, the one off the coast of Peru is the most productive by far - it alone accounts for 5-6% of the world's fishing. However, this cornucopia sometimes dries up completely, as in 1972, causing the sudden collapse of an entire economic sector.

Such abrupt changes have led research teams to question the upwelling's local and global mechanics. It appears that the driving force is not located in the depths of the ocean - rather, the winds and Coriolis force push surface waters out to sea like a conveyor belt, causing the nutrient-rich waters beneath to rise... very slowly.

••• Scientists have sought to gain a better understanding of the complex mechanics of upwellings in order to anticipate fluctuations in fishing productivity •••

This is the key to the zone's extreme productivity. Because in these calm, nutrient-rich, well-lit waters, phytoplankton flourish and, with them, so does the entire food chain. However, in some years during the El Niño phenomenon, the machine breaks down and the deep waters no longer rise. A layer of water from the Equatorial Zone, warm and low in nutrients and plankton, then accumulates on the surface, stopping photosynthesis and driving away the fish.

Conversely, when the upwelling is in full swing, so much organic matter is produced that some of it (dead organisms, faecal pellets, etc.) sinks and is consumed by ocean bacteria, which breathe and consume the ambient oxygen. This creates a deep layer of water with very low oxygen content which, in certain cases, due to an ocean wave from the north, can rise and destroy the entire ecosystem in one go.

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Collecting oceanographic data during the intense upwelling season, Senegal.

The way in which upwelling zones are stirred up by winds and waves therefore influences their productivity. This complex mechanism could be at work in other parts of the world, such as in West Africa, along the coast of Senegal, and in South Africa. What will happen to it in the context of climate change? In the 1990s, measurements suggested that wind speeds would increase, speeding up the engine and therefore the productivity of upwellings. But more recent research shows that this trend is only true for high latitudes. In regions close to the tropics, this would not be the case, which could ultimately lead to a drop in the productivity of upwellings in Peru and Senegal.

Mapping the tsunami hazard

In just a few minutes, a tsunami can cause major human, economic and environmental damage. Greater understanding of these events is needed to establish early warning systems, effective evacuation plans and greater resilience in coastal communities.

© Inocar

Satellite stations to monitor the coastline and calculate tsunami propagation, Ecuador.

Some events have a before and an after. This was the case for the 2004 Indian Ocean earthquake, which had a magnitude of over 9 and caused a devastating tsunami that killed 250,000 people. In the aftermath of this tragedy, more warning systems to alert coastal populations of incoming tsunamis were put in place, but these approaches alone are not enough. It is necessary to identify the areas likely to be impacted and those that are permanently protected beforehand.

To obtain this information and produce hazard maps, it is essential to build robust digital simulations capable of describing how a tsunami spreads and impacts the coast. These simulations require reliable physical models, solid knowledge of the nature of the source (e.g. an earthquake) and extensive data on the underwater and coastal topography. These models make it possible to assess the hazard at a lower cost, complementing the tsunami observation network.

Research carried out over the last 20 years has resulted in a number of maps, mainly around active fault zones, such as in Southeast Asia, the Caribbean, the Southwest Pacific and the Mediterranean.

These models, supplemented by hydrographic tsunami data or eyewitness accounts, can also sometimes be used retroactively, to acquire

"The Oceanographic Research Institute of the Ecuadorian Navy (INOCAR) is responsible for navigational safety and marine hazards. The North Andean seismic zone is a site of recurrent tsunamis, which means that Ecuador is the relay for the Pacific tsunami warning system. One of our key tasks is to establish tsunami risk maps and keep them up to date, which we share with civil protection authorities for risk prevention."

Andrés Pazmiño, Oceanographic Research Institute of the Ecuadorian Navy, Ecuador

••• New digital simulation and risk-mapping tools offer ways to adapt coastal development to the threat of tsunamis •••

© IRD/DR

Tsunami damage in Indonesia in 2004.

information about the source of a tsunami and estimate, for example, the magnitude of historic earthquakes. The aim is to help create a better description of the seismic hazard. Examples include the Indian Ocean earthquake and certain famous 19th-century earthquakes in Liguria and the Loyalty Islands in the South Pacific.

Studies are continuing on the North Andean subduction zone. Tools and methodologies are currently being implemented within the Ecuadoran Oceanographic Research Institute. The objective is to be able to create flood and intensity maps for all communities in the country. The work is time-consuming and will have to be constantly updated, but once done, it can be replicated in other places.

PARTNER

Oceanographic Research Institute of the Ecuadorian Navy, Ecuador

Understanding the complexity of Southeast Asia's climate

Climate modelling on a regional scale is complex for multiple reasons. For one, it involves cross-referencing a large number of interconnected variables related to the atmosphere, hydrosphere, land surface and biosphere.

Monsoon rainfall in Nha Trang Bay, Vietnam.

For anyone interested in climate or weather, Southeast Asia is undoubtedly one of the most complex regions on the planet. It combines local hazards (such as typhoons), seasonal variability (such as monsoons), interannual fluctuations (such as El Niño/La Niña) and the influence of global changes, especially those linked to climate change.

But that is not all, because this region is also home to some 22,000 islands, as well as high cloud formation and precipitation. In addition, a significant amount of freshwater is provided by the region's major rivers and heat by the atmosphere. All this can disrupt global thermohaline marine circulation, the great loop of ocean currents that circles the globe and whose surface branch runs from the Pacific to the Indian Ocean via the seas of Southeast Asia. Not only is it diluted and warmed, but the tide also mixes it with the deep waters of the region, which are the only ones of their kind on the planet.

• • • Modelling that accounts for air-ocean interactions and fine-scale processes can improve simulations of climate phenomena in Southeast Asia • • •

The region is therefore subject to a jumble of atmospheric, hydrological and ocean phenomena that are difficult to disentangle and predict... which causes problems, given the human and economic stakes in the region. 10% of the world's population live in Southeast Asia, mostly on coasts and deltas, less than 5 m above sea level.

To gain a better understanding of this complex system, scientists from different disciplines decided to combine their models, initially

PARTNERS

Hanoi University of Science and Technology, Vietnam

LMI Lotus (IRD, CNRS, Hanoi University of Science and Technology, Vietnam Academy of Science and Technology)

"For more than ten years, the CORDEX-SEA (Coordinated Regional Climate Downscaling Experiment - Southeast Asia) community has been downscaling global simulations carried out for the Intergovernmental Panel on Climate Change (IPCC) in order to project future climate change for Southeast Asia, based on regional models focusing solely on the atmosphere. Our new coupled ocean-atmosphere model will play a major role in guiding the CORDEX-SEA community's research in the years to come."

Thanh Ngo-Duc, Hanoi University of Science and Technology, Vietnam

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Typhoon Chanthu in the Philippines.

developed to simulate the region's atmospheric and oceanic movements respectively. This long-term project has produced the first coupled ocean-atmosphere model capable of realistically reproducing meteorological and climate phenomena in Southeast Asia, with a hitherto-unrivalled spatial resolution.

It appears that air-sea interactions are particularly important in coastal areas, and that they occur very quickly - much quicker than we imagined. In order to capture them, the model has to recalculate every 15 minutes, rather than every hour, as was traditionally the case.

With this research, scientists are offering a more cohesive vision of the region's ocean and atmospheric temperament, which plays a decisive role in the climate. This should improve weather forecasts, as well as the IPCC's long-term climate projections.

The unsuspected variability of lagoons

In Africa, two-thirds of the population live less than 100 km from the coast, exerting significant pressure (fishing, pollution, development, etc.) on coastal ecosystems, particularly lagoons.

© IRD/T. Stieglitz

Measurement of salinity profiles over the entire depth of the Iguela Lagoon, Gabon.

Coastal lagoons are highly productive ecosystems, serving as nurseries and habitats for a majority of fish species living on or passing along the coast. However, little is known about their hydrological and ecological functioning. This is what led to the idea of comparing three different lagoons: two that are highly anthropised, in Madagascar (Ambinanibe) and Benin (Nokoué), and the third in Gabon (Iguela), where direct human impacts are still limited despite major oil activity in its watershed.

The results show that each lagoon has a unique way of functioning, with highly varied biological processes that respond to the specific physical and biogeochemical characteristics of the lagoon system. In Gabon's Iguela Lagoon, the largest of the three, freshwater brought in by rivers never completely flushes out the salt, even during the rainy season. As a result, saltwater fish populations can survive even the intense rainy season.

On the other hand, in Nokoué Lagoon in Benin, the influence of rivers during the rainy season is such that the entire lagoon fills with freshwater, radically changing the composition of fish populations

"Lagoons are a common feature of the Gabon coastline. These natural areas deserve particular attention, as they not only support a large part of the livelihoods of local populations, but also play a central role in supplying ecosystem services well beyond their respective perimeters, such as spawning grounds for coastal and marine fish. Knowledge of the functioning, services and processes associated with these particular ecotones is a priority for Gabon, in its pursuit of sustainable development and use of these natural resources."

Jean Hervé Mvé Beh, Directorate General of Aquatic Ecosystems, Ministry of Water and Forests, Gabon

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The Ifaho River, which flows into the Ambinamibe Lagoon, Madagascar.

according to the period. Lastly, in the smaller Ambinanibe Lagoon, the river water is sufficiently abundant to flush out the saltwater quickly and intermittently, 5 or 6 times during the rainy season. As a result, fish adapt and change their diet according to fluctuations in salt and nutrient levels.

••• Studies carried out in Africa show that each lagoon system is unique •••

It is clear that the word "lagoon" can refer to several different types of coastal ecosystem. Those subject to the most environmental variability could be the most resilient to climate change or human pressures. However, there are limits: in Ambinanibe Lagoon, for example, a pipeline project that would transport 90% of the freshwater to arid regions could profoundly affect the lagoon environment and associated ecosystem services. A study is currently underway to assess the risk, with local communities actively opposing the project.

PARTNERS

Benin Fisheries and Oceanological Research Institute

National Oceanographic Data and Information Centre, Gabon

National Centre for Scientific Research and Technological Development, Gabon

Anosy Higher Education Institute, Madagascar

Resilient Mexican mangroves

Mangroves have demonstrated their resilience in the face of global change, as well as their ability to maintain their essential ecological functions. This strength is documented by scientific data combined with local knowledge and could guide investment choices effectively in the current race for carbon credits.

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Salt on the leaves of the black mangrove, a species adapted to the salinity of the environment, Marismas Nacionales, Mexico.

© IRD/C. A. Zabre Rojas

Reforestation by planting mangroves in the Marismas Nacionales Sinaloa area, Mexico.

Although Mexico is one of the countries with the largest areas of mangroves in the world, these ecosystems are under serious threat, mainly due to rapid population growth and the urbanisation of coastal areas. How does the degradation of mangroves affect their ability to store carbon? To answer this and other questions, a Franco-Mexican scientific team has carried out an in-depth study of three Mexican mangroves with different characteristics, located on the Pacific and Gulf of Mexico coasts.

Analysis of sediment cores has made it possible to trace the evolution of carbon storage in these ecosystems. To the surprise of scientists, despite the differences between these areas, the mangroves show a general increase in the accumulation of sediment and carbon over the 20th century, suggesting that they respond more to global dynamics than to local influences.

This increase, which has been particularly marked since the 1950s, is largely due to the increased erosion of watersheds, itself linked to deforestation and urbanisation in these regions. As a result, the mangroves are storing more and more carbon of terrestrial origin,

"Mangrove resilience depends on the dynamic interaction between tides, river water and sediment, and the capacity of sediment to maintain itself in the face of climate and anthropogenic pressures. In favourable conditions, such as river-fed floodplains, mangroves show a remarkable ability to adapt to environmental change, even in the face of rapidly rising water levels."

Francisco Javier Flores Verdugo, National Autonomous University of Mexico

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Black mangrove roots in Marismas Nacionales, Mexico.

transported by rivers to the coast, and thus becoming vast, sustainable reservoirs of stable carbon.

> ••• Analysis of sediment cores has made it possible to measure the increase in carbon storage in Mexican mangroves throughout the 20th century •••

These results illustrate the resilience of mangroves in the face of global change, as well as their ability to maintain their essential ecological functions. This is a key argument for identifying priority areas for conservation and restoration. Combined with local knowledge, solid scientific data can help guide the massive investments linked to the carbon credit market and ensure that it becomes an effective driver of change.

PARTNERS

UMR Locean (SU, CNRS, MNHN)

National Autonomous University of Mexico

University of Tours, France

An oasis in an ocean desert

Along Tonga's volcanic arc, off the coast of New Caledonia, a highly productive major fishing zone has been identified in the vast ocean "desert" of the tropical Pacific. A mysterious phenomenon brought to light by oceanographic research.

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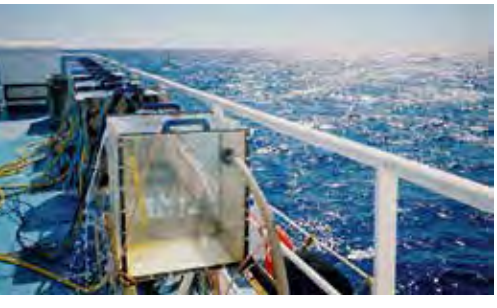
Samples of plankton strains, Mediterranean Institute of Oceanology, Marseille.



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Plankton incubators, Tonga.

PARTNERS

Mediterranean Institute of Oceanology (MIO, CNRS, Aix-Marseille University, IRD, University of Toulon), France

UME LOV (CNRS, Sorbonne University, Imev)

Direction de l'industrie, des mines et de l'énergie de la Nouvelle-Calédonie (New Caledonia Department of Industry, Mines and Energy), France

UMR Lemar (CNRS, IRD, Ifremer, UBO), France

University of Tasmania, Australia

Off the coast of the Tongan Islands, scientists have discovered an area of high biological productivity with a surface area two to three times the size of France. This is somewhat unusual in this region of the Pacific, where the waters are reputed to be poor, encouraging the scientists to examine the area as part of an oceanographic campaign.

Here beneath the surface of the water lies a 2,000 km long chain of undersea mountains. It was created by the convergence of the Pacific and Australian tectonic plates, and is riddled with active volcanoes. Some are very deep, but others lie close to the surface, releasing their iron-rich hydrothermal fluids at depths of between 200 and 50 metres. This enriches the surface layer of the ocean, which otherwise lacks this essential nutrient. According to physical, chemical and biological analyses, the surface waters around active volcanoes contain ten times the normal concentration of dissolved iron. This element is essential for diazotrophic cyanobacteria to fix atmospheric nitrogen dissolved in the water and make it available to plankton. This constant and sustained supply of iron dating back thousands of years from the dozens of shallow volcanoes in Tonga's volcanic arc explains the vast plankton blooms that cover an area of 360,000 km^2.

This plankton, which is also photosynthetic, fixes the CO_2 dissolved in seawater. The results of this research showed that this oasis of life contributes to the absorption of atmospheric carbon in the ocean depths (> 1,000 m). This process, which has only recently come to light, is now the subject of in-depth research involving the sampling

••• In the Pacific, shallow hydrothermal springs produce massive plankton blooms that can be detected by satellite •••

© IRD/T.Vergoz

Plankton scanner analysis, Mediterranean Institute of Oceanology, Marseille.

of data transmitted by an intelligent profiling buoy equipped with autonomous high-tech sensors powered by solar and wind energy, which can scan the ocean both at the surface and at depth.

Resilient coral in New Caledonia

With climate change comes acidification and warming of the oceans, and if this increases, the consequences for coral reefs could be dramatic.

© IRD/J.-M. Boré

Mangroves in the Bouraké Lagoon, New Caledonia.

Around ten years ago, French and Australian scientists identified an astonishing coral reef in the Bouraké mangroves in New Caledonia: it thrives in extreme conditions of heat, pH and deoxygenation. This environmental context is similar to conditions predicted by the end of the century, which, according to experiments conducted in aquariums, would sound the death knell for coral reefs. But perhaps that is not the case after all...

Since the discovery, scientists have been analysing this unique site. They are studying the ability of coral reefs to adapt to changes in the environment. To date, around 60 species of coral have been identified in this acidic, warm, low-oxygen environment. Surprisingly, these same species are the first to succumb to extreme heat in other parts of the world.

••• Some hardy corals can survive in completely unexpected physicochemical conditions, offering a way to restore parts of coral reefs •••

During the high temperatures of 2016, only 20% of the coral at the Bouraké "laboratory site" was bleached, compared with the vast majority of coral in the rest of New Caledonia. This unexpected capacity for resistance could be linked to symbiosis with a special heat-resistant single-cell alga. But it could also be explained by the high level of nutrients in the rich mangrove waters.

Various experiments were carried out and the coral's genetic material analysed. A comparison of the genetic make-up of coral at Bouraké with coral at other sites produced the most surprising results: the Bouraké coral is no different from the others. This means it has not been selected by the hostile environment, acting as a filter. In fact, the population is the same as at other sites.

PARTNERS

Palau International Coral Reef Centre (PICRC)

International CO_2 Natural Analogues Network (ICONA)

"Giving coral ecosystems a chance in the face of global change is an ecological and socioeconomic imperative. Through their heritage value, coral reefs provide a living for 500 million people in tropical areas. Results of studies carried out in New Caledonia on the Bouraké site underline the urgent need for action. I hope these results encourage decision-makers to take the necessary measures in order to strike the right balance between profit and sustainable environmental management."

Claude Payri, IRD, New Caledonia

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Research into the effects of ocean acidification at the Palau International Coral Reef Centre.

This suggests that most corals may have a pool of individuals capable of withstanding these conditions and therefore of surviving climate change. So there is hope, to a certain extent... However, these resilient corals would not be enough to repopulate entire reefs; as it stands, they could only be used to save or restore parts of coral reefs. Only a drastic and sustainable reduction in greenhouse gas emissions will ensure the survival of certain existing reefs.

Sargassum taking over

Two pelagic species of brown sargassum seaweed, *Sargassum natans* and *Sargassum fluitans*, have been growing in large quantities in the Tropical Atlantic since 2011. Their build-up along coasts threatens ecosystems and economies in the Caribbean and West Africa.

© IRD/P. Quenehervé

Damage caused by rafts of sargassum in the port of Marigot, Martinique.

Although Christopher Columbus first reported the presence of floating rafts of sargassum in the North Atlantic in 1492, pelagic sargassum seems to have been confined to the subtropical gyre and the Gulf of Mexico for several centuries. However, from 2011 onwards, it began to appear much further south and in unprecedented quantities, particularly on the coasts of the French West Indies. These sargassum blooms hamper economic activities such as fishing and tourism, threaten the health of coastal populations, particularly through hydrogen sulphide emissions on beaches, and also disrupt fragile coastal ecosystems, such as seagrass beds, mangroves and coral reefs.

To explain this scourge, researchers initially thought that there was a link with the continued development of human activity in the Amazon and Congo watersheds, which could have increased the input of nutrients into the ocean and encouraged sargassum bloom in new latitudes. However, analysis of satellite images and development of digital models have shown that the places where sargassum grows are actually little or not at all connected to the plumes of these major rivers. So, what is the real reason? Studies combining observations and digital modelling have revealed that a certain interannual climate phenomenon known as the North Atlantic oscillation, associated with particularly strong fluctuations in 2009-2010, led to abnormal ocean currents for a certain time. They transported the sargassum further south, where it found a favourable environment for growth and has persisted ever since.

Researchers then developed a seasonal forecasting system for the Tropical Atlantic, to anticipate seaweed strandings up to seven months in advance. This should enable local authorities and private actors to adapt coastal protection and clean-up campaigns. Research currently underway will make it possible to estimate whether areas of proliferation are likely to expand in the years or decades ahead, or whether the situation can still be reversed.

PARTNERS

UMR Lemar (UBO, CNRS, IRD, UT3), France

Mercator Ocean International, France

UMR MIO (Aix-Marseille University, University of Toulon, CNRS, IRD)

Ensenada Center for Scientific Research and Higher Education, Mexico

South Border College, Mexico

São Francisco University, Brazil

••• Satellite observations and digital modelling have shown that the recent appearance of sargassum in the French West Indies - and its persistence - is linked to a temporary anomaly in ocean currents •••

Sargassum floating on the surface of the ocean.

"Although major scientific advances have been made in addressing the sargassum problem, we still have more questions than answers, and major debates remain on nearly every aspect of new sargassum blooms. However, almost all scientists agree that sargassum blooms will continue in the future, and that the harmful effects will be felt in other ecosystems, particularly, and with great concern, on the reefs of the Mesoamerican Barrier Reef System."

Julio Sheinbaum, Ensenada Center for Scientific Research and Higher Education, Mexico

Soot in the water

When organic matter burns, not only does it emit carbon dioxide (CO_2) into the air, but it also produces particles, including black carbon (commonly known as soot), which impacts the climate and human health, among other things.

Nickel processing plant at Doniambo, New Caledonia.

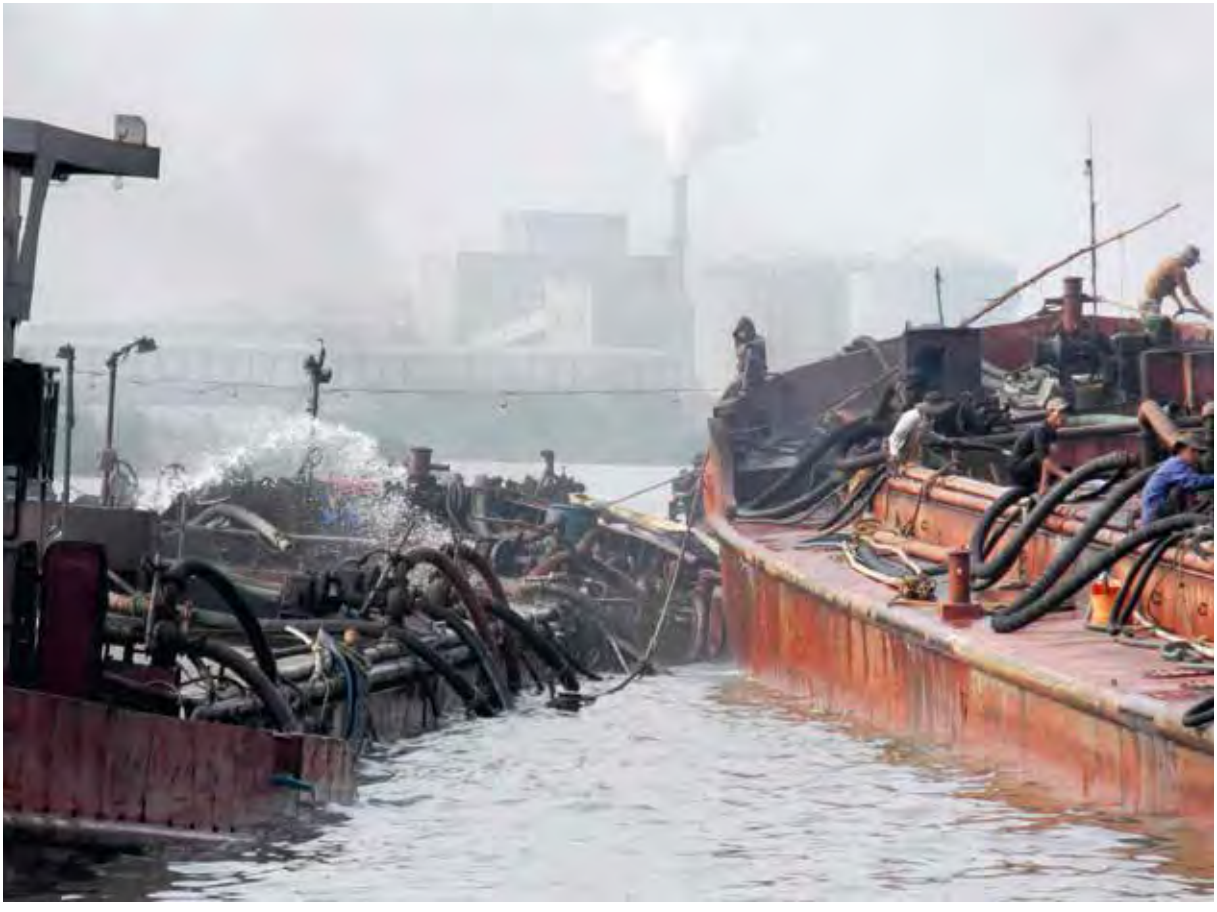
In 2005, a very strange phenomenon was observed in the lagoon of New Caledonia, near Nouméa: in the surface waters, bacterial activity suddenly increased and microbial processes changed... then returned to normal. Many hypotheses would have to be tested to understand the origin of this phenomenon, which turned out to be a high concentration of black carbon in the air. When winds dropped for several days, atmospheric particles, particularly those emitted by the nickel plant's oil-fired power station, concentrated above the lagoon in a thick brown cloud. This facilitated the deposit of black carbon in surface waters, which affected marine micro-organisms.

This was how black carbon, a particle produced by the incomplete combustion of fossil fuels or biomass, came to have a life and influence in the aquatic world, marking the start of a whole new field of research. Until that point, black carbon was only studied in the atmosphere, where it resides for less than a month. What happened to it afterwards was not greatly considered - and wrongly so.

To develop knowledge on this subject, research was launched in Vietnam, a major emitter of black carbon, to describe the path taken by these particles in the water cycle. It has shown that the vast majority of black carbon emitted into the atmosphere ends up in the ocean.

"The subject of black carbon in the air and water is a recent one in Vietnam. Thanks to our collaboration with IRD, we have studied the fluctuations of this pollutant and its impact on northern coastal ecosystems. This work, which is scientifically and practically significant, provides a solid foundation for the country's managers and decision-makers. It can be used to develop effective solutions for monitoring and protecting the environment, while including this pollutant in environmental policy."

Chu Van Thuoc, Institute of Marine Environment and Resources, Vietnam



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High-pollution industrial activities in the Halong region, Vietnam.

Although largely ignored, this pollution is a major problem for the oceans, with inputs 2 to 10 times higher than plastic. Scientists have been working to understand the impact of this through laboratory experiments and *in situ* observations.

••• Black carbon has antagonistic effects on the marine environment that could influence the ocean's efficiency as a carbon pump •••

Studies reveal that in the marine environment, black carbon absorbs organic matter, nutrients, toxic compounds and viruses, leading to antagonistic effects: on the one hand, it stimulates bacterial activity at the expense of phytoplankton, which reduces ocean CO_2 pumping; on the other, it encourages the formation of large organic aggregates, which increases CO_2 pumping. These two mechanisms could therefore influence the efficiency of the biological ocean pump. However, there is still a great deal of work to be done to determine the effects of marine black carbon on ecosystems, health and climate more precisely.

PARTNERS

Institute of Marine Environment and Resources, Vietnam Academy of Science and Technology

Hanoi University of Science and Technology, Vietnam

Plastics: from the rivers to the ocean

The Indian Ocean is facing serious plastic pollution, which needs to be curbed as a matter of urgency - and research data can help.

©IRD/L. Weiss

Plastic waste washed up on Manhame Beach, away from human activity, Mozambique.

It is estimated that 15-25% of the world's marine plastic pollution accumulates in the Indian Ocean, a basin connected to a third of the world's population via rivers. Studying the distribution of this plastic pollution is crucial for local countries. According to scientists, most of the debris come from the Bay of Bengal and Southeast Asia, particularly during the summer monsoon season, when extreme rainfall intensifies soil leaching and waste discharge into the sea.

Once plastic pollution enters the sea, ocean currents disperse it thousands of kilometres from its source, over drift times of several years. For example, large quantities of floating microplastics have been observed between Madagascar and Australia, where current modelling has highlighted a convergence of large-scale marine currents forming the accumulation zone of the Indian Ocean subtropical gyre. The gyre extends as far as the shores of Reunion Island, where certain seabirds feed, increasing the risk of them ingesting plastic waste.

While some observations have been carried out in Asia and around the islands, the coasts of East Africa are still largely undersampled. A count of macroplastics transported by the Komati River in Mozambique was therefore undertaken during the rainy season, to establish the state of pollution in the estuary. Almost all of the waste identified

"Human activities on land and hydrological processes are key to understanding plastic pollution. In tropical climates, prolonged dry periods encourage the build-up of rubbish on land, and heavy rainfall sends waste towards drainage channels. The key processes involved in transporting plastics in tropical environments remain underexamined, underlining the need for scientific data and effective measures to reduce pollution passing from land to sea."

Dinis Juizo, Eduardo Mondlane University, Mozambique

••• One approach aims to better quantify the flows and track the trajectories of plastic in the Indian Ocean •••

© IRD/L Weiss

Plastic bottle in the vegetation on the banks of the Incomati Estuary, Mozambique.

was food packaging, half of which was plastic bottles. The peak level of waste was 10 plastics per hour, which remains well below the maximum estimated for the Rhône in France (293 plastics per hour). Understanding the flows of plastic pollutants into the marine environment requires a number of factors to be taken into account: different hydrological regimes, waste management strategies, anthropogenic activities in watersheds and complex transfer dynamics.

Beyond quantifying flows, this research is helping to better trace the trajectories of plastics in the sea, in order to identify landing areas that need to be cleaned up - particularly when sensitive ecosystems are involved - as well as areas that produce pollution, where it is essential to put appropriate measures in place to curb the sources. All of this will add weight to the arguments of countries trying to change international regulations on the issue of plastics.

PARTNERS

Faculty of Civil Engineering, Eduardo Mondlane University, Mozambique

Dunes de Dovela Ecolodge, Mozambique

UMR Entropie (IRD, University of La Réunion, CNRS, Ifremer, University of New Caledonia), France

The fate of river water in the ocean

Rivers provide freshwater, but also nutrients, contaminants and sediment. All these elements must be monitored in the ocean and on the coast, especially pollutants.

© IRD/G. Courcoux

Village on stilts and boats in Halong Bay, Vietnam.

The Red River Delta in Vietnam is one of the most densely populated regions in the world, and the site of intense agricultural and industrial activity. Domestic use, agricultural practices (particularly the use of fertilisers, herbicides and pesticides), industrial discharge and the wastewater treatment system are all factors that impact water quality in soil and rivers.

Nutrients, contaminants such as heavy metals and plastics, and organisms that are potentially pathogenic for ecosystems and humans are transported by various branches of the delta and then pass through the estuaries, ending up in the ocean.

What becomes of these pollutants in seawater or sediment is crucial for water quality in provinces where aquaculture and fisheries are a mainstay of the local economy. Though analysing samples taken *in situ* offers a way to monitor contamination levels and explore their sources, knowledge of the dynamics of river plumes is crucial to better understanding and predicting the dispersal of pollutants. For the Red River, these dynamics are studied using digital modelling and a classification method.

••• A series of simulations follows the path of the waters of the Red River to the sea in Vietnam •••

Scientists have shown that the river plume is highly variable, due to fluctuating freshwater inflows and wind, as well as the degree of mixing between freshwater and saltwater, which enters the estuary with the tides. These parameters greatly modify the length and dispersal of the plume, as well as its physical behaviour.

During monsoon season in the northeast, which corresponds to the dry period in the south, the plume is narrow (around 20-30 km wide)

PARTNERS

LMI Lotus (IRD, CNRS, Hanoi University of Science and Technology, Vietnam Academy of Science and Technology)

Hanoi University of Science and Technology, Vietnam

Institute of Marine Environment and Resources, Vietnam

UMR Legos (Cnes, CNRS, IRD, UT3), France

"In-depth analysis of the variability of the Red River plume provides valuable information on the transport and dispersal of river water in the ocean, contributing to the effective management of pollution risks. In addition, this work paves the way for future research, such as on the impact of climate change on the variability of the Red River plume, which will be essential for developing sustainable management plans in the future."

Nguyen Duy Tung, Hanoi University of Science and Technology, Vietnam

© IRD/P. Cayré

"Industrial" fishing boats moored in Halong Bay, Vietnam.

but deep, running southwards along the coast. In early summer, the monsoon reverses and the plume changes direction, moving northwards. In late summer, during the wet season, it heads out to sea in the Gulf of Tonkin. During this phase, it forms a very thin layer of low-salinity water on the surface, stretching for 50 to 100 km.

This research can be used to explore development scenarios, as well as to advance our understanding of particularly vulnerable environments for which risk prevention plans are needed, as well as mitigation and adaptation measures.

On the trail of ocean plastic

Plastic owes its commercial success to its durability. But this quality becomes a flaw when it comes to plastics in the environment, where they pose toxicity problems, among others.

© IRD/T. Berr

Masked booby surrounded by plastic waste, Clipperton.

The story begins like a holiday anecdote, with a researcher finding two plastic bottles on a beach in New Caledonia. According to their labels, one came from the Solomon Islands, the other from Papua New Guinea. How strange... Because according to ocean circulation models, neither should have been on that beach - no known surface current could have carried them there.

This inconsistency led a research team to model the movement of plastics in the region. They began by using surface geostrophic currents, tracked over the last 30 years by satellite altimetry, to show that these bottles should have ended up in Australia - which is not what happened. To get them to New Caledonia, the scientists had to factor in the influence of wind and oceanic mesoscale eddies (10-100 km), the maritime equivalent of depressions and anticyclones in the atmosphere.

This allowed them to reconstruct the journey the bottles took over 60-90 days travelling from the Solomon Islands and Papua New Guinea to New Caledonia. They were able to highlight the role of winds, waves, currents, tides and eddies in transporting plastics across the open sea. Thanks to these cumulative factors, scientists were able

"Research around the dispersal of marine pollution in Indonesia and Southeast Asia has mainly focused on the distribution of plastics at the ocean surface, while the behaviour and fate of plastics in the water column have not yet been sufficiently studied. To fill this gap, I am seeking to understand the dynamics of plastic dispersal at different ocean depths, using a digital model and Lagrangian methods. The results should offer new insights into plastic distribution pathways, support Indonesia's efforts to mitigate marine pollution, and ultimately, strengthen international collaboration for sustainable ocean management."

Dava Amrina, University of Western Brittany, France

••• Ocean currents alone do not explain the trajectory of floating plastics in the ocean •••

© Unsplash/N. Bertolt Jensen

Plastic waste on the surface of the ocean.

to simulate large ocean gyres in subtropical regions, which accumulate and trap plastics that have been floating on the surface, sometimes for more than 20 years.

This work was then adapted to simulate the flow of plastics across Indonesia's 17,000 islands. The country is aiming to reduce its plastic waste emissions by 70%. Furthermore, it is trying to improve the way it tracks this pollution, to identify landing areas and organise clean-up campaigns. Analysis of models has confirmed the importance of sources of pollution coming from rivers. It has also highlighted the key role of landing areas not only as waste sinks, but also as sources of pollution when rubbish is recaptured by the sea. 60% of waste washes up less than 1,000 km from its point of entry into the ocean. A significant level of connectivity on a larger scale, towards the Indian Ocean, has also been demonstrated.

PARTNERS

National Research and Innovation Agency, Indonesia

Meteorology, Climatology and Geophysical Agency, Indonesia

French Development Agency, France

Embassy of France in Indonesia

Our friends from the deep

Research carried out in the deep ocean over the last ten years has revealed a varied environment, connected to our own, which provides immeasurable ecosystem services.

© IRD/A. Bertrand

Sorting material collected during a deep-water trawl, Brazil.

Deep-sea fish are particularly fascinating. They are strange, they sometimes eat things bigger than they are, and some light up the darkness like beacons in the night. And yet, these fish could not be more distant from us, with their strange mouths and shapes that traverse the vast ocean, somewhere between 200 and 5,000 metres below the surface. The only way we get to see them is in a natural history museum, leafing through a book or watching a film. They are virtually foreign to our world, and yet they are an unsuspected cornerstone of it.

Acoustic and trawl data from the first 1,000 metres of the water column, particularly off the coast of Brazil, show that they are far more numerous, diverse and complex than imagined. Although relatively small in size, they are thought to constitute the largest biomass of vertebrates on Earth.

••• Observations in deep waters reveal the key role played by this fascinating ecosystem •••

Observations also show that these deep-sea fish undertake major vertical migrations. They can cross a vast range of the water column, and therefore a large number of pelagic zones, in a single day, making them great travellers, but above all great transporters. They are essential participants in the transport of carbon to the ocean depths,

"The research carried out by IRD in Brazil has been a successful model for the advancement of studies on the biodiversity, ecology and conservation of historically neglected deep sea ecosystems. This partnership goes beyond traditional academic objectives, not only fostering high quality scientific outputs, but also serving as a tool to train and equip young scientists to take the lead in their field, creating opportunities for significant progress in priority areas of science."

Michael Maia Mincarone, Institute of Biodiversity and Sustainability, Federal University of Rio de Janeiro

© IRD/G. Roudaut

Viperfish *Chauliodus sloani*, deep-sea fish, Brazil.

a phenomenon that contributes to the "biological carbon pump", itself essential to the oceanic carbon cycle.

In the current context of global change (global warming, biodiversity loss, etc.), these ecosystems absolutely must be preserved. They play a crucial role in marine food chains, feeding tuna and whales in particular, and thus indirectly influencing fishing activities. They also represent enormous potential for biotechnology.

Even before fully understanding the consequences of potential harvesting, the fishing industry is starting to take a close interest in these deep-sea fish, which are valuable to them for their essential role in feeding tuna and whales. However, scientific exploration must continue before these areas can be fished, if we are to gain a better understanding of this still mysterious ecosystem and preserve these deep-sea fish, which although strange, are nonetheless essential to marine life.

PARTNER

Institute of Biodiversity and Sustainability, Federal University of Rio de Janeiro, Brazil

From micronekton to tuna

Tuna fishing accounts for over 70% of GDP in small island countries in the Western and Central Tropical Pacific. However, this activity is threatened by global warming, which could displace or reduce tuna populations.

© IRD/F. Marsac

Tuna fishing in the West Pacific.

Tuna feed on micronekton, which are organisms of all shapes (molluscs, crustaceans, fish) measuring between 2 and 20 cm, which move through the water column, mainly between the surface and 1,000 m deep. And because tuna is a food source for humans, the challenges to micronekton in the face of the climate and various environmental variations have become objects of study and monitoring, as well as causes for concern.

According to recent studies, micronekton in the tropical zone is likely to lose between 3 and 22% of its biomass by the end of the century. If we continue on the same trajectory, by 2050, three species of tropical Pacific tuna (skipjack, yellowfin and bigeye) could move eastwards, leaving exclusive economic zones (EEZs) and moving into international waters, where they could be caught by large industrialised countries.

This geographical change could have a huge economic impact. Pacific island nations, which until now have intelligently negotiated fishing days in their EEZs among themselves, could lose up to 20% of their tuna resources and therefore, of their income. This would create a "climate injustice" for countries that are in no way responsible for climate change. In such a context, scientific documentation of this phenomenon is necessary, so that the small island countries in question can defend themselves and claim compensation.

Understanding the future behaviour of micronekton is therefore crucial, but difficult, because these organisms are not easy to observe. Current observation systems used during marine campaigns (direct trawl sampling, active acoustics, environmental DNA, video systems) offer very different representations of micronekton species and biomass.

This is why we need to deploy new, broader means of observation. Negotiations are underway to ensure, for example, that all vessels in

PARTNERS

The Pacific Community, New Caledonia

French Research Institute for Exploitation of the Sea, France

CNRS, France

UMR Entropie (IRD, University of Reunion Island, CNRS, Ifremer, University of New Caledonia), France

UMR Marbec (IRD, Ifremer, CNRS, UM, Inrae), France

UMR Lemar (UBO, CNRS, IRD, Ifremer), France

UMR GET (CNRS, IRD, UPS, Cnes), France

UMR Locean (SU, CNRS, MNHN), France

••• Recent studies have highlighted the negative impact of global warming on micronekton, an essential food source for tuna •••

the French scientific fleet automatically take acoustic measurements of micronekton in the water column whenever they move. Studies have also been launched to better understand how contaminants such as methylmercury accumulate at various trophic levels, from phytoplankton to tuna.

© CPS/É.Vourey

Micronekton caught during surveys off New Caledonia and Wallis and Futuna.

The end of the reign of the anchovy?

The Peruvian anchovy, one of the most heavily fished species in the world, accounts for up to 10% of the total catch in the best years and plays a key role in aquaculture and animal feed, thus indirectly contributing to global food security.

Head of an anchovy caught during an oceanographic campaign off Peru.

The Peruvian upwelling is the most abundant in the world, particularly for anchovies. But this might not last. As a result of climate change, the waters will become warmer and less oxygenated, which could profoundly transform the local ecosystem, according to two main hypotheses: either the fish, including anchovies, will become smaller, or their populations could collapse in favour of other smaller species, such as the goby, a fish with a high tolerance of such anoxic conditions.

This hypothesis about gobies does not come out of the blue. In another upwelling, off the coast of Namibia, overexploitation of fishery resources until the 1960s, combined with low oxygen levels, caused the ecosystem to shift towards another stable system dominated by gobies and jellyfish, two species of little economic interest. Could the Peruvian upwelling be heading in the same direction?

To answer this question, scientists analysed sediment cores and looked back in time to the last interglacial period, around 116,000 to 130,000 years ago, when environmental conditions in the region corresponded to those predicted by models for the end of the 21st century. They discovered that, during this period, anchovies were not smaller, but much rarer. And the king of the seas back then was the goby!

Does this mean that the goby is set to return to reign? Whatever the case, this possibility is being taken very seriously because it could have dramatic consequences for the local economy, as it did in Namibia. Examination of the sediment cores also shows that the extreme abundance of the Peruvian upwelling is a recent phenomenon. An anomaly which, according to scientists, will not last. *Goby or not goby*, that may not be the only question. Whatever happens, it seems inevitable that local economic activities will have to adapt.

PARTNER

Marine Institute of Peru

••• Projections suggest that Peru's marine ecosystem could be transformed by climate change, calling for adaptation of local economic activities •••

© IRD/A. Bertrand

Anchovy fishermen, Peru.

"The sustainability of Peruvian anchovy fishing is tied to the breadth of scientific knowledge, the implementation of effective regulations and the commitment of all those involved in Peruvian industrial fishing to ensure the conservation of resources and the balance of the marine ecosystem. It is an example that could be replicated in other fisheries around the world".

Eduardo Ferreyros, National Fisheries Society, Peru

PART 2

SOCIETIES FACING THE OCEAN

Small-scale net fishing in Maputo Bay, Mozambique.

© IRD/S. Duvail

Senegal: the emergence of a resilient fishing industry

Due to pressure from local and foreign fishing fleets, fish stocks along the West African coast are now considered vulnerable.

© IRD/P. Brehmer

Drying fish at Ndayane, Senegal.

PARTNERS

UNESCO Chair on "Integrated Management and Sustainable Development in West African Coastal Regions" (Cheikh Anta Diop University, Dakar), Senegal

International Joint Unit for Sustainability and Resilience (UVSQ, IRD)

In Senegal, artisanal fishing is booming: it provides 75% of West Africa's animal protein and accounts for a significant proportion of GDP. This success can be attributed to the ability to adapt and innovate shown by artisanal fishing communities, which are growing despite the rise in foreign fishing, tolerance of illegal fishing in Senegalese waters, newly established fishmeal processing industries and inefficient governance.

Historically, artisanal fishing began to rise in the 1950s and 1960s with the motorisation of boats. It continued in the 1970s with the influx of farmers to the coast, driven from inland by drought. This historical development, together with competition from foreign trawlers, increased the pressure on fish stocks, which are now considered vulnerable.

Senegalese fishermen have tried to adapt by seizing every available opportunity: first, they extended their fishing grounds as far as Angola and Mauritania, then they learnt how to preserve fish stocks, in particular by adopting the knowledge provided by the creation of marine protected areas in 2003.

••• Certain Senegalese fishermen have adopted empirical and scientific knowledge, particularly insights gained from creating marine protected areas, to better manage fish stocks •••

Community initiatives, backed by the Senegalese government, were then set up to support the establishment of these new marine protected areas. Fishermen have tried, to a certain extent, to adapt their practices to respect reproduction periods, particularly for octopus and some other species. "Community" regulations have been established in certain localities (Cayar, for example) to facilitate ecosystem restoration, by setting up quota systems respected by all.

"The vulnerability of Senegalese and West African fisheries in general no longer needs to be demonstrated, despite their competitiveness and local know-how built up over many years of recognised practice. Senegal's coastal communities, which contribute significantly to the country's food security and sovereignty, have been able to adapt to the increasing scarcity of resources. They have modernised their work tools, withstood climate shocks and, above all, developed adaptation strategies to improve fishing practices and governance in this sector. Preserving fish stocks and maintaining sustainable activity in marine and coastal ecosystems are huge challenges for sustainable development today. The problem has become complex, with the overexploitation of resources, influx of people, competition from industrial and foreign fishing, and illegal, unreported and unregulated fishing."

Alioune Kane, Cheikh Anta Diop University, Dakar, Senegal

© IRD/Ifremer/O. Dugornay

Returning from fishing in Ouakam, Senegal.

Marine protected areas, which were heavily criticised when first set up, have helped to bring about changes in fishing practices. Among women shellfish farmers, collective management practices for mudflats and mangroves were introduced, with the aim of rationalising shellfish harvesting. By becoming part of these organisational and economic dynamics, women have become aware of their role in enhancing the value of the products they farm and exporting their goods. These developments show that fishing communities have great resilience and the ability to adapt.

The future of the Vezo

Tourism in Madagascar offers many economic advantages, but it also causes environmental damage and changes local populations' way of life.

© G. Todinanahary

IOT (Indian Ocean Trepang) sea cucumber farm, Madagascar.

In trying to do good, major investment funds and NGOs sometimes make serious mistakes. This is the case with tourism development projects in Madagascar, which threaten the activities of the Vezo, a fishing people living in the south-west of the island. Marine protected areas have tripled in surface area since 2003. And this expansion of protected zones has been accompanied by the development of an ever-growing ecotourism industry: in Andavadoaka, the population has risen from 3,000 to 13,000 since 2006; and foreign hotels and restaurants have been built, gradually privatising the coastline, buying up the Vezo people's land and reducing their access to the lagoon. So much so that, at this rate, the Vezo may no longer have land on the coast in 10 to 20 years' time.

Faced with this situation, international funds and the World Bank have developed their own solutions, such as supporting the Vezo in setting up sea cucumber farms or growing seaweed for the Chinese market. These may be interesting ideas on paper, but they reveal a total lack of understanding of the local context in at least two respects. Firstly, because produce from sea cucumber farms is regularly stolen for consumption and they have to be monitored by the police. Secondly, because such a conversion radically alters the Vezo way of life, taking them from a subsistence culture to a profit-based culture. This would turn them into sea farmers, making them lose a cultural identity that is in reality inseparable from fishing.

According to the scientists, it is as if Madagascar had been colonised by a number of foreign "powers" that are using the country for their own ends, without any structuring project for local populations. They set up investment and conservation initiatives without any dialogue with local stakeholders. However, for a solution to be sustainable, it has to come from the residents themselves. So instead of developing farms dedicated to export, we should be allowing the Vezo to go fishing outside the lagoon, in the open sea, with suitable boats.

PARTNERS

University of Toliara, Madagascar

"Knowledge, Environment and Society" Joint Research Unit (UMR Sens, CIRAD, IRD, UPVM3), France

UMR Passages (CNRS, Université Bordeaux Montaigne, Université de Bordeaux, Ensap Bordeaux), France

••• Foreign investment is driving out the Vezo, a fishing people in Madagascar's lagoons •••

© IRD/M. Léopold

Traditional fishing by the Vezo at Anakao, Madagascar.

"Promoting the tourism industry, preserving marine zones and combating poverty are major issues, especially given that the Vezo people depend on the sea for their livelihood. The results of our study shed light on reality in south-west Madagascar, where Vezo fishermen testify to the harmful consequences of foreign development. Faced with extreme poverty, the Vezo are forced to give up their land. They sell their land at extremely low prices to fund their children's education or buy fishing equipment, which is gradually eroding the fishing village's reputation and raising concerns about the future of these coastal communities."

Sylvie Varellas, Tsimbazaza Zoological and Botanical Gardens, Madagascar

Alexandria, how not to adapt?

Coastal cities are particularly vulnerable to risks of marine submersion and must find ways to adapt. But public authorities still need to implement sustainable protection solutions.

© IRD/J.-F. Silvain

Alexandria Bay, Egypt.

With six million inhabitants, the city of Alexandria has been the largest coastal and port city in the Mediterranean since antiquity. It is also the most studied, with its two thousand years of human and environmental history a subject of research for many archaeologists and historians. This is an extremely valuable source of knowledge for those seeking to understand how Alexandria was able to survive, and even prosper, in such an extreme environment, characterised by difficult access to fresh water and the constant risk of submersion due to storms and tidal waves.

The first thing to note is that, over the centuries, various nearby cities were submerged, as shown by the joint discovery of Canopus and Thonis-Heracleion under the sea. Yet Alexandria was never moved or abandoned, no doubt because of the site's extraordinary potential for international trade. The city enjoys a unique and privileged location between the Red Sea, Africa and the Mediterranean. Local populations have therefore adapted to the city, despite the environmental risks.

... Though the Egyptian city has existed for two millennia in a particularly inhospitable environment, the current risks associated with marine submersion are not being taken into account ...

Alexandria's topology has also contributed to its longevity. The oldest parts are built on three rocky ridges parallel to the coast, rising to a height of 35 m. The lower, more vulnerable parts are home to working-class neighbourhoods, particularly the fishermen's districts. At least, that was the case historically. However, the city's current development on low-lying flood zones is based on a short-term vision, making Alexandria a very poor case study for adaptation.

© Wikipedia/H. Ashour

Port of Alexandria, Egypt.

The risks of marine submersion are being denied. Parts of the protective rocky ridges are being levelled off for the development of new industrial projects, and the coastline as a whole is being concreted over to create seaside resorts for the wealthy, particularly the dunes.

These policies break with a tradition of adaptation that goes back thousands of years - for example, huge underground cisterns were built in ancient Roman times to hold water from the annual flooding of the Nile - and create new risks for local populations. Environmental and climate issues are being overlooked by public initiatives, which favour more visible technical adaptation measures (breakwaters, protective walls) over developing sustainable approaches based around nature and protecting biodiversity, particularly in the dunes. The catastrophic floods of 2015 are unfortunately one of the first illustrations of this.

PARTNER

Centre for Alexandrian Studies, Egypt

Is the sinking of the Mekong Delta inevitable?

With a surface area of 55,000 km² and a population of 17 million, the Mekong Delta is the equivalent of the Netherlands, in terms of both size and population density... for now. Because the delta is sinking.

Seawater filtration for nutrient analysis, Vietnam.

By 2100, 85% of the Mekong Delta could be swallowed up by the sea. Some of this is due to rising sea levels, but much of it results from human activity in the area. To explain in more detail, from a geomorphological point of view, the Mekong Delta resembles a mille-feuille of alternating layers of mud and waterlogged sand. This geological structure is subsiding and becoming denser, especially because local residents are drawing too much water from it.

The more groundwater is extracted via wells, the higher the rate of subsidence. This phenomenon is further exacerbated by the sometimes-illegal extraction of sand for use in construction and reduced supply of alluvial deposits, stored upstream by numerous dams.

••• Studies have outlined adaptation strategies to ensure that most of the Vietnamese delta does not end up under water •••

For some years now, the Mekong Delta has been one of the most vulnerable areas in the world, sinking by 2 cm per year while sea levels rise by only 3 to 4 mm. However, as the predicted submersion

"The Mekong Delta is a vital region for Vietnam, home to 17.4 million people. While groundwater extraction is the main cause of sinking ground (subsidence) in this area, local communities believe that other factors are also key. Studies carried out in the field of hydrology and hydrogeology by the Asian Centre for Water Research are very useful for identifying and prioritising these factors, as well as developing optimal paths for adaptation, thus ensuring the delta's long-term resilience."

Ha Quang Khai, Ho Chi Minh University of Technology, Vietnam

© IRD/J.-M. Boré

Ho Chi Minh City, on the banks of the Saigon River, Vietnam.

is mainly caused by urbanisation and other human activities, it can be counteracted. Because what humans do, they can also sometimes undo.

Research shows that controlling or reducing the amount of water pumped from the aquifers could lessen or even halt the sinking of the delta, which is currently shrinking by 12 m every year. All that remains now is to identify and remove the social, technical and political obstacles to resilience, adaptation and even survival. The stakes are high, because this phenomenon is affecting other cities located on deltas - such as Jakarta, which is sinking so fast that the Indonesians have already decided to move their capital 2,000 km to the island of Borneo, destroying part of the forest in the process.

PARTNERS

CARE International Joint Laboratory (Ho Chi Minh University of Technology, IRD, INP Grenoble)

Ho Chi Minh University of Technology, Vietnam

Reducing vulnerability in the city of Douala

Most of the major cities in the Gulf of Guinea are highly attractive economic capitals undergoing rapid development. As such, there are many major human, socioeconomic and environmental issues.

© Wikipédia/J.-N. Konda Yansa

Aerial view of Douala, Cameroon.

Douala is the economic capital of Cameroon. It attracts many young people (students, job seekers, entrepreneurs) and up to 100,000 new migrants every year. Not only does this attractiveness have a direct impact on the environment, but it also affects the city's vulnerability to flooding and marine submersion. Douala is on the coast, with 20% of the area less than 5 metres above sea level. Parts of the city are submerged several times a week with the tides, but also several times a year due to rainfall, one of the highest in the world - the city receives 4,500 mm annually.

• • • A research-action project is proposing practical solutions to reduce the risk of flooding and marine submersion in Douala • • •

However, due to a lack of housing, many new migrants build makeshift dwellings in the lower parts of the city, in wetlands that are normally undevelopable and open to the sea, since the mangroves are no longer there. Around 200,000 households, almost one million people out of the city's five million inhabitants, are in this situation. This was the impetus for a pilot project in the Tongo Bassa catchment area. The objective is to model the area's hydrology in great detail to produce maps of physical and human vulnerability. This meticulous work, which has now been incorporated into the city's planning documents, has shown that in some areas, water can rise by 2.5 metres in six hours.

At two sites that are most exposed to flood risks, solutions such as setting up an early warning system to facilitate evacuation, creating assembly points and establishing a crisis unit that includes the prefect and mayor have been proposed to local authorities. In response, roads have been upgraded and studies are continuing to determine

PARTNERS

University of Douala, Cameroon

Philia Ingénierie, France

University of Quebec at Rimouski, Canada

Association for Research on Ocean-Continent-Atmosphere Interactions, Cameroon

Douala Urban Community, Cameroon

©Wikimedia/Njehoyab

A crossroads in Douala at the height of the rainy season, Cameroon.

the appropriate alert thresholds. In the long term, however, residents of these areas will have to be relocated. This is why other recommendations have been made, such as finding ways to impose vertical development through regulation. The need to regenerate natural barriers, such as mangroves, has also been highlighted. A test of this kind is currently underway on 5 hectares of Manoka Island.

Food security in Polynesia

Climate change is making French Polynesia more vulnerable, affecting food security in particular. It is therefore necessary to implement adaptation strategies.

© IRD/S. Andréfouët

Parrotfish fishing in Reao, French Polynesia.

As a result of climate change, extreme weather events are expected to become increasingly destructive, particularly in French Polynesia. But of far greater concern to local populations are the insidious and irreversible changes that are gradually altering ecosystems and threatening their livelihoods.

In the lagoons, for example, the gradual rise in water temperature is leading to the death of coral reefs, creating an environment conducive to the proliferation of toxic microalgae. The *Gambierdiscus toxicus* endemic algae is known to cause a severe form of food poisoning, ciguatera. It secretes ciguatoxins that contaminate fish and make them unfit for consumption, without it being visible to fishermen or consumers. This has resulted in an increase in the intensity and frequency of poisoning episodes, which is causing Polynesians to avoid eating fish from the lagoon. They therefore turn to other sources of food, produced in Tahiti or imported, increasing food dependency in the islands.

• • • The growth of a toxic microalgae is threatening the food security of people living in Polynesia • • •

However, fishermen and local communities have long developed detailed knowledge of contaminated fishing grounds and the most ciguatoxic species, in order to prevent poisoning. In insular environments, where community links exist, this information can be easily circulated to limit the risks of poisoning. The local knowledge of Polynesians is therefore a key factor in allowing these populations to adapt to climate change.

Ciguatera is a major issue for most Pacific territories, for which specific measures are required (development of inshore and offshore fishing, support for local food production) to help guarantee food security during outbreaks. This will reduce the vulnerability of local residents to food shortages.

PARTNERS

Louis Malardé Institute, French Polynesia

"In regions affected by major endemic diseases, people's often fatalistic attitude to the risk of ciguatera explains the remarkably high number of cases of fish poisoning reported each year. It is therefore essential to draw on ancient traditional knowledge used within these communities to better manage the health and socioeconomic impacts of this foodborne illness, ensuring greater acceptance of preventive measures implemented by authorities."

Mireille Chinain, Louis Malardé Institute, French Polynesia

© IRD/P. Marmey

Tahaa Lagoon, French Polynesia.

The role of women in fishing

Throughout history, women's contributions have been systematically underrepresented or obscured by male-dominated narratives. What was true in the past is still true today.

© IRD/A. Burgos

Gathering mangrove bivalves in Sarausau, Indonesia.

PARTNERS

WorldFish, Malaysia

National University of East Timor, Indonesia

National Research and Innovation Agency, Indonesia

University of Papua New Guinea

Food and Agriculture Organization of the United Nations, Italy

In the mangrove swamps of the Pacific, men devote themselves to raising livestock and hunting, while women contribute to meals by fishing and gathering invertebrates (prawns, crabs, shellfish, etc.) from the shore. A discreet but fruitful practice. The effectiveness of fishing techniques used by women in villages close to reefs in East Timor and Papua New Guinea is a case in point. Combined with a wide range of socioecological knowledge, these practices enable them to collect more than 220 species of marine invertebrates from mud, mangrove roots, coral reefs and under rocks. Some are used for food, others for ornamentation, for sale or for children's games.

This fishing is far from anecdotal; it is one of the keys to local food security, thanks to the high nutritional value of the species collected, which make a major contribution to the nutritional balance of the local community. However, this activity is not at all accounted for or recorded by systems for quantifying or managing fish stocks. In the official statistics, this subsistence fishing simply does not exist. It is invisible, as is the essential role played by women who are considered to be "homemakers" when in fact they are fisherwomen.

For the moment, at least. In Timor, the creation of marine protected areas in women's traditional fishing grounds is threatening these valuable cultural practices. Because of the distance they now have to travel to collect molluscs, crabs and other marine invertebrates, the village women are gradually giving up this practice and turning to manufactured products with little nutritional value. On top of the nutritional deficit, this phenomenon threatens to wipe out valuable knowledge and skills. Steps are being taken to recognise the significance of these fisheries and ensure fair access to aquatic resources.

... In the Pacific, fishing by women plays a predominant but largely underestimated role ...

© IRD/A. Burgos

Shellfish harvesting in Limonak, Papua New Guinea.

Nokoué, a lagoon under pressure

Nokoué Lagoon in Benin is under increasing pressure from pollution, overfishing and urbanisation. These threats damage the biodiversity of this natural area and adversely affect the quality of life of local residents.

© IRD/F. Tremege

Drinking water supply in Ganvie, a town on the edge of Lake Nokoué, Benin.

Since the late 19th century, Nokoué Lagoon has undergone major changes due to human activity. In 1885, a channel dug by the French to alleviate flooding in the city of Cotonou linked the lake to the Atlantic Ocean, allowing saltwater to enter and transforming it into a lagoon. With a surface area of 150 km^2, the lagoon also receives freshwater from two rivers that drain a watershed of 5,000 km^2, one of the most fertile in Africa.

Today, almost 1.5 million people live near Nokoué Lagoon and depend on it, particularly for fishing. However, it is threatened by silting that is increasing over time, reducing its average depth to 1.3 m in the dry season. In addition, urban waste and effluent from large nearby villages contribute to the deterioration in water quality.

••• An environmental observatory has been set up to explore the functioning and fragility of Nokoué Lagoon in Benin •••

Faced with these issues, a multidisciplinary observatory was set up in 2018 to better understand the hydrosedimentary functioning of Nokoué Lagoon and identify some of its vulnerabilities. It appears that, during monsoon season, the large influx of freshwater creates a 1 m rise in the water level, leading to rapid and complete desalination of the lagoon. It then takes several months for salinity to return to significant levels during the dry season, meaning that the aquatic ecosystem undergoes major changes from one period to another.

Based on these observations, a digital model was developed to simulate exchanges between fresh and saltwater, reproduce variations

PARTNERS

UMR Lemar (UBO, CNRS, IRD, UT3), France

Benin Fisheries and Oceanological Research Institute

Centre for Research and Teaching in Environmental Geosciences, France

"Ongoing monitoring of the lagoon ecosystem, in collaboration with IRD, aims to improve the living conditions of local populations and respond to a longstanding request from Benin. The creation and maintenance of such an observatory will overcome the limitations of previous sporadic studies and support the country's sustainable development objectives."

Zacharie Sohou, Benin Fisheries and Oceanological Research Institute

© IRD/A. Chaigneau

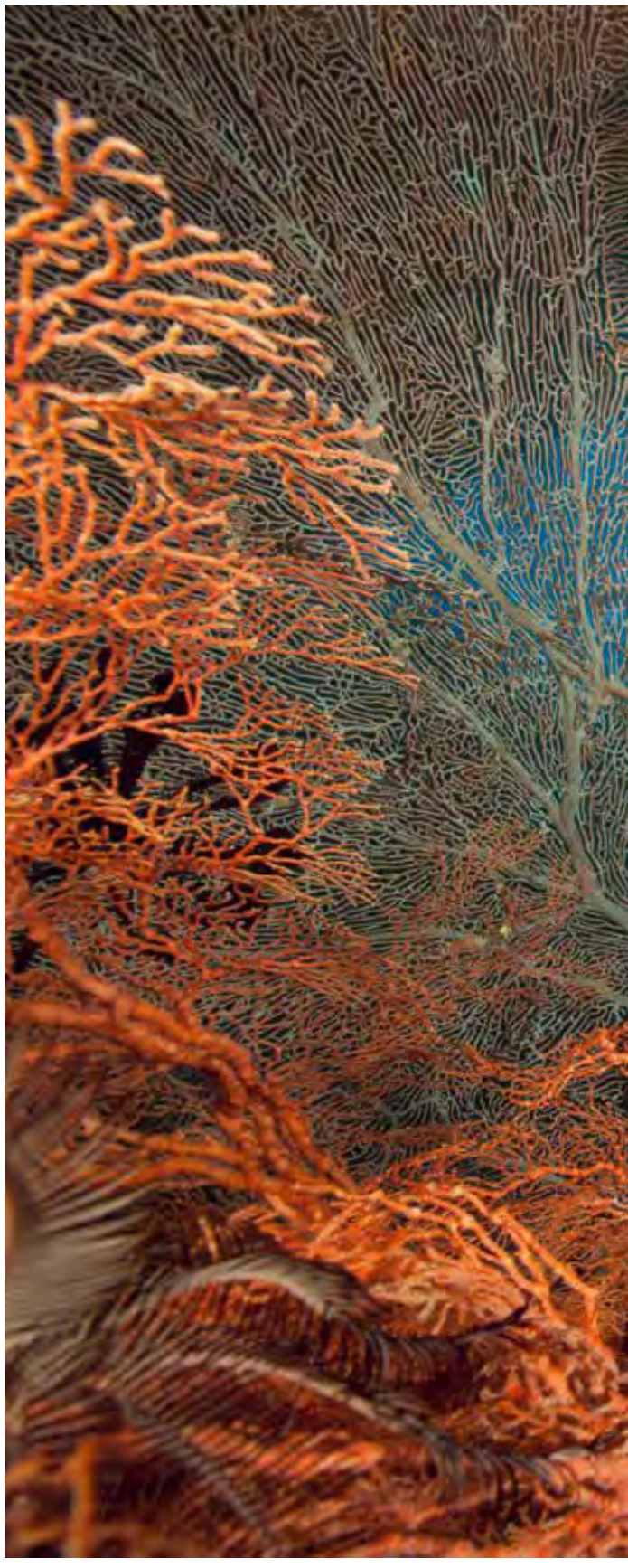
Installation of a brush park (*acadja*): when fishing shapes the lagoon. Lake Nokoue, Benin.

in water levels and assess how long pollutants stay in the lagoon. It revealed that pollutants accumulate during the dry season and are massively and rapidly discharged into the ocean during the rainy season.

In addition, the lagoon is filling at a rate of around 1-2 cm per year in some areas. This sedimentation is due to alluvial deposits, the accumulation of organic matter encouraged by the proliferation of water hyacinths and the gradual decomposition of branches used to create fishing areas, which cover more than 15% of the lagoon. Results of this work will enable scientists to gain a better understanding of the lagoon's response to possible developments or different climate change scenarios.

PART 3

TOWARDS SUSTAINABLE RESOURCES



Diver exploring the coral reef, West Papua, Indonesia.

© IRD/E. Bahuet

A plankton model

Plankton accounts for 80% of ocean biomass. However, it is still relatively poorly understood and modelled. These gaps in understanding are problematic when it comes to projecting the evolution of marine ecosystems, as planktonic organisms are at the base of the entire food chain.

© PlanktEco

Plankton under the microscope.

The term plankton comes from a Greek word that means "wandering". It refers to a world within a world, one that allows itself to be carried along by the currents. However, that does not mean it is passive - far from it. Because behind this word lie microscopic plants (phytoplankton) and tiny grazing and predatory animals (zooplankton). Together, they form the basis of ocean food chains. It is therefore important to understand how they function, their ecological role and the factors that determine their development.

One current approach is based on modelling. Scientific teams are seeking to model the physiology, behaviour and evolution of plankton biomass and its role in the functioning of a fish ecosystem off the coast of Senegal, which supplies a large part of West Africa with sardinella.

To achieve this, the scientists have developed four different models: the first reproduces the region's physical functioning, the dynamics of temperature and currents; the second looks at biogeochemical dynamics, from nutrient salts to phytoplankton; the third simulates zooplankton and fish, including sardinella; and the fourth represents the socioeconomic processes that determine sardinella fishing. By linking these four models, it will be possible to reproduce the entire chain of processes and deduce the societal impacts of ongoing climate change or overfishing, for example. This is what makes the approach unique.

The importance of each model will be assessed and validated using observations gathered during oceanographic campaigns. This modelling work will make it possible to regionalise and refine the predictions of the Intergovernmental Panel on Climate Change (IPCC) based on large-scale, low-resolution simulations, and thus better anticipate the local repercussions on an ecosystem and fisheries of great socioeconomic importance to the region.

PARTNERS

Tara Ocean Foundation, France

French Facility for Global Environment, France

CNRS, France

Oceanographic Research Centre of Dakar-Thiaroye, Senegal

••• The development of four interlinked models will make it possible to reproduce the functioning of the marine ecosystem off the coast of Senegal and deduce the socioeconomic impacts of certain processes, such as resource overexploitation or global warming •••

© IRD/Y. Thomas

Small-scale fishing in Djiffer, Senegal.

Tropical tuna under surveillance

Excessive development of fishing practices using artificial floating objects could threaten populations of tuna and other vulnerable marine species caught accidentally.

© IRD/J.-P. Hallier

Tuna fishing vessel using FADs, Seychelles.

Any object floating on the surface of the ocean is likely to attract tropical tuna. In the early 1990s, this observation led fishermen to use artificial floating objects ("fish aggregating devices" or FADs) to concentrate fish and catch them more easily with large sliding nets called seines, which encircle shoals of fish. This undoubtedly increases their catch, but it also raises concerns about the sustainability of tuna resources and the environmental impact of this practice.

Research has confirmed that FADs tend to concentrate young fish (juveniles) for yellowfin and bigeye tuna, which have life spans of around 15 years. This could have harmful consequences for these two populations. However, a lack of knowledge about the natural mortality of juvenile fish prevents us from having a clear idea of the real impact of this method of fishing. Fishing with FADs also generates the most bycatch of non-target and vulnerable species, such as sharks, rays and swordfish. Some are kept on board and others thrown back, usually dead.

••• Data on tropical tuna fishing, collected since the late 1960s, can be used to measure the environmental impact of this fishery and changes in tuna populations •••

Since French fishing vessels began catching tropical tuna in the late 1960s, the Observatory of Exploited Tropical Pelagic Ecosystems has been mandated to collect and verify commercial data from French vessels operating in tropical waters, in collaboration with fishing professionals and partners in the Global South. Fishing data is collected from fishermen's logbooks, which record fishing locations and dates, catch by species and fishing method used (FAD or open shoal).

This information is corrected and validated by catch samples taken when fishing vessels land, as well by scientific observers regularly taken

PARTNERS

Oceanology Research Centre, Côte d'Ivoire

Oceanographic Research Centre of Dakar-Thiaroye, Senegal

Seychelles Fishing Authority

Ministry of Fisheries and the Blue Economy, Madagascar

International Commission for the Conservation of Atlantic Tunas

Indian Ocean Tuna Commission

Spanish Institute of Oceanography

Institute of Fisheries Science and Technology, Spain

"The lack of knowledge about the number of fish aggregating devices (FADs) used each year by fishing vessels leads to major uncertainties in stock assessments. FADs are therefore an important and topical research theme for developing countries, whose leaders need scientific advice if they are to respond effectively to the challenges of sustainable development."

Justin Monin Amandé, Oceanology Research Centre, Côte d'Ivoire

© IRD/T.Vergoz

FADs ready for use, Seychelles.

on board, who add observations on bycatch and accidental catch. Electronic observation methods can also sometimes complement human observation. This data is used by scientists at regional fishery management organisations to assess the state of tropical tuna stocks and certain species caught accidentally, and to measure the environmental impact of this fishing, although they have not yet been able to exactly quantify the FAD effect. Watch this space...

Towards more sustainable baits

Tuna, a major resource in the world's oceans, is caught mainly by two types of fishing equipment: pelagic longlines and purse seine nets. These two techniques have a similar economic weight and a large environmental footprint.

© IRD/P. Bach

Artificial baits filled with fishing waste to replace whole natural bait, Reunion Island.

Pelagic longline fishing involves setting a line, sometimes over 100 km long, with up to 4,000 hooks. Each one carries natural bait (mackerel, sardine or squid) to catch large fish (such as tuna or swordfish). However, sometimes protected species - turtles and marine mammals - or seabirds are caught accidentally. And that is not the only flaw of this method.

Worldwide, it is estimated that this type of fishing uses 600,000 to 800,000 tonnes of marine resources each year, which could be consumed by humans instead of being used as bait. The amount of waste is all the greater given that only 5 to 10% of this bait is actually successful in catching the target fish species. The rest is thrown back into the sea. Plus, the cost of bait is always increasing, and it has to be kept frozen both on land and at sea, which represents a significant expense.

Artificial and reusable lures are emerging as sustainable alternatives to natural bait. A first step in this direction was made with the development of the first eco-friendly artificial bait, which was tested and then patented. In practical terms, it is a semi-rigid, reusable shell made from a bio-based polymer and filled with fish waste pulp.

Trials have been encouraging, showing that this bait can catch tuna and swordfish while avoiding protected species. But acceptability surveys among fishermen have led to the project being abandoned, as it would require changes to fishing equipment that would likely reduce yields. Furthermore, though the shells are reusable, they contribute to plastic pollution.

A new concept is proving more promising: fish- or squid-shaped bait made from a silicone-type paste made from protein waste and food texturisers. Already being tested by fishermen in mainland France and Reunion Island, this alternative bait could be on the market by 2028.

PARTNERS

Polytech, University of Montpellier, France

School of Engineering, University of Reunion Island, France

Fiiish, France

••• Alternative baits are being researched to reduce the environmental impact of longline fishing •••

School of yellowfin tuna, Seychelles.

"Thanks to the efforts of professional fishermen in our organisation of producers promoting ethical fishing, as well as longstanding scientific partnerships, sustainable alternatives are emerging: reusable bait made from marine waste offers a new way of preserving ecosystems, while responding to the needs of the tuna industry. Let's work towards using the oceans more responsibly!"

Nolwenn Cosnard and Bertrand Wendling, SATHOAN, France

The birds' share

Between sustainable fishing and overfishing, it is a matter of numbers. What is the acceptable catch limit to allow the renewal of fish stocks and the maintenance of the rest of the ecosystem, particularly seabird populations? That is the question.

© IRD/P. Fréon

Anchovy fishermen hauling in their nets north of Lima, Peru.

How does overfishing of anchovy and sardine stocks impact the reproductive success of seabirds? This question has long remained without a satisfactory answer. The data available only demonstrated this impact in a very localised way and was not enough to convince local authorities to reduce catch limits.

To overcome this difficulty, an international scientific network has pooled global data from 20 to 40 years of monitoring seabirds and caught fish, and analysed correlations between fluctuations in the sizes of these two populations. The results clearly demonstrate that there is a catch threshold above which the reproductive success of seabirds is affected. In addition, by comparing data from seven marine ecosystems in the Arctic, Antarctic, Pacific and Atlantic, covering 14 bird species and 483 years of cumulative observations, scientists found that the reproductive success of birds declines when the abundance of forage fish is below a certain threshold (one third of maximum abundance observed over the long term). Sardine and anchovy fisheries should therefore limit their catches and not fish around nesting areas.

The correlation established provides a reliable indicator for fisheries management. This threshold has since been incorporated into various

"In South Africa, ecosystem-based fisheries management has resulted in 'a third for the birds'. A recent study has catapulted global thinking in this area, and made it possible to propose meaningful, science-based catch limits for forage fish. This will protect predators and the overall functioning of the ecosystem. In a fisheries management structure that has long been protected by single-species approaches which have become restrictive and overcomplicated, this work has provided a basis for a refreshing, more holistic way of thinking at the ecosystem level."

Lynne Shannon, Marine and Antarctic Research Centre for Innovation and Sustainability, University of Cape Town, South Africa

••• Sharing international data has made it possible to review the optimum catch level for sardines and anchovies •••

An Atlantic puffin with anchovies in its beak, Isle of May, Canada.

fisheries management policies around the world (South Africa, Australia, New Zealand, United States), enabling the implementation of an ecosystem-based approach to fisheries and helping reconcile the exploitation of marine resources with the protection of marine biodiversity.

PARTNERS

Marine and Antarctic Research Centre for Innovation and Sustainability, University of Cape Town, South Africa

Ministry of Fisheries and Marine Resources, Namibia

Lüderitz Marine Research Centre, Namibia

Farallon Institute for Advanced Ecosystem Research, USA

Stockholm Resilience Centre, Stockholm University, Sweden

British Antarctic Survey, United Kingdom

Artisanal fishing on an industrial level

In the countries of the Global South, artisanal fishing is both a source of protein and of income. But, just like industrial fishing, it exerts significant pressure on fish stocks, particularly in Peru.

© IRD/A. Bertrand

Tropical fish caught by an artisanal flotilla off the coast of Paita, Peru.

Artisanal fishing is reputed to be less harmful to marine ecosystems - or at least, it appears to be. However, the reality is sometimes more nuanced, particularly in Peru. In this country, industrial fishing is very tightly supervised and regulated. In contrast, artisanal fishing is erratic, heterogeneous and poorly regulated, despite the fact that it is an essential sector, providing tens of thousands of jobs and protein for the population.

In the absence of regulations, since 1996, the Peruvian government has continuously monitored landings and, in some years, carried out major surveys on the activity and level of education of fishermen working along the 3,000 km Peruvian coastline. Some 3.5 million logs have been collected through these efforts. French and Peruvian research teams have analysed this wealth of information to develop knowledge on the 270 species fished.

••• Multiple studies have shown a risk of collapse in Peruvian fish stocks •••

The conclusions are concerning. Between 1997 and 2016, the number of artisanal boats rose from 6,200 to 16,000, and catches from 200,000 to 1.2 million tonnes per year. By way of comparison, the entire French fleet only catches around 500,000 tonnes of fish per year, all seas and species combined.

This rush to the sea accelerated following changes in legislation and the introduction of quotas per shipowner for industrial fisheries, leading to a drastic reduction in the number of industrial vessels. Under these sidelining measures, many fishermen have reverted to artisanal fishing, significantly increasing the pressure on fish and giant squid stocks.

PARTNER

Marine Institute of Peru

"Peru urgently needs to improve the management of artisanal fishing, which is unregulated and oversized, threatening species sustainability and the country's food security, on top of climate change. This excessive artisanal fishing is a result of the 2003 decentralisation law, which gives regional governments (GORE) fisheries management powers, enabling them to grant licences for all fishing methods, whether on boats or otherwise, and for all species. Measures to remedy overfishing include: (1) creating a fisheries and aquaculture superintendency that would take back control of fisheries granted to GOREs; (2) a new census of artisanal fishing; and (3) formalising the artisanal fleet. The Peruvian government is making progress in these areas, while improving cross-sectoral fisheries control and inspection initiatives."

Mariano Gutierrez, Humboldt Institute for Marine and Aquaculture Research, Peru

© IRD/A. Bertrand

Fishermen catching small coastal fish in the port of Paita, Peru.

This is a cause for concern given the high level of environmental variability that characterises this part of the world, as well as climate change, which could ultimately lead to a collapse in the system's productivity. These results highlight the urgent need to implement measures to limit fishing, which has not been possible to date for fear of violent social unrest.

Food biodiversity

In countries of the Global South, malnutrition is common and could become even more acute as a result of climate change and the increasing scarcity of commonly consumed foodstuffs.

© IRD/F. Sardenne

Ethmalosa (or bonga) caught in Corisco Bay and then smoked, Gabon.

© IRD/Ifremer/O. Dugornay

Smoking fish, Senegal.

In Côte d'Ivoire, Senegal and Gabon, around 20% of the population suffers from a deficiency in iron, iodine, zinc or omega-3. It is therefore important to study local food resources such as seafood, which is rich in omega-3, vitamins and minerals, especially as culturally, it is very popular: 40-60% of animal protein consumed locally comes from fish.

In 2022, a research project was launched to better assess the nutritional qualities of the fish and shellfish consumed, particularly after drying or smoking, two common conservation techniques. Traditional smoking appears to be a way to preserve some of the light-sensitive nutrients such as vitamin A and omega-3, whereas drying does not achieve this. However, surprisingly, drying reduces the arsenic content of certain fish.

Regarding the species themselves, small forage fish (used to produce meal or oil for the international market) such as sardinella and ethmalosa are high in omega-3 and vitamin A, although levels vary according to season and region. Studies have also shown that there is little heavy metal contamination in the regions studied. Industrial exploitation is therefore a real loss for local populations. Shellfish, on the other hand, are rich in minerals (iron, calcium, zinc) but contain little omega-3. They can therefore be used to complement fish in order to reduce dietary deficiencies.

"This research is essential in Gabon, where average annual fish consumption is around 40 kg per capita, one of the highest in Africa. Furthermore, overfishing, climate change and the related consequences of possible species redistribution are paired with an increase in local demand. Identifying new species to meet local demand for protein in terms of quantity and quality is a national priority."

Jean-Hervé Mvé Beh, Ministry of Water and Forests, Gabon

••• The use of diversified marine resources is a good way to improve food quality for people in Central and West Africa •••

© IRD/M. Cormier-Salem

Selling prawns, oysters and ark clams at the Boucotte market, Senegal.

Research is now focusing on identifying marine species that are both edible and present little contamination, but which are still rarely consumed. The aim is to broaden the range of resources available so that local populations are less dependent on species that are vulnerable to environmental changes linked to overfishing and climate change. Eventually, this information will be passed on to management or national bodies so that they can adapt fish stock leaders, as well as communicate more effectively on the species that would be beneficial for locals to add to their diet.

PARTNERS

National Centre for Scientific Research and Technological Development, Gabon

Oceanology Research Centre, Côte d'Ivoire

Oceanographic Research Centre of Dakar-Thiaroye, Senegal

Aquaculture for better nutrition

Aquaculture species are rich in essential nutrients. However their nutritional value is not always considered account in aquaculture development and management strategies. Integrating this approach is crucial to meeting the dietary needs of populations.

© IRD/M. Darias

Sea urchin fed on *Ulva* seaweed in an integrated multi-trophic aquaculture farm, South Africa.

In many regions, aquaculture is primarily managed based on economic objectives, without fully harnessing its potential to improve the food security and well-being of populations. A recent scientific partnership between South Africa and France aims to lay the foundations for an approach to aquaculture that improves nutrition in the region.

The goal is to ensure the production of a diverse range of affordable, nutritious, culturally appropriate and safe aquactic foods, in sufficient quantity and quality, to sustainably meet the dietary needs of populations.

••• A research and training programme aims to develop nutrition-sensitive marine aquaculture in Africa •••

One area of research focuses on evaluating the nutritional composition of aquaculture species to guide production choices not only based on yield but also on their nutritional quality. An initial study analysed the nutritional composition of marine species farmed in South Africa – fish, shellfish and seaweed – as well as their by-products, in order to quantify the nutrient contribution provided by national marine aquaculture production.

The results show that these species are rich in essential nutrients and make a significant contribution to recommended intakes of omega-3 fatty acids, vitamins B12 and D, selenium, iodine and zinc. However, each species has a specific nutritional profile, highlighting the need for a diversified diet to meet overall nutrient requirements.

PARTNERS

Department of Forestry, Fisheries and the Environment, South Africa

Cape Peninsula University of Technology, South Africa

University of Cape Town, South Africa

"Research conducted within the framework of the African Interdisciplinary Laboratory for Sustainable and Nutrition-Sensitive Marine Aquaculture (International Joint Laboratory Limaqua) serve as an inspiring example of how a nutrition-sensitive approach to aquaculture can sustainably transform aquatic food systems. Beyond traditional economic objectives, this approach fully integrates the nutritional value of farmed species, thereby guiding the evolution of aquaculture towards optimising its nutrient contribution."

Brett M. Macey, Department of Agriculture, Forestry & Fisheries, South Africa

© IRD/P. Brehmer

Aquaculture course for a group of women in Dakar, Senegal.

The study also showed that by-products (heads, bones, viscera) are very rich in nutrients, and their reintegration into the food supply chain would significantly increase nutrient intake (+144% on average for the nutrients and species analysed).

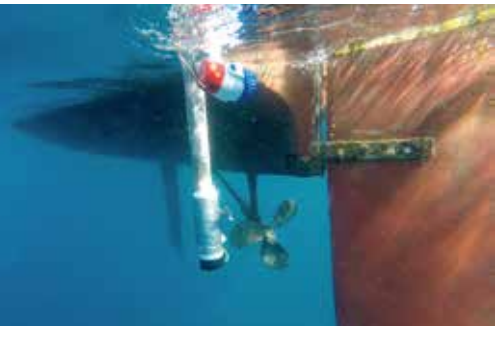
These findings emphasize the importance of considering the nutritional value of species in aquaculture development and management strategies and exploring innovative solutions to utilize by-products. Such an approach is crucial to sustainably meeting the dietary needs of populations and enhancing their well-being.

Gathering data by sailboat

An oceanographic campaign has succeeded in collecting data from non-research vessels (sailboats, dugouts, ferries), paving the way for low-carbon, low-cost marine exploration.

© IRD/E. Machu

Doctoral student checking measuring equipment before deploying it from the pirogue, Senegal.



© IRD/E. Machu

Boom fitted with measuring equipment on a sailing boat, Senegal.

Senegal's national dish is Thieboudienne, a mixture of rice, vegetables and fish, often large sardines known as sardinella. Every year, 400,000 tonnes of sardinella are caught for regional consumption. However, since 2008, Senegalese consumption has been halved in favour of processing the fish into oil and flour for export to Europe and Asia. This is undermining the food balance of local populations and raising concerns about the state of sardinella stocks, as fishing of this species is either unregulated or poorly regulated.

Furthermore, the physical functioning of the area is both complex and poorly understood. Over the last twelve years or so, several oceanographic campaigns have been implemented, each with a specific objective: to gain a better understanding of the massive upwelling of nutrient-rich cold water; to analyse the ecosystem, and in particular the plankton that forms the basis of the sardinella diet; and to collect fishing data. In 2015, a physical measurement campaign was set to begin, but due to a lack of funding, it had to be scaled back and low-cost alternatives sought. Sensors were installed on a single sailing boat to collect physical data (temperature, salinity, current) and biogeochemical data (oxygen, nutrients, plankton communities, biodiversity) on the southern Senegalese plateau and in the Sine Saloum and Casamance estuaries. Regular transects were carried out, not over two or three weeks as during oceanographic campaigns, but throughout the whole year, in order to cover the region's seasonal variability.

Collaborations were also launched with fishermen to equip their dugouts with data sensors. In the same vein, a ferry called the Diambogne, which runs between Dakar and Ziguinchor, will also be collecting data. These measures will provide a wealth of information, particularly for shallow areas (< 15 m) that are never explored by large oceanographic vessels. The low-cost approach has proved very interesting and opens the way to a new kind of low-carbon marine exploration for collecting data in coastal environments.

PARTNERS

Higher Polytechnic School, Cheikh Anta Diop University, Dakar, Senegal

Assane Seck University, Ziguinchor, Senegal

Higher School of Engineering Science and Technology, Amadou Mahtar M'Bow University, Senegal

••• Regular data collection by a sailing boat off the coast of Senegal has offered a better understanding of ocean dynamics •••

© IRD/V. Turmine

Seine fishing for *Sardinella Aurita* off the coast of Joal, Senegal.

Swimming over underwater habitats

When it comes to environmental observation, data is often lacking. To assess the health of coastal ecosystems, we need better monitoring of variations in shallow ocean habitats, such as coral reefs and seagrass beds.

© IRD/P. Dupont

Mapping of coastal marine habitats using very high resolution remote sensing, west of Grande-Terre, Mayotte.

In a few years' time, it will be possible to map the habitats in a seagrass bed or coral reef in less than an hour! At least, that is the vision of a scientific team based in Reunion Island, which is developing new methods for mapping areas in the ocean's shallow waters, particularly coral reefs.

These areas are teeming with diverse habitats that are not always easy to describe or monitor as they evolve. High-resolution satellite images can be used to detect habitats, but are not sufficient to produce reliable maps on their own, even if the water is clear.

Hence the idea of combining approaches and supplementing satellite imagery with underwater videos, taken 1 to 2 metres below the surface by a diver swimming over the coral reef, equipped with a GPS tracker and propelled by a sea scooter. The huge quantity of video thus obtained is then analysed using an artificial intelligence model which, once trained, will interpret and classify the images to produce a high-resolution habitat map. A first!

In Mayotte, this method was used to map the habitats of a reef that was very close to the beach and therefore impossible to assess by boat. The results show that the algorithms are able to classify certain

"The project is a fantastic opportunity to capitalise on our marine environment expertise in collaboration with IRD, to develop innovative R&D tools that meet the growing expectations of managers of marine protected areas. By integrating the cumulative pressures from land and sea, our results will help better plan and preserve coral reefs, which is essential for the sustainable development of island territories."

Alexandre Sneessens, Créocéan Océan Indien, France

IRD/D. Theuerkauff

Underwater photography with camera and high-resolution positioning system, east of Grande-Terre, Mayotte.

habitats with over 90% reliability. Such an approach could therefore make it possible to monitor variations in habitats from one season to the next and, consequently, the evolution of coral ecosystems or seagrass beds over time.

••• A new, inexpensive approach, combining satellite imagery, underwater video and algorithms, is helping to speed up the mapping of coastal habitats •••

Eventually, this mapping technique could be carried out automatically by underwater drones. It is inexpensive, and would enable all countries to monitor the health of their coastal ecosystems at a low cost. As we know, these ecosystems are particularly vulnerable to the impact of human activity, whether fishing, tourism, transport or climate change.

PARTNERS

Créocéan Océan Indien, France

Mayotte Marine Natural Park, France

University of Mayotte, France

Shining a light on invisible biodiversity

Based on technology that has been in use for over twenty years, the study of DNA fragments left behind by organisms in the environment is undergoing unprecedented development thanks to a revolution on two fronts - microelectronic and digital.

Damselfish and coral, New Caledonia.

Anyone who has ever seen a detective show knows: we leave traces of DNA behind us. Not only is it useful for cracking cases, but it can also help when studying marine ecology. Because, just like criminals, aquatic organisms release fragments of DNA into the environment. This genetic material, known as environmental DNA (eDNA), can be recovered from the water and analysed by scientists to get an idea of marine biodiversity - at least in theory.

In reality, this "soup" contains mainly the eDNA of the most abundant species, such as microscopic plankton. Finding rarer species, such as fish, dugongs or sharks, is like looking for needles in a haystack. But advances in microelectronics (miniature sensors built into sequencers) paired with developments in digital technology (bioinformatics and artificial intelligence) have changed the game.

It is now possible to very quickly detect species that were previously difficult to observe using traditional approaches (diving, video), either because they are rare or because they cannot be distinguished from other species with the naked eye. While much remains to be done, including identifying the DNA of thousands of marine species, this genetic revolution opens up a whole range of applications, particularly for ecosystem managers.

"In an area with one of the greatest degrees of biodiversity on the planet, environmental DNA technology represents a way forward for the study, conservation and management of our maritime space. This work by IRD is essential both for the management of our reefs, which are listed as a World Heritage Site by the United Nations Educational, Scientific and Cultural Organisation (UNESCO), and for the development of tools to rapidly detect species of interest such as sharks."

Emmanuel Coutures, Sustainable Territorial Development, Southern Province of New Caledonia, France

••• Studying environmental DNA is now making it possible to detect previously invisible species and get a better idea of an ecosystem's biodiversity •••

© IRD/K. Bussone

Taking marine surface samples for analysis, New Caledonia.

Studies carried out in New Caledonia have shown that this approach can detect 44% more shark species than traditional methods. Continuous analysis of eDNA in the lagoon's water could be used to create a brand new surveillance system capable of detecting the presence of sharks in a matter of hours. Clearly, this would reduce the risk of attacks.

eDNA analysis has also made it possible to compare the ecological diversity of seamounts, depending on their depth. Scientists have shown that the shallowest of these (50-100 m) are home to a high number of large predatory fish species, which are threatened by human activity everywhere else. It is therefore vital to protect these refuge ecosystems.

PARTNERS

Government of New Caledonia, France

Southern, Loyalty Islands and Northern Provinces, New Caledonia, France

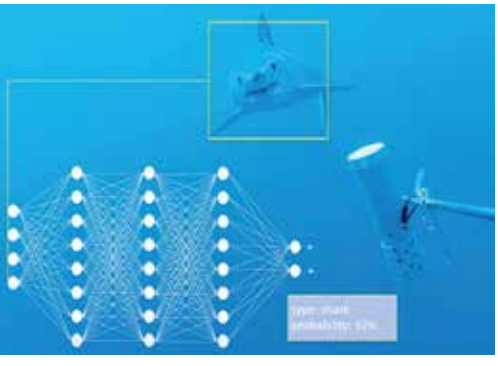
New Caledonian Biodiversity Agency, France

Ginger-SOPRONER, New Caledonia, France

Bluecham, New Caledonia, France

Using artificial intelligence to measure biodiversity

Urbanisation, resource overexploitation, pollution, habitat destruction and climate change are responsible for the sixth mass extinction of species - a global phenomenon that scientists are trying to quantify as much as possible.



© IRD/L.Vigliola

Identification of a pelagic Mako shark using deep learning, New Caledonia.

PARTNERS

Government of New Caledonia, France

Southern and Northern Provinces, New Caledonia, France

Cadi Ayyad University, Morocco

Cheikh Anta Diop University, Dakar, Senegal

University of Yaoundé I, Cameroon

Ginger-Soproner, New Caledonia, France

Bluecham, New Caledonia, France

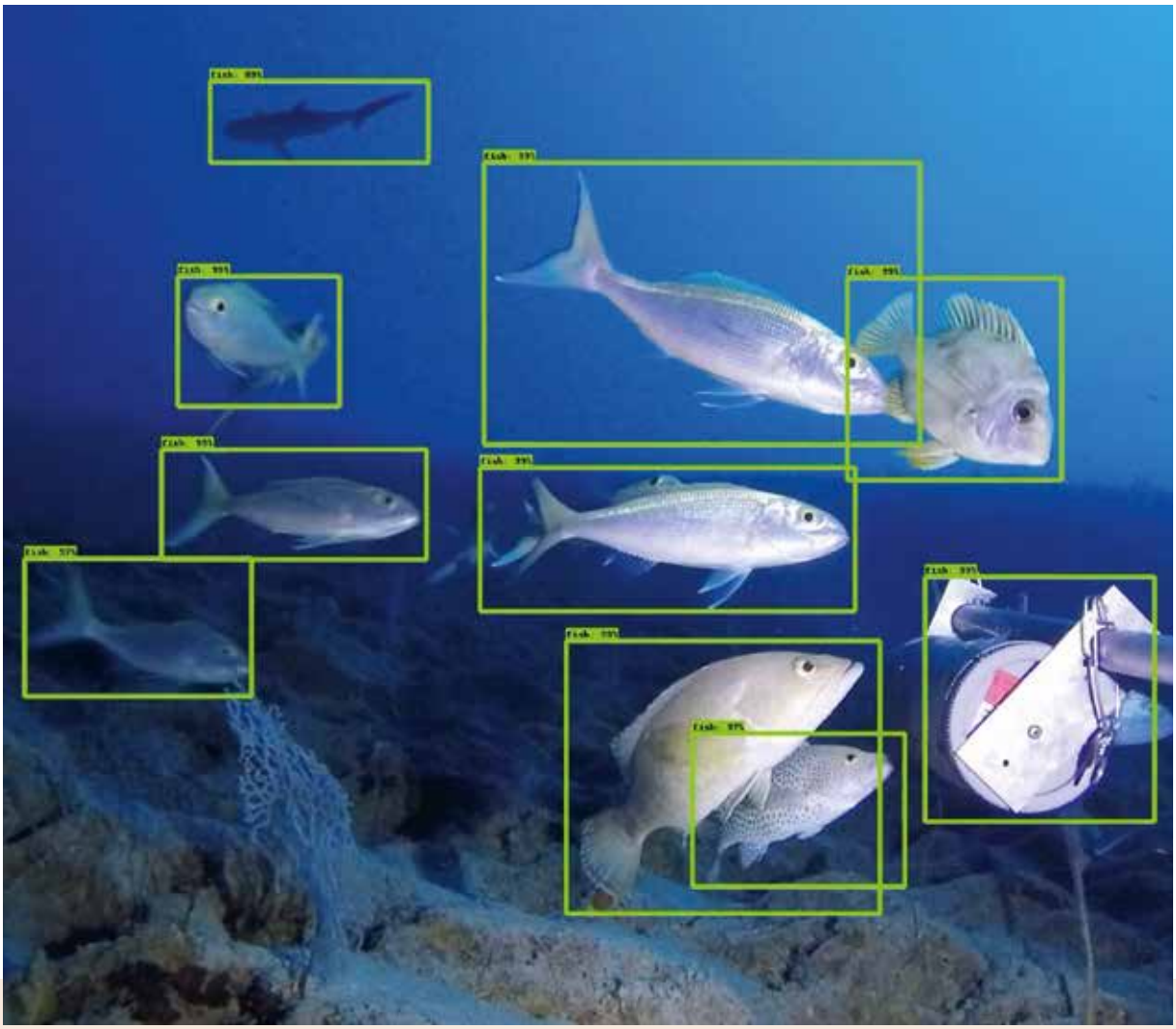
To measure global warming, we can use sensors, sea buoys and satellite images - in short, continuous recordings of physical parameters. But things become much more complicated when it comes to documenting the erosion of something as fluid and varied as biodiversity. In this respect, artificial intelligence (AI) is changing the game.

Data mining, for example, can be used to extract useful information from the diverse bestiary of global databases, be it counts, bioacoustic sound recordings or environmental DNA sequencing. AI can then highlight unsuspected links between species, reconstruct networks of interaction, highlight their sensitivity to environmental variations, or identify indicators - all results that would have been impossible to obtain using conventional methods.

Another very promising example is deep learning, which automatically analyses data from sensors, such as video recordings. This process can be used to detect animals or habitats in underwater photos or videos. However, AI does not perform well in all areas. It even has an essential flaw in that, to learn to recognise a species, it needs images of it. And not just one or two - on average, it needs 1,000! This is very difficult to provide, since from a biodiversity perspective, the majority of species are in fact rarely observed.

Despite these difficulties, the arrival of AI represents a scientific breakthrough whose impact is only just beginning to be felt. One of the challenges now is to store scientific data in dedicated, reliable warehouses.

••• New approaches to analysis, based on artificial intelligence, are helping gauge the erosion of biodiversity •••



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Fish detection using deep learning, New Caledonia.

"All managers of marine species, whether rare, endangered or of interest to the fishing industry, are on the lookout for innovative measurement and efficient monitoring techniques that do away with the need for human observers. For this purpose, IRD's algorithms have already proved highly effective (dugongs, turtles, sharks, snappers)."

Emmanuel Coutures, Sustainable Development Department, Southern Province of New Caledonia, France

The AI that thought it was a seabird

Knowing and understanding how marine ecosystems function requires vast quantities of observational data that is often difficult to collect and analyse. Artificial intelligence offers a number of advantages in the face of these difficulties.

© IRD/S. Bertrand

Masked boobies on the Fernando de Noronha archipelago, a haven for biodiversity, South Atlantic.

Seabirds adapt their movements to the distribution of their food resources, which are themselves changing and dependent on ocean variability. Living at the interface between air and sea in all the planet's oceans, they are easier to observe than underwater animals. Their journeys are therefore excellent indicators of marine biodiversity. But deriving reliable information from seabird observations requires huge quantities of data to identify the factors that are truly behind them, based on solid statistics.

Artificial intelligence is proving extremely useful in overcoming these difficulties. It can simulate the behaviour of living organisms based on an exploration of observational data and help us understand changes in marine biodiversity in the face of climate variations and human pressure (fishing, pollution, development of renewable energies).

Using artificial intelligence, a digital avatar reproduces seabird behaviour. Initially created using simple artificial neural networks, then deep learning tools, its performance improves as new data from a variety of observational contexts is added.

This simulator makes it possible to conduct virtual experiments on marine ecosystems and predict the effects. This means we can test the impact of offshore wind turbines, changes in fishing regulations or new environmental parameters at an early stage. The scope of applications is broad, and already includes coastal regions of Brazil, Cuba and Morocco.

PARTNERS

Federal University of Rio Grande, Brazil

Federal University of Alagoas, Brazil

Federal University of Rio de Janeiro, Brazil

Cadi Ayyad University, Morocco

Coastal Ecosystem Research Centre, Cuba

Institut Mines-Télécom Atlantique, France

UMI Ummisco, France

Montpellier Laboratory of Computer Science, Robotics and Microelectronics, France

••• A digital seabird avatar makes it possible
to explore the possible impacts of development projects
or natural phenomena on marine biodiversity •••

Flight of a tern colony in the Great South Lagoon, New Caledonia.

Bacteria on the back of plastic

Like any surface, plastic can be home to bacteria, which can aggregate and form a biofilm to protect themselves. In the sea, these bacteria may be ingested by aquatic species and then consumed by humans, raising new health risks.

© CNRS/T. Bouvier

Sampling bacteria on plastics, Mauritius.

© CNRS/T. Bouvier

Accumulation of plastic, port of Mauritius.

Plastic is fantastic - except when it gets into the marine environment. There, it represents a mortal danger to animals through strangulation, obstruction and chemical poisoning. But less well known is the fact that it can also pose a microbiological risk, transferring potentially pathogenic bacteria along the food chain to humans.

At least, this is the hypothesis currently being tested in Madagascar, a country where plastic waste management policies are inadequate and there is a lack of wastewater treatment plants. This creates particularly favourable conditions for the contamination of macro- and microplastics in coastal waters by potentially pathogenic bacteria - hence the importance of quantifying this risk.

••• An experimental study tracks the fate of fluorescent bacteria carried along the food chain by plastic •••

To do so, there were two approaches: the first used molecular tools to identify the bacteria on plastics in situ and find out if they remain alive, if there are many of them and if they are resistant to antibiotics; the second used microplastics contaminated in the laboratory

"The project to assess the microbiological risk of plastics is an innovative research initiative, both locally in Toliara and nationally in Madagascar. It is an important subject in a country where public policies on waste and wastewater management are being developed. The results will provide Malagasy decision-makers with concrete information on which to base future guidelines."

Irène Rasoamananto and Gildas Todinanahary, Fisheries and Marine Sciences Institute, Madagascar

© IRD/Didem/Rijasolo

Open canal blocked by vegetation and plastic waste in Mahajanga, Madagascar.

by a test bacterium (*Escherichia coli*-GFP, which is fluorescent green), to determine whether it is transferred to marine animals once the microplastics have been consumed. Two species that are commonly consumed in Madagascar were tested: sea cucumber and rabbitfish.

The results show that *E. coli* is transferred to the intestinal lumen of these organisms, creating a new health risk. An integrated approach proved necessary to assess this risk, using microbiological results from in situ and experimental measurements, as well as anthropological studies of local populations, particularly in the commercial and non-commercial fishing sectors, and their perceptions of the risk.

Finally, artist residencies were organised to raise public awareness of this research. The invited songwriters and cartoonists worked with scientists and children aged 10-15 to create a comic strip and a song that is now broadcast on the radio. It was so successful that this type of residency will be repeated in Madagascar and the Seychelles.

PARTNERS

Fisheries and Marine Sciences Institute, Madagascar

CNRS, France

Montpellier University Hospital, France

Pasteur Institute, Madagascar

Towards home-made electricity?

According to the most pessimistic scenarios, Tunisia's energy demand could triple by 2050. This projection is pushing the development of new technologies to support local electricity production.

Modelled image of *Thermotoga maritima*.

PARTNERS

Higher Institute of Applied Biological Sciences of Tunis, Tunisia

National Institute of Research and Physical and Chemical Analysis, Tunisia

Mediterranean Institute of Oceanology, France

Toulouse Biotechnology Institute, France

Eating fruit and vegetables is good for your health... but it could also be used to generate electricity, especially in Tunisia! In this country, where fossil fuels are in short supply, 70-80% of waste is food waste, compared with 40% in France. There is therefore an excellent opportunity for this organic matter to be used to produce biogas. Not methane, but biohydrogen, which can be stored and easily converted into electricity!

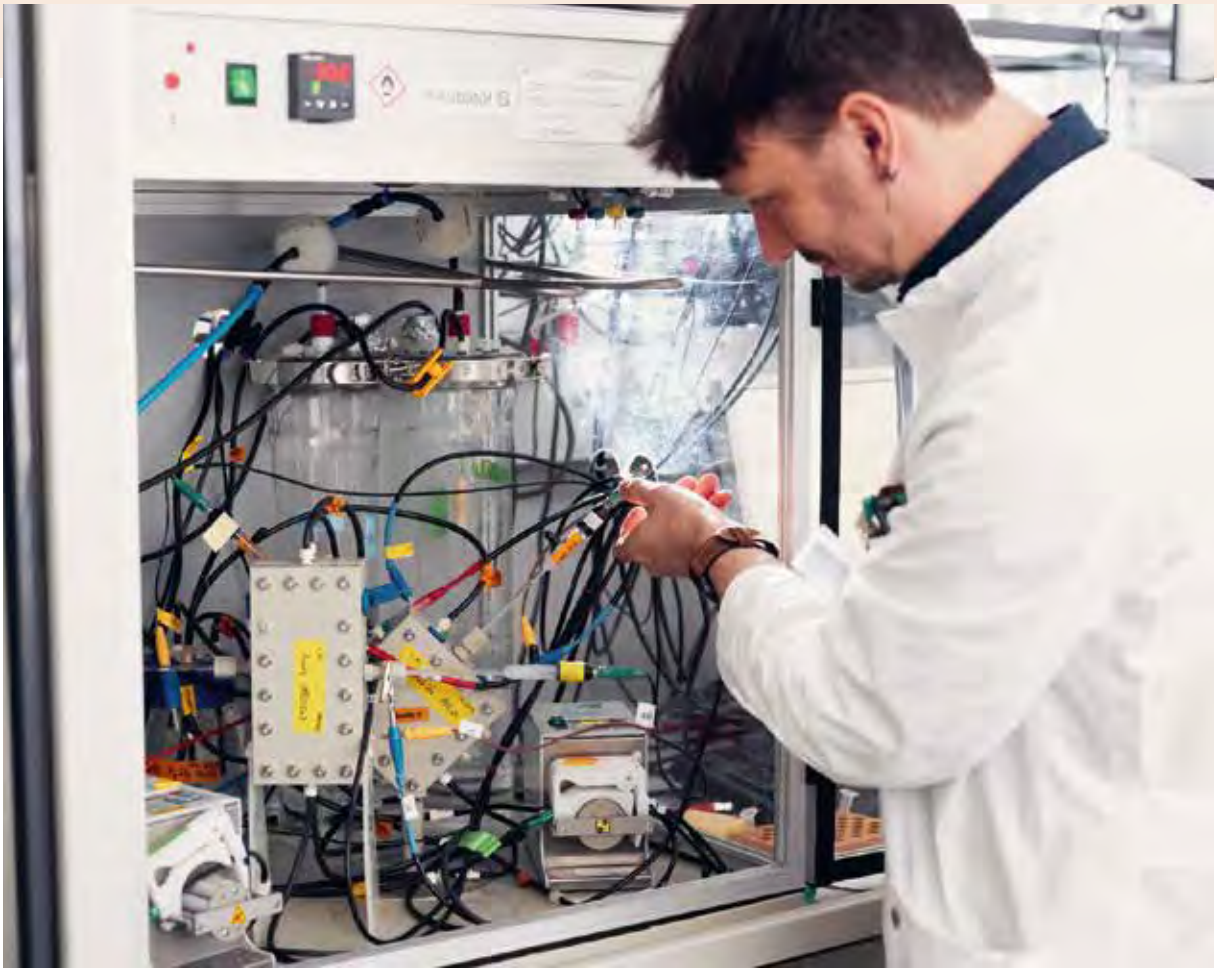
••• Deep-sea bacteria could be used to produce hydrogen •••

The process has been studied since the 1990s: certain bacteria living at room temperature produce biohydrogen during the anaerobic digestion (decomposition process) of organic matter. But their production yield is poor. Furthermore, the culture medium can easily be contaminated by other bacteria, further hampering the bacteria's productivity. This led to the idea of working under stricter temperature and pressure conditions and using microorganisms that live in the deep ocean, around hydrothermal hot springs.

Among them is Thermotoga maritima, the most extensively studied hydrogen-producing bacteria. It is capable of fermentation, i.e. transforming polysaccharides (of which there are many in biomass) into dihydrogen molecules, and twice as efficient as bacteria on the surface. It can produce three times as much if we add co-cultures, i.e. companion microorganisms capable of supplying essential vitamins, digesting meat or even fully mineralising organic matter. This new avenue is being explored through a sampling campaign around deep hydrothermal springs.

"Recycling organic food waste to produce energy in Tunisia could both improve waste management and support the energy transition, while reducing dependence on fossil fuels. With 2.8 million tonnes of waste a year, 68% of it organic, the potential biogas could cover up to 13% of energy demand by 2030. Bacteria such as *Thermotoga maritima* can transform biomass into biohydrogen, offering a sustainable solution to increase the country's energy autonomy."

Hana Gannoun, Higher Institute of Applied Biological Sciences of Tunis, Tunisia



© IRD/University of Bremen/G. Pilot

Sampling microorganisms from hydrothermal springs in a fermenter, Tunis, Tunisia.

Eventually, the aim would be to create individual composters (which could be placed on people's balconies, for example). They would be heated to 80°C by solar energy and pressurised to 250 bars, which would also make it easier to store the dihydrogen. It is estimated that with this type of device, 5 kg of household waste could produce enough dihydrogen to power a four-person household for a day under European living conditions.

The Comoros in need of sand

Over the past 30 years, coastlines in the Comoros have undergone widespread erosion. At the same time, more and more sand is being removed, changing beach dynamics.

© IRD/N. Mihani

Topographic measurements on the coast, Comoros.

The Comoros archipelago is made up of volcanic islands originating from the same hotspot, of varying ages, from the youngest, Grande Comore, to the oldest, Mayotte, with its coral reefs and lagoons. Between the two lie Anjouan and Mohéli, of intermediate ages and surrounded by black sand beaches created by the erosion of volcanic rock. However, on these two islands, the beaches are gradually disappearing. And it is not just the sea that is to blame.

Until the 1950s, Comoros residents used plant-based materials to build their homes. But this practice changed after a particularly destructive cyclone. They now opt for solid buildings, constructed from sand taken in large amounts from the shore. This 'thins down' the beaches, which would usually absorb the power of waves thanks to their slope. As a result, the coastline is eroding, endangering roads, infrastructure and housing.

... The vulnerability of the Comoros to coastal erosion could be reduced by introducing erosion indicators and topographical monitoring of beaches, but also by changing local perceptions ...

This observation has led scientists to establish landscape indicators of coastal erosion and monitor the topographical profile of beaches. The aim is to make both decision-makers and people who extract sand aware that these practices have a real impact. As part of the project, they taught the local technical teams responsible for the coastline and environment how to use topometers, simple and inexpensive tools that can be used to measure the profile of beaches two or three times a year and monitor changes. Furthermore, teachers will be instructed in the use of landscape erosion indicators that are even simpler to use, laying the foundations for participatory research.

© IRD/N. Mirhani

Habitat damaged by erosion in Mohéli, Comoros.

These topographical profiles of beaches and indicators are presented in an atlas published to raise awareness among decision-makers and guide certain decisions. For example, rather than taking sand from beaches for building purposes, it would be preferable to subsidise the import of pozzolan (natural rock) from Grande Comore, the extraction of which does not require deforestation. Another option would be to use clay, which is a sufficiently abundant resource, to encourage housing made from brick, as in Madagascar. Grande Comore could also provide sand to replenish the most depleted beaches in the Comoros, thereby reducing their vulnerability to coastal erosion.

PARTNERS

University of Comoros, Comoros

Mohéli National Park, Comoros

National Network of Protected Areas, Comoros

Governorate of Mohéli, Comoros

Governorate of Anjouan, Comoros

Let the mangroves grow back on their own

Blue carbon refers to the carbon captured and stored by marine and coastal ecosystems. It plays an important role in combating climate change and provides many ecosystem services, but it can also become a pretext for harmful policies.

© IRD/M. Cormier-Salem

Oyster gathering in the mangrove, Santa Cruz Estuary, Pernambuco, Brazil.

© IRD/J. Andrieu

Irula women catching prawns in the mangroves at Pichavaram, South India.

Since the Kyoto and Paris climate agreements, the carbon credit market has taken off and, with it, massive private investment aimed at protecting and restoring ecosystems capable of sequestering blue carbon (seagrass beds, coral reefs and mangroves).

From this list, mangroves are a subject of particular interest. Firstly, because they are often cited as threatened and in decline. Secondly, because they provide many services to the ecosystem: they limit coastal erosion, protect against typhoons, purify water and act as breeding grounds for fish. Lastly, because these "sea forests" have strong evocative power, easily exploited for communication purposes.

This reality is at the root of the abusive practices observed by scientists. Under the guise of offsetting, carbon sequestration and reforestation, governments are ceding mangroves that previously belonged to local communities to the private sector. These companies plant a single species of mangrove, the one that grows the fastest, so that they can quickly show the impact of their initiatives.

"The results underline the importance of creating mangrove restoration projects aimed at re-establishing the structure and function of this ecosystem by restoring soil and water quality, thereby promoting biodiversity and ecosystem services. In addition, this research highlights the need to recognise the rights and access of local communities to mangrove resources, promoting an approach that respects their traditional uses and contributes to the social and cultural sustainability of these ecosystems."

Claudia M. Agraz Hernández, Autonomous University of Campeche, Mexico

© IRD/C. Proisy

Mangrove undermined by wave erosion, French Guiana.

But these monospecific forests are nothing like natural mangroves: they lack diversity and therefore do not provide the same ecosystem services... or the same social services, since the planted land is no longer accessible to the people who used to gather oysters, collect dead wood, produce salt, grow rice or walk around and celebrate ritual ceremonies there.

••• Research is pointing to abusive practices associated with "blue carbon" and calling for a better understanding of how mangroves function •••

Scientists are denouncing the negative effects of these mechanisms and calling for a more holistic approach: before thinking about offsetting, we need to do everything we can to reduce greenhouse gas emissions. And if offsets are to be used, they must take local socioeconomic and ecological realities into account.

In the case of mangroves, the best way to restore them is not to replant them, but to recreate the environmental conditions that will enable them to regenerate, for example, by encouraging sediment deposit.

PARTNERS

Amadou Mahtar Mbow University, Senegal

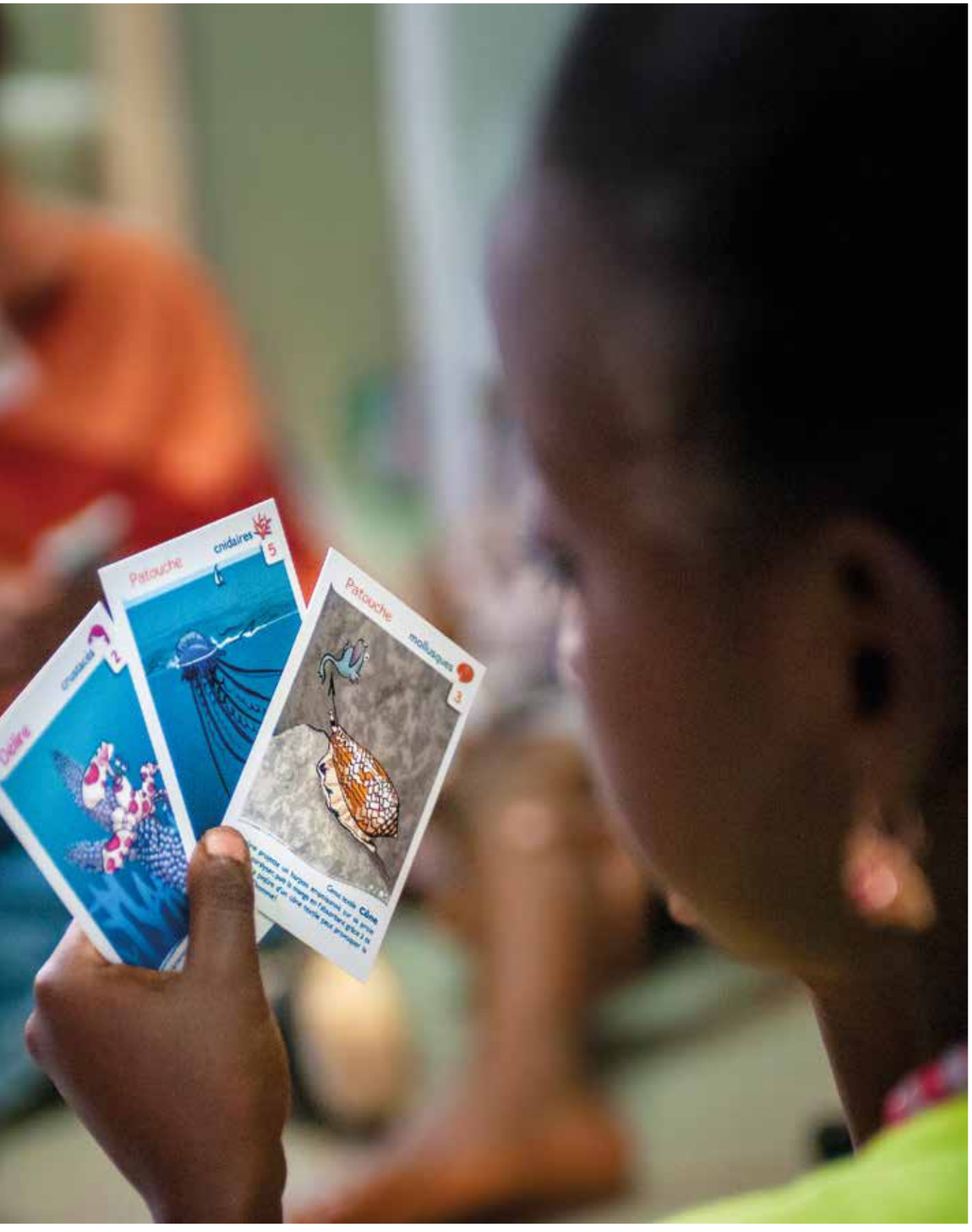
Pernambuco State University, Brazil

Autonomous University of Campeche, Mexico

PART 4

SHARED KNOWLEDGE

Marec card game on coral reefs, Comoros.

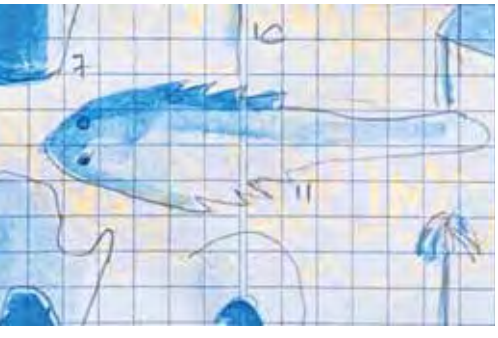


The sound of silence

The world of the sea is not one of silence: sounds are abundant and enable oceanologists to identify the organisms that live there, to understand some of their behaviour and to give indications about the state of health of ecosystems.

© IRD/T. Brochier

Batrachoides Liberensis, nicknamed "sea hyena" by Lebu fishermen, Dakar, Senegal.



© Grain des choses/ C. Gatineau

Drawing illustrating the recording of underwater sounds, later commented on by freedivers.

In 2018, off the coast of Dakar, an oceanologist used hydrophones to continuously record underwater sounds and gather information about the local marine ecosystem. As these are expensive devices, he worked with a local freediver to set them up at key sites, while camouflaging them so that they would not be picked up by other fishermen. He then looked for a way to make sense of all the data collected. At this point, an anthropologist told him about an experiment being carried out in Cairo, in which people's movements around the city were recorded and then commented on by them in order to learn from their knowledge of the urban environment. Drawing inspiration from this experiment, the researchers adapted the method to the underwater environment, with the collaboration of a freediver who recorded his dives and then commented on them in his native language, Wolof. This brought meaning to the sounds of the sea.

••• The knowledge of Dakar's freediving fishermen brings meaning to underwater sound recordings •••

A number of themes emerged from these comments, ranging from climate change to fish behaviour and the effects of pollution. For example, the crackling sounds heard on the recordings are thought to be caused by sea urchins feeding on the rocks. The absence of this sound would indicate pollution of the site. Some species cry out when hit by a spear. Sometimes this sound scares off other members of the species, as is the case of lobsters, and sometimes it attracts them, as is the case of flying fish. Such behaviour is well documented in terrestrial environments, but this is the first time it has been described for aquatic species.

PARTNERS

Higher Polytechnic School of Dakar, Cheikh Anta Diop University, Dakar, Senegal

Dakar-Thiaroye Oceanographic Research Centre, Senegal

"In Senegal, the fish are disappearing. Some of the fish sounds we have described are no longer there. People need to be made aware of this, so that they know that we are killing nature, even though we can't see it. By giving a voice to those who go underwater, we can make people more aware. This experience has improved my own understanding of the issue. Now I can raise awareness among those around me, as well as other fishermen."

Babacar Sy, Senegalese freediving fisherman

© IRD/N. Puig

Fisherman making a diving commentary along the coast of Dakar, Senegal.

Five Senegalese freedivers took part in this "immersive method", which enabled them to gather knowledge that would have been impossible to glean from questionnaires or interviews. This local, empirical knowledge can provide a wealth of useful information for understanding marine ecosystems. This information contributes to scientific knowledge and can be transmitted to an artificial intelligence system trained to analyse hydrophone data. In Dakar, the sounds recorded were put to artistic use, transformed into music to raise awareness of the richness of marine biodiversity.

Changing our approach to corals

Raising awareness among coastal communities is a key step in promoting the conservation and protection of aquatic ecosystems, particularly coral reefs.

© J. Cosse

Field trip to the Étang Salé lagoon in Saint Leu, Reunion Island.

Coral reefs are suffering as a result of human pressures and climate change, leading to a loss of biodiversity in coral ecosystems and associated activities such as fishing and tourism. Although scientists have long been sounding the alarm, people are often poorly informed about the issues surrounding these ecosystems. It is therefore crucial to encourage the sharing of knowledge to raise awareness among society, particularly the younger generations, of the significance of the biodiversity of coral reefs and the importance of protecting them.

In the Indian Ocean, this observation has encouraged scientists to develop awareness-raising tools designed to change the way local communities see coral reefs. For example, they have designed an educational kit to make scientific concepts more accessible, and have forged links between the arts and sciences. Even more originally, they have drawn inspiration from an educational initiative that began in 2012 in the Marquesas Islands, where the scientists' stories inspired schoolchildren to create the very first marine educational area. This innovative scheme, which encourages learning through an educational and civic-minded approach, has since spread around the world. In 2016, it was introduced on Reunion Island to raise children's awareness of the vulnerability of the island's coral reefs.

"By managing a maritime area themselves, students become actively involved in preserving the coastal environment. Research shows that marine educational areas are being used to educate the younger generations, in the hope that they will become responsible, informed adults capable of making the right decisions to protect the coral reef socio-ecosystem while taking ancestral knowledge into account."

Georgeta Stoica, University of Mayotte, France

© IRD/L. Massé

Discovering reefs through a game, Madagascar.

••• In the Indian Ocean, ocean education is flourishing, in particular with the establishment of marine educational areas •••

In practical terms, marine educational areas are created at the request of a teacher. Pupils discover coral reefs both in the classroom and underwater, with the support of scientists and partners associations. Then, it is up to the teacher and the pupils to identify the issues to be addressed and implement solutions in collaboration with the local authorities: for example, planting local trees to prevent erosion and run-off, thereby reducing the turbidity in the water which is harmful to corals.

The programme has been so successful that it is now extended to the islands of the Western Indian Ocean (Comoros, Madagascar, Mauritius, Seychelles). The aim is for the children involved in the programme to become ambassadors for the coral reefs in their communities, and to be aware of their ability to have an impact on this submarine world. An invisible world that provides many ecosystem benefits, starting with protecting coastlines from erosion.

PARTNERS

French Biodiversity Agency, France

Regional Biodiversity Agency, Réunion, France

Indian Ocean Commission, Mauritius

Mayotte University Training and Research Centre, France

Institute of Fisheries and Marine Sciences, University of Toliara, Madagascar

University of Comoros, Comoros

Ministry of Education, France and Seychelles

NGO Bel Avenir and Elite 3A, Madagascar

Adolescent Non Formal Education Network, Mauritius

Changing estuary water flows

Understanding global and local environmental mechanisms is a good thing. Even better is using them to make a real difference to people's everyday lives. What follows is the perfect example.

© IRD/S. Duvail

Returning from fishing on the Incomati Estuary, Mozambique.

In the Incomati Estuary in Mozambique, freshwater is in short supply because it is being held upstream in South Africa by hydroelectric dams and used for sugar cane and eucalyptus plantations. As a result, the flow of the Incomati has been reduced 100-fold over the last 75 years. Very little water reaches the estuary, despite hard negotiations with South Africa as part of a treaty whose terms are to be re-examined soon.

The flow is currently insufficient to prevent the salinisation of the farmland used by the small-scale fishermen living in the delta, whose are struggling to have their voices heard. A transdisciplinary programme has therefore been set up to develop methods for better assessing the estuary's water needs, from both an ecological and a societal point of view.

To do this, researchers modelled saltwater and freshwater flows in the estuary. They then compared this model with the number of fish-eating birds in the area. This indicator, which gives an idea of the state of health of the ecosystem (presence of fish and shrimp), is recorded on a participatory platform that collects observations from professional and amateur ornithologists throughout the year.

Interviews were also conducted with fishermen in the estuary. Over a period of two years, 15 local people from different parts of the delta

"I live in Marracuene, near Matsinane. I go out in the morning to catch crabs and fish. The problem with the river is the changing waters. It used to be fresh water, but now it's salt water. Because of this change, the fish we used to catch are no longer there and it has become difficult to catch them. The fish have disappeaered upstream."

Horacio Manhica, fisherman in the Incomati Estuary, Mozambique

••• Transdisciplinary work has culminated in recommendations for managing the water of a river flowing into the Indian Ocean in Mozambique •••

© IRD/O. Hamerlynck

Collared Pratincole flying over the plains of the Incomati Delta, Mozambique.

were asked to keep photographic logbooks to record their fishing and farming strategies in relation to the water flows. These methods made it possible to document their difficulties and their strategies for adapting when the estuary is flooded by fresh water or, conversely, when it becomes saline.

By combining all these data, the researchers have demonstrated that, instead of negotiating an annual volume of water, Mozambique would benefit from negotiating a schedule for flows reaching the coast. The recommendation is that the country should obtain more water between September and October to soften the waters of the great equinox tides, which are responsible for the salinisation of the land, making the delta more productive in terms of fish, prawns, crabs, agricultural produce, plants and pastures.

PARTNER

Eduardo Mondlane University, Mozambique

Draw me the sea

Drawings can be used to identify and understand children's ecological knowledge, as well as their representations and emotions, and as a medium for dialogue between science and society.

© IRD/É. Fache

Drawing workshop in Yaté, New Caledonia.

In Fiji and New Caledonia, children aged between 9 and 14 living on the coast were asked to draw the sea, what they do there and what others do there, as part of classroom sessions in urban and rural settings. Nearly 300 drawings were made, then presented and discussed by the children in short interviews.

The drawings show how children perceive the land-sea continuum, with its ecological connections (such as the links between different marine species and their habitats) and social connections (for example, attachment to certain emblematic species). The children observe and experiment with these connections through their own fishing practices. In Fiji, 70% of the drawings show fishing practices, compared with around 30% in New Caledonia, where the drawings tend to depict the beach and the various associated recreational activities.

When children draw fishing practices, girls draw men and boys as well as women and girls, whereas boys tend to draw only male characters. Children learn at a very early age that men and women engage in various fishing activities, but in different ways. As the drawings show, women generally fish without a boat, close to the shore, and gather shellfish and other invertebrates more than men do. The absence of female characters in the boys' drawings reflects the fact that the role of women in onshore fishing is often less valued and therefore relatively "invisible" compared to that of men.

... Anthropologists and ethno-ecologists are proposing to use drawings to help children express their relationship with their maritime environment ...

The interviews also provided a better understanding of the extent of the knowledge and skills that the children develop – and pass on – through their fishing practices. Particularly in rural areas, in both Fiji and New Caledonia, children are able to identify and name a large number of fish species, know the behaviour of marine animals and can describe different fishing techniques.

PARTNERS

University of the South Pacific, Fiji

Leibniz Centre for Tropical Marine Research, Germany

"In Fiji, we need to focus on raising students' environmental awareness, as they are the leaders of the future and can play a crucial role as guardians and defenders of the environment. Using visual aids, such as drawings, is a creative approach that allows these students to express their understanding of the marine ecosystem and document their sociocultural values in order to bring about positive change."

Ulamila Matairakula, Project Manager, Pacific Blue Foundation, Fiji

"These research projects enable primary school teachers to reflect on the challenges of sustainable development by involving the children in our schools. By opening up the class to scientific partners, pupils have the opportunity to talk to specialists, acquire knowledge as part of their project, find out about careers in research and develop vocations. These pupils can also raise awareness of climate change and its consequences among other schoolchildren."

Vanessa Montagnat, New Caledonia Education Department

Drawings by a 10-year-old boy in Yaté, New Caledonia.

The drawings collected show that the children have detailed knowledge of the land-sea continuum. The exhibition of these drawings in the villages involved has created a sense of pride, as well as a forum for dialogue between the children, scientists, teachers, families, local authorities and, more broadly, the general public.

Towards a sustainable mangrove crab industry in Madagascar

Mangrove crab fishing has long been a secondary economic sector in Madagascar. But the situation has changed dramatically since 2014 with the expansion of live crab exports to the Asian market, which have boosted fishing effort and production.

Measuring the size of a mangrove crab *Scylla serrata*, Madagascar.

In recent years, mangrove crab *(Scylla serrata)* fishing has become so important to Madagascar's economy that most stocks are now fished before they reach their legal maturity size (11 cm). This is a real challenge for sustainable management, which requires concerted action to strengthen the capacity of local bodies to monitor and manage fisheries, as well as exchanging information on the sector to improve joint management.

How can this be achieved? An action-research project has, among other initiatives, organised a series of regional workshops bringing together fishermen, fish traders, collection companies, government departments, NGOs and scientists to share knowledge about the fisheries and discuss research to address local concerns. This iterative approach has enabled progress to be made at a regional level, culminating in a national workshop. Alongside this, collaborative activities were undertaken in the villages, including participatory monitoring of fisheries, socioeconomic studies and tests of more selective fishing equipment.

"The participatory diagnosis of the fisheries played a key role in empowering some of the stakeholders involved, such as NGOs and export companies. The project has provided a framework for interaction, strengthening trust, social learning and collective action in favour of sustainability. We also need to remedy the serious lack of data and its management, which affects government decision-making despite the advice given by researchers".

Deutz Zafimamatrapehy, Institute of Fisheries and Marine Sciences, University of Toliara, Madagascar

Thierry Razanakoto, Centre for Economic Studies and Research for Development, University of Antananarivo, Madagascar

••• Action research on the mangrove crab industry is aimed at the sustainable use of resources and concerted management of them •••

© IRD/J. Beckensteiner

Field interview with fishermen and fish merchants in the mangrove crab industry, Madagascar.

What impact has this had? The multi-stakeholder workshops resulted in a collective diagnosis of the industry and the co-production of knowledge, which was then aggregated on a larger scale. However, on-site interactions did not improve technical knowledge within the villages, nor did they diversify exchanges. The poorly developed social network limited the flow of information. This outcome raised questions about the project's strategy and scale of intervention, but did not discourage the researchers.

The researchers are now giving priority to action research led by local partners and based on practical, local experimentation with promising solutions. These solutions, which are tested beforehand, reduce the number of small crabs being caught without reducing local incomes, which are often very low. The aim here is to show local communities and businesses that this strategy can ultimately be more profitable and sustainable. Proof by example, in short, before extending the scheme.

PARTNERS

University of Antananarivo, Madagascar

University of Mahajanga, Madagascar

University of Toliora, Madagascar

Centre for Economic Studies and Research for Development, Madagascar

Institute of Fisheries and Marine Sciences, Madagascar

National Oceanographic Research Centre, Madagascar

SHARED KNOWLEDGE

Managing milky waters

The waters off the Peruvian coast are highly productive, but they are experiencing extreme phenomena that pose a direct threat not only to fishing, but also to aquaculture, particularly scallop farming, which employs some 200,000 people in the country.

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Peruvian scallops in Paracas Bay, Peru.

Some turquoise waters are paradise in photographs only. This is the case for waters that turn "milky" and smell of sulphur, a phenomenon that sometimes occurs in Peruvian coastal areas at the end of summer. This happens because this region, one of the most productive in the world, generates large quantities of organic matter, which is constantly being broken down by bacteria. This bacterial activity is so intense that, over time, it can consume all the oxygen in the water. When this happens, the bacteria change their metabolism and start to produce hydrogen sulphide, giving the water a milky, turquoise appearance that is toxic to the organisms living in it. In some years, this can lead to the almost total loss of production in scallop farms, which are an important part of the local economy.

These areas are also subject to harmful algal blooms that pose real risks to human health, with impacts on local consumption and exports. Marine heatwaves can also occur, generating quite abnormal and significant increases in water temperature. Heavy rainfall can cause a layer of warm freshwater to settle on the surface, preventing oxygen transfer to the underlying layers and creating anoxic conditions. These phenomena cause multiple stresses to the ecosystem, often in combination, and therefore pose very significant risks to the local economy. Especially given that their frequency and intensity are set to increase with climate change.

Scientists are working to develop a low-cost early warning system that will alert fish farmers to the occurrence of any of these episodes. In response, fish farmers will be able to adapt their operations, for example by bringing their farms closer to the surface to escape the oxygen-deprived water layer. A better understanding of the seasonal nature of these events will also facilitate recommendations for adapting fish farming cycles.

PARTNERS

Marine Institute of Peru

La Molina National Agrarian University, Peru

••• Understanding certain extreme ocean events could help reduce losses for Peruvian fish farmers •••

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Milky waters of Paracas Bay, Peru.

Marine heatwave alert

Marine heatwaves have existed for decades. But they are now tending to be longer, more frequent and have a greater impact on both the environment and the economy.

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Coral reef bleaching, New Caledonia.

Heatwaves do not just affect land: they also occur in the marine environment, with surface waters becoming abnormally warm, affecting both the environment and the economy. In 2011, a marine heatwave along the west coast of Australia led to major destruction of coastal ecosystems and their habitats, massive coral bleaching and serious repercussions for aquaculture and fishing.

Since then, similar phenomena have proliferated around the world, with varying impacts. The most well-known episode, nicknamed the "Blob", lasted several months in the North Pacific in 2014-2015. It led to harmful algal blooms and affected the entire food chain, right down to seabirds. In 2016, in New Caledonia, another marine heatwave led to unprecedented coral bleaching, which until then had been remarkably well preserved. In recent years, there has been worldwide interest in studying these marine heatwaves. For many researchers, the aim is to gain a better understanding of the processes behind these extreme events, measure their impact, and better anticipate the consequences for island societies. In New Caledonia and French Polynesia, for example, transdisciplinary work began in 2024 to develop practical solutions, starting with sending marine heatwave alerts to local actors. They will be prepared in advance to respond to different crisis scenarios through dedicated units. Eventually, vulnerability maps will also be drawn up jointly with decision-makers.

At the same time, and more surprisingly, studies are beginning to improve the resilience of oysters and other marine species sold during marine heatwaves, by stressing them when they are young and/or selecting the hardiest ones. Similar work will be carried out on corals that are highly exposed to marine heatwaves.

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Directorate of Health and Social Affairs, New Caledonia, France

New Caledonia Development Agency, France

... New Caledonia is trying to adapt to marine heatwaves by launching transdisciplinary studies to find practical solutions ...

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Reefs of the Chesterfield "V", near the Loop Islet.

"The goal of the educational coral farm in Lifou is to raise environmental awareness and restore damaged coral reefs. The Mahewa project's research aims to optimise coral restoration methods, by targeting reefs with heat-resistant coral, and identify ideal restoration sites around the island of Lifou. The results of this scientific work will be shared with the general public, to raise awareness and inform them. This synergy between researchers, the private sector and local authorities strengthens our efforts to reduce the impact of human activity and meet the challenges of global warming."

Georges Kakue, Loyalty Islands Province, New Caledonia, France

Gregory Lasne, Biocénose Marine, New Caledonia, France

A little-known but coveted deep-sea

The deep oceans are made up of a variety of geological landscapes and are home to a wide range of ecosystems. The scientific exploration of these areas, which are still poorly known and arouse the curiosity and imagination of many, also raise complex economic, political and environmental issues.

© IRD/Fabrice Charleux

Regional platform for dialogue on the deep seabed, Tahiti, December 2024.

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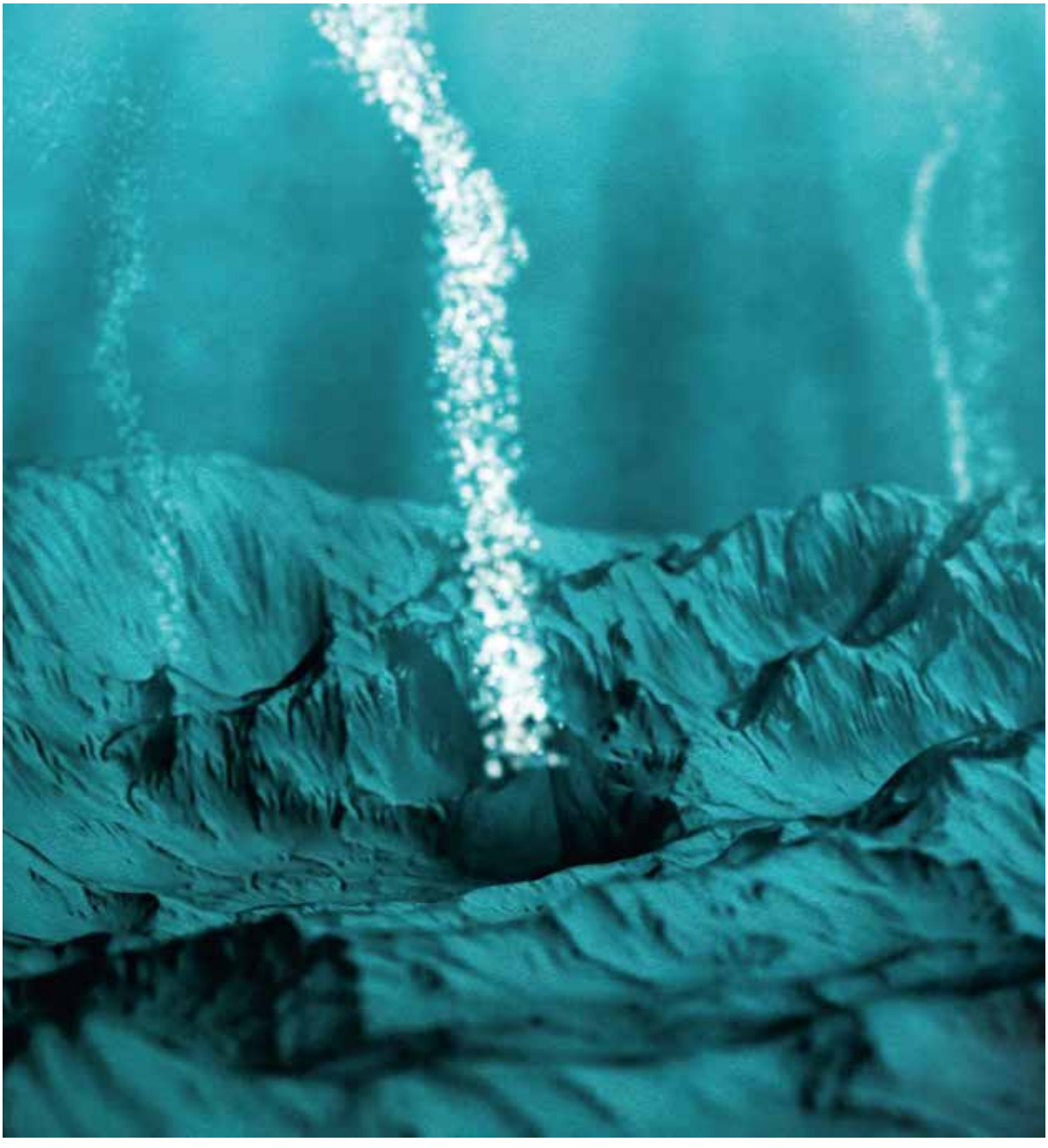
Political and customary institutions in New Caledonia, French Polynesia and Wallis and Futuna

The deep ocean floors are by definition invisible, distant and obscure. Our only knowledge about them comes from sophisticated science and technology capable of sending robots and submarines to explore them. Is this a neutral approach? Not necessarily. This is what researchers in human and social sciences highlight in their study of the reasons that drive the various scientific, political and industrial stakeholders to produce knowledge about the deep ocean floors.

••• The human and social sciences have been examining the multidisciplinary scientific approach to deep-sea exploration •••

In challenging the neutrality of the context in which knowledge is produced, the human and social sciences are looking at the environmental, political, economic and geopolitical issues that this knowledge reveals. Although science produces new knowledge, it does so at the risk of overlooking other registers of knowledge and representations, particularly those of indigenous populations. And yet this knowledge also expresses visions of the world made up of sovereign assertions about marine spaces.

The people of the Pacific see the ocean as a whole. They have in-depth knowledge of the currents, navigation, fishing sites, climate and identification of seamounts. The ocean is where they live, and sometimes die. The Kanak people of New Caledonia believe that the ocean floor is the resting place of the souls of the deceased and therefore call for it to be preserved. This cultural vision has gradually been taken into account, notably with the incorporation of a customary college into the governance of the Natural Park of the Coral Sea, created in 2014.



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Modelled image of volcanic activity in Tonga.

This fundamental approach, underpinned by the human and social sciences, plays a central role in a recent programme of research into the deep ocean floor, led by several institutes. In particular, two regional dialogue platforms have been set up in the Pacific, with the aim of better defining the role of the various bodies of knowledge in public decision-making on issues relating to the deep ocean floor.

PART 5

TOWARDS A NEW OCEAN GOVERNANCE

Participatory mapping workshop on the cultural heritage of the Marquesas Islands, French Polynesia.

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The Seychelles: towards a truly sustainable blue economy?

The concept of the blue economy, which emerged in 2010, aims to promote sustainable use of ocean and coastal area resources, encouraging economic growth while protecting marine ecosystems.

© IRD/T.Vergoz

Fishing with traps aboard a boat near Victoria, Seychelles.

In the 1980s, fishermen from Brittany and Spain began working in the abundant waters of the Seychelles. With them came an economy devoted to a largely foreign industrial fishing industry, with the creation of a port and a canning industry that now employs some 2,000 people.

During the Covid pandemic, tourism came to a halt, but the canning industry's exports soared to unprecedented levels, thanks in particular to strong global demand for long-life food products.

However, this canning industry may prove vulnerable under other conditions: during El Niño climate periods, pelagic fish stocks move eastwards, taking with them the foreign fishermen, who then prefer to unload their fish in Thailand, resulting in a significant loss of income for the Seychelles. And for a good reason: 10% of the GDP of this small country, which is highly vulnerable to external hazards, comes from tuna fishing and related activities.

In 2022, in light of this observation, the Seychelles' economic circuit was modelled. This digital model, which can be combined with physical and environmental data, incorporates the impact of medium- and long-term climate variations on the economy, thereby helping to create the conditions for a more stable and sustainable economy in the Seychelles.

Several approaches have been tested: installing offshore wind turbines to improve the country's energy independence, acquiring industrial or semi-industrial local boats to reduce dependence on foreign fishing fleets, or developing circular economy channels to recycle fishing equipment (such as used nets and fish aggregating devices left in the water by fishermen).

PARTNERS

Seychelles Fishing Authority

Yes Consulting, Seychelles

••• A digital model is helping the people of the Seychelles to gauge the economic impact of political decisions and environmental changes, and therefore to look to their future •••

© IRD/TVergoz

Artisanal fishing boat next to an industrial tuna boat in Port Victoria, Seychelles.

Regulations based on local realities

To ensure that management measures for marine areas and species are appropriate and properly applied, key stakeholders and local realities must be taken into account. New Caledonia's local authorities are experimenting with different approaches to tailor their environmental policies to the social and environmental challenges they are facing.

Net fishing, one of the main activities of the Kanaks, Bélep archipelago, New Caledonia.

The environmental codes of New Caledonia's North Province (2008) and South Province (2009) include exemption principles for the harvesting of protected species for customary ceremonies. These exemptions recognise the symbolic value of certain species, such as the green sea turtle *Chelonia mydas*. However, applying this right is not a straightforward matter, either for the customary authorities responsible for submitting requests, or for the technical officers in the provinces who are responsible for assessing the requests: what constitutes a customary ceremony? How many specimens can be harvested? Who is entitled to make a request?

In order to provide well-founded answers and stimulate discussion, social science research describes and analyses the symbolic representations that local communities have of their environment. In the South Province, for example, a study by anthropologists and geographers, based on interviews with local residents and officials, was carried out prior to the initiation of local consultations. The study identified which customary events required the use of turtles and for what purpose, and analysed changes in these practices over time. The survey also revealed the wide range of misunderstandings that can lead to conflict. This study was presented to the local residents, along with a biological study showing the fragile nature of the turtle population. These presentations helped to shed light on the debate and subsequently to initiate consultation between the provincial and customary authorities to clarify the regulations and discuss the size of the specimens to be harvested.

The Loyalty Islands Province has taken an even more innovative approach, recently opting to establish the Kanak culture and way of life as the basis of its environmental code. To achieve this, it called

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Fondation de France

New Caledonia Technopole

... In New Caledonia, approaches involving dialogue between scientists and stakeholders (local authorities, customary authorities and local communities) are being tested to improve the regulation of ways in which the environment is used, both on land and at sea ...

on environmental lawyers and a wide range of scientific experts to reconcile existing local management standards with constitutional and international norms.

Drawing on this philosophy of dialogue and backed by scientific expertise, since 2020, representatives of the authorities, fishermen and other industry stakeholders have been working on an innovative joint management system for four species of commercial sea cucumbers, which has since been made official. The system now makes it possible to adapt fishing pressure according to biological and socioeconomic conditions, balancing objectives for both the conservation and use of biodiversity that may seem at odds with each other in the short term.

By incorporating local knowledge and expertise and jointly developing the rules through negotiation, more sustainable choices can be made, which are based on consensus rather than compromise, and which are accepted and integrated into the lifestyle of local communities.

Green sea turtles *Chelonia mydas*, a protected species, in the Great South Lagoon, New Caledonia.

The Mediterranean Sea, a legal entity

The concept of the rights of nature has been gaining ground in various parts of the world over the last fifteen years. Several ecosystems, including rivers and lagoons, have been given recognition as legal entities. But the creation of the status of "natural legal entity", a promising concept, raises many questions.

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The Capri coast, Italy.

It's a fact: the state of the Mediterranean Sea is deteriorating. In 1976, the Barcelona Convention was adopted by the Coastal States with the aim of reducing pollution. The outcome of this convention and subsequent legal instruments have not always lived up to expectations, far from it. Hence the current idea of granting legal status to the Mediterranean Sea, to enable it to defend itself.

This approach is part of a wider movement which, since the early 2000s, has argued in favour of a paradigm shift. And with good reason: in the courts of law, the interests of nature are not, or hardly ever, represented, in particular because collectives and associations are not always legally recognised as having the right to act on its behalf. This effectively nips in the bud a number of legal appeals, which are rejected on their merits before they are even examined.

This situation has led indigenous communities in particular to campaign for the recognition of the rights of nature. Successfully so, as in 2008 the concept was enshrined in the Constitution of Ecuador. Subsequently, a river in New Zealand and a lagoon in Spain were recognised as legal persons. This was a step forward, but also slightly flawed, given that a legal person has rights as well as duties and

"The work being done to have the rights of the Mediterranean Sea recognised is inspired by age-old traditions and is part of a common project for the future that Tunisia shares with its neighbours on the *Mare Nostrum*. There is a renewed determination to give full effect to the joint commitments made under the relevant international, regional and national instruments. The potential effects of recognition will affect the entire Mediterranean basin, from north to south and east to west, in environmental, sociopolitical, economic, cultural and scientific terms. It could also set an example for all regional seas."

Leila Chikhaoui, University of Carthage, Faculty of Political, Legal and Social Sciences, Tunis, Tunisia

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Coastal fishing boats in Essaouira, Morocco.

responsibilities. This notion becomes quickly absurd, if not ineffective, when it comes to nature.

... A research project is exploring the feasibility of recognising the Mediterranean Sea as a subject of law, with the status of natural legal entity. This would be the first time this innovative concept is applied to a cross-border entity other than a river ...

Hence the idea of proposing the creation of the status of "natural legal entity" as a new category of subject of law. This innovative concept is now being studied as part of a project to determine the feasibility of conferring this status on the Mediterranean Sea. The research is all the more complex in that it also raises the question of sovereignty. This is the first time that the rights of nature have been applied to a cross-border entity other than a river. And it is no mean feat, since the Mediterranean is bordered by 21 States, governed by 21 national legislations and divided into as many legal areas that need to be harmonised as they will not be unified.

The aim of this project is therefore to progressively map the legal framework of the countries bordering the Mediterranean, to measure their (in)effectiveness and to propose a unified system that respects environmental solidarity. This may one day help to prevent or punish serious and repeated attacks on the physical integrity of the Mediterranean Sea and its living resources.

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Gabon proactive in protecting biodiversity

The Gulf of Guinea is one of the least studied regions in the world, yet according to the Intergovernmental Panel on Climate Change (IPCC) scenarios, the area will be heavily impacted by climate change. Its biological productivity is expected to plummet by 2050, and numbers of fish caught could fall by almost 30%.

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Crabs at the entrance to their burrow, Akanda National Park, Libreville, Gabon.

In Gabon, urbanisation is gaining ground and threatening the mangroves, which provide numerous ecosystem services both locally and across the region. For example, they help to purify water, act as nurseries for fish, provide local medicines and protect the coast from the onslaught of the waves. Gabon's coastal areas are also key points for the reproduction and migration of marine species such as hammerhead sharks and leatherback sea turtles, for which strict protection measures have been put in place on certain beaches.

••• A team of researchers has shown that, despite difficulties, Gabon's proactive conservation strategy is essential to preserving the ecological balance of the Gulf of Guinea •••

Gabon is a sparsely populated, highly unspoilt country with a proactive environmental conservation policy. It was the first country in Africa to create a network of marine protected areas, which now covers 26% of its exclusive economic zone. Although Gabon is a regional hub for conservation, it does not always have the means to maintain this strong and commendable position.

Firstly, because there is a lack of resources for control and, in the Gulf of Guinea, illegal fishing is widespread, contributing to the accelerated decline in fish stocks. Although difficult to quantify, illegal fishing represents $20 billion a year worldwide, a third of which occurs in Africa. It is a lucrative market which, in the region, goes hand in hand with trafficking in human beings, goods and drugs with neighbouring countries.

PARTENAIRES

Centre national de la recherche scientifique et du développement technologique, Gabon

Ministère des Eaux et Forêts, Gabon

"Gabon remains one of the leaders in Target 3 of the Global Biodiversity Framework. However, combined with the current impacts of human activities, the threats to coastal and maritime areas posed by climate uncertainty are challenging researchers more than ever to provide policy-makers with the information they need to make decisions. The research aims to contribute to the marine spatial planning process for blue bonds, ultimately to create the necessary conditions for completing a network of marine protected areas, guaranteeing the proper functioning and vitality of the marine biosphere in territorial waters. Finally, these research activities also offer Gabonese scientists the opportunity to conduct marine research and gain access to valuable data, thereby promoting scientific progress and capacity building."

Jean Hervé Mvé Béh, Director General, Directorate General of Aquatic Ecosystems, Ministry of Water and Forests, Gabon

Bac Aviation landing platform, Libreville, Gabon.

There is also the issue of pollutants that can influence the reproductive cycle of fish. For example, analyses of fish caught have shown contamination by microplastics and mercury, which raises the question of the nutritional quality of the fish consumed (40 kg/year/inhabitant in Gabon compared with 30 kg/year/inhabitant in France).

Despite these difficulties, Gabon's proactive approach is contributing to the ecological balance of the Gulf of Guinea, an area where marine resources are heavily exploited by industrial, often foreign, activities.

Making assessments for more effective steering

Current public policies fail to meet the challenges posed by climate change and biodiversity loss. This raises questions about the relevance of the Sustainable Development Goals proposed to governments.

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An increasingly popular beach at Ouakam, Senegal.

On 25 September 2015, 193 countries adopted the 2030 Agenda for Sustainable Development, which sets out 17 Sustainable Development Goals (SDGs) to steer public policy. But almost ten years down the line, we have to admit that the strategy has not proved very effective, as the situation in terms of climate change and biodiversity has continued to deteriorate. One of the reasons for this has been that, in practice, the SDGs have turned out to be too vague or downright contradictory. For example, one of the SDGs encourages economic development, which often comes at the expense of protecting the environment.

••• A new framework for assessing environmental issues is making it possible to develop relevant indicators to steer public policy more effectively •••

This calls into question not only the relevance of these SDGs, but also the methods and indicators that need to be put in place in order to make effective progress. To address these issues, a British team, in collaboration with French stakeholders, has developed a new assessment framework, which focuses more closely on the state of the environment. This approach proposes focusing on just four areas, namely the sustainable use of natural resources, reducing local and global pollution, the state of health of ecosystems and their heritage value. The method was developed within a European framework and can be applied elsewhere. But it requires the development of relevant indicators.

Research along these lines has been carried out in Senegal. It has drawn on the data available to establish a dozen relevant indicators. Initial comparative studies show that while countries like France are using their natural resources in a fairly sustainable way, they are lagging

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Coastal pollution near Dakar, Senegal.

behind when it comes to pollution and greenhouse gas emissions. By contrast, environmental issues in Senegal tend to focus on the sustainable management of its natural resources. This approach makes it possible to articulate the wide range of environmental issues and give them meaning, which will enable public policies to be steered and adapted in very practical ways.

PARTNER

Ecological Monitoring Centre, Senegal

AI at the service of marine environmental law

Environmental law plays a crucial role in protecting and preserving marine ecosystems. Yet its impact on marine ecosystems remains little studied and poorly documented.

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Plastic waste on a Moroccan beach.

Marine environmental law is essential for establishing standards and regulations that protect marine biodiversity and ensure the sustainable use of marine resources. It covers a wide range of issues, from the protection of endangered marine species to the regulation of fishing activities, the management of marine debris and the prevention of pollution. Each topic addresses specific aspects of marine conservation and requires appropriate legal approaches in order to be effective.

Although artificial intelligence (AI) has long been used in the legal field, it has only been applied to a limited extent to marine environmental law. An international, interdisciplinary team has set the ball rolling by launching an analysis of African countries and certain bans, such as those on plastic bags and bottom trawling. The aim of the study was to gain a better understanding of the impact of legal regulations on improving the marine environment.

To achieve this, the researchers used natural language processing techniques to process large quantities of legal texts, making it easier to identify trends, shortcomings and inconsistencies in national laws. Thanks to this methodology, legal indicators have been created that can be compared with environmental and/or economic data.

This makes it possible to analyse the impact of legal rules on the marine environment, for example by analysing data on marine biodiversity and pollution levels before and after the implementation of certain laws. This integrated approach not only provides a better understanding of the effects of existing regulations, but also enables recommendations to be made for improving marine environmental legislation.

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••• Natural language processing applied to an international corpus of legal texts will make it possible to create robust indicators of the impact of marine environmental law •••

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Fishing port in Essaouira, Morocco.

Protecting marine areas more effectively

Under the impetus of major international treaties, marine protected areas have multiplied over the last twenty years with the aim of conserving marine ecosystems. But without the backing of all stakeholders, who sometimes have divergent interests, the effectiveness of these areas is compromised.

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Fishing boat in the Mediterranean, Alboran Marine Protected Area, Morocco.

The zoning of marine protected areas (MPAs) is decided by state institutions or major international NGOs on the basis of criteria for the protection of species and their habitat areas. There is little involvement of local authorities, economic stakeholders or associations, which leads to conflicts and difficulties in implementing MPA management plans.

The case of the Alboran marine protected area in Morocco is a prime example of this. In 2015, a study involving the protected area's management services and local small-scale fishermen led to the installation of small reefs in the MPA to prevent the passage of trawlers, which cause a great deal of damage. However, no sooner than they were installed, these lightweight structures were moved by trawlers, as a ministerial decree had authorised fishing in the area.

••• In addition to deciding on zones for marine protected areas, there is a need to create forums for consultation to ensure that all stakeholders are on board •••

In this example, small-scale fishing and trawler fishing, with divergent interests and working with different government departments, were in competition with each other, which had an impact on the effectiveness of the MPA. This is a recurring problem, not least because the managers of these protected areas are unfamiliar with the fishing territories and have no grasp of the social conflicts in the different countries. As a result, only a tiny proportion of the 10% of marine areas that should be protected internationally are actually protected.

To improve effectiveness, it would be necessary to involve all the economic stakeholders, to take account of the diverse range of interests, to adopt a multi-sectoral approach and to put in place a compensation

"By studying the Alboran marine protected area (MPA), the Integrated Coastal Management in the Moroccan Mediterranean project (Gilmar) has highlighted the complex nature of integrated coastal management in the Moroccan Mediterranean, involving fishermen, farmers and tourism stakeholders. The team has produced scientific knowledge, trained students and managers, and used the results of its research to support decision-making. Its collaboration with public, professional and voluntary bodies lays the foundations for a new approach to MPA projects in Morocco."

Hicham Masski, National Institute for Fisheries Research, Morocco
Mohamed Naji, Hassan II Institute of Agronomy and Veterinary Medicine, Morocco

© IRD/T. Dahou

Fishing nets drying on Aouchtam Beach, Alboran Marine Protected Area, Morocco.

policy when adaptation is not possible, which is often the case for certain categories of fishing. In the absence of support, monitoring and consultation, these fisheries come into conflict with each other and compromise the success of the conservation project.

Hence the need to develop alternative management scenarios and create forums for dialogue to generate consensus, even if this means redefining the zoning and structural diagnosis of MPAs.

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When science emancipates people

How can we give a voice to people living in areas coveted by economic powers for resource extraction, urbanisation or tourism? This issue is crucial, particularly for local populations, and requires the creation of specific arguments and data acquisition.

© Tapioca outreach team

A fishing family processing their mussel catch in Recife, Brazil.

Living in an area does not necessarily mean having a say in how it is run. To influence decisions, you not only have to be invited to express your views, but you also need to be able to argue and defend your opinions against well-organised economic and political lobbies – hence the need for data co-constructed by scientists and members of civil society. Work along these lines has begun in north-east Brazil, with two fishing communities that share the same issues around asserting their rights in coastal territories, as well as systems of organisation in which women play a central role.

... Through studies in north-east Brazil, research teams are helping fishing communities make their views heard ...

The first community is located in an urban area, on a small island in the heart of the megalopolis of Recife, surrounded by shopping centres and factories in a highly polluted environment. Shellfish are harvested from the mud, mainly by men, while women handle all the stages of processing. Shared between fishermen and major economic groups, this area is the site of conflicts over use, risks to fishermen's health and discrimination. While women represent the community's voice, they are unable to assert the importance of their socioeconomic role, which is therefore invisibilised.

The second community is located two hours from Recife, in Rio Formoso, in a rural area that attracts many tourists whose motorised boats disrupt the local subsistence fishing industry. Men use small boats to catch fish in the estuary, while women harvest shellfish

© Tapioca outreach team

Fishing village of Rio Formoso, Brazil.

and crustaceans in the mangroves. This division of labour is, to some extent, maintained by public policies that favour men in the allocation of boats and access to navigation training. Once again, the community's voice, mainly represented by women, struggles to make its demands heard.

Not only do scientific studies carried out in these areas map environmental vulnerability, analyse pollution risks and assess the state of biodiversity, but they also help develop a participative management approach and back up the two communities' arguments, supporting them in making their voices heard and influencing decisions.

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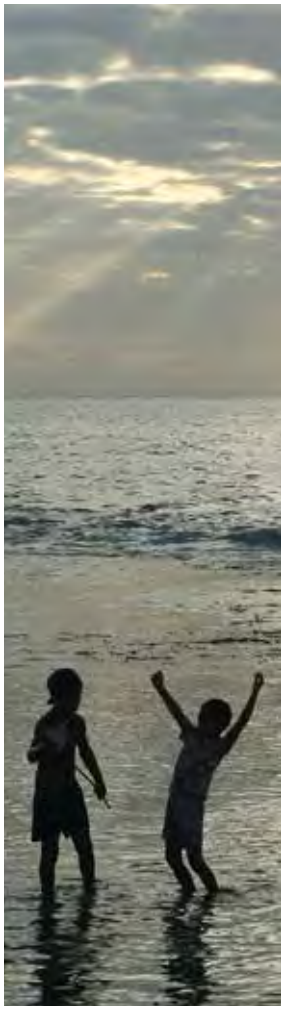

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