Chapter 44

The challenges of modelling coral reef ecosystems

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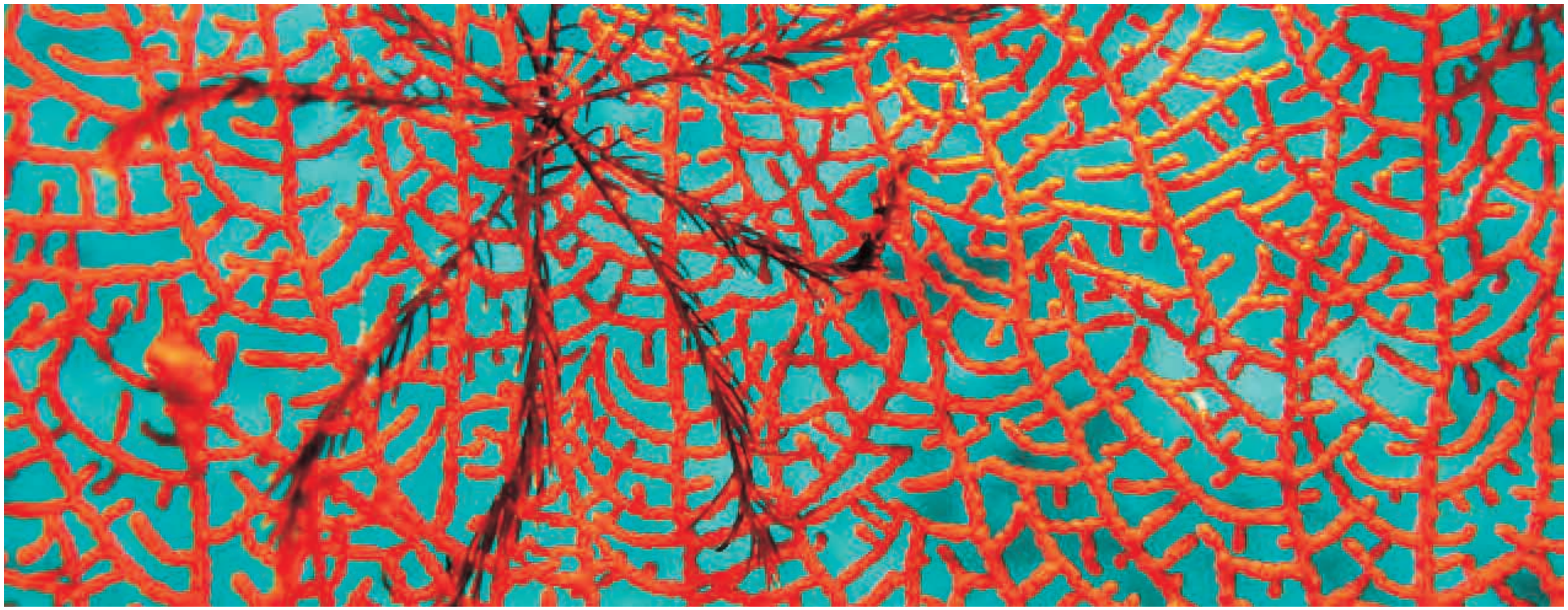


Gorgonian and feather stars, east coast, 2012. © IRD/J. L. Menou

Coral reef ecosystems are complex and their health relies on a balance between the composition of the associated fauna and flora, and the environment. When they are healthy, coral reefs perform many functions that translate into "ecosystem services". They contribute to the well-being of local communities and participate in coastal economic development. Coral reefs support recreational and tourism activities, produce biomass that contributes to economic development and food security through fishing, and provide other services such as protection from wave action and carbon sequestration. These ecosystems also have high symbolic and identity values, and their cultural and heritage aspects are essential at local, national and international levels.

Modelling (box. 33) coral reef ecosystems and the pressures they are exposed to, as well as the interactions with human populations and the links to ecosystem services, is, therefore, a real challenge. The stakes are high: modelling coral reef ecosystems provides a better understanding of the internal and external rules by which they are governed, as well as a detailed analysis of the relationships between the fundamental elements they consist of. Modelling can also estimate the responses of the coral reef ecosystem to different scenarios of future environmental and human pressure. In addition, by including control variables in the model it is possible to determine which combination of actions can be effective for ecosystem stabilization and to avoid major degradation.

Box 33

What is modelling?

Modelling involves defining a set of equations or rules intended to describe a phenomenon and its dependencies in a reproducible and simulated way. A model is used to predict the response of a system to known stresses. Modelling generally requires a calibration phase, which involves estimating a set of parameters so that the model's response is close to what would be expected by experts or reproduces past observations.

There are several types of models and a distinction can be made between "mechanistic" and "statistical" approaches. The mechanistic approach equates the biological, ecological or physical mechanisms that induce the dynamics of the studied phenomenon. The statistical approach builds on the data available to determine a function capable of "approximating" the interactions between the variable to be explained (the phenomenon) and the explanatory variables (the factors that influence the dynamics).

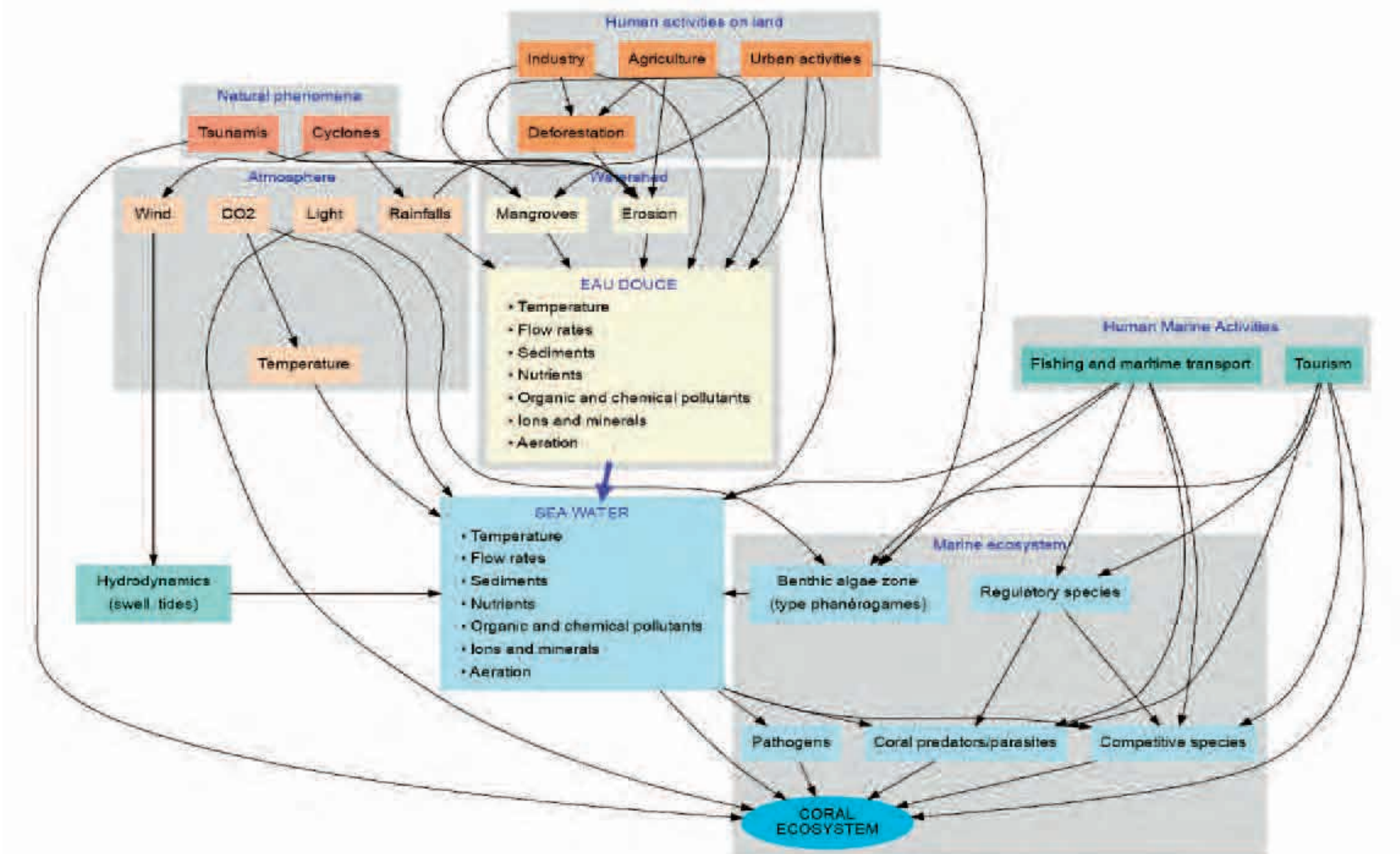


Figure 1: Relationship between the main stressors of the coral reef ecosystem, their potential impacts and the indicators used for assessing the state of the environment. Arrows describe the known relationships between these different elements. © IRD/M. Mangeas

As is often the case with complex ecosystems, the modeler is confronted with spatial and temporal scale issues. Some pressures can be occasional, such as an industrial chemical spill in the lagoon, which massively disrupts the coral reef ecosystem in the very short term. Others can act over several decades, such as the slow rise in seawater temperatures (+0.7°C on average since 1990), which strains the adaptive capacity of the flora and fauna of coral reefs. Similarly, at the spatial level, modelling processes limited to coral colonies will require detailed and highly localized information, which is not available at the scale of a reef of several square kilometers. Model design therefore depends on the nature of the phenomenon under study and the spatial and temporal scales of the relevant and available data. Lastly, a problem-oriented model always represents a compromise between complexity, robustness and the ability to simulate observations

Pressures and impacts

The Knowledge Representation Model of pressures (ICRI, 2016) that impact the health of a coral reef ecosystem (Fig. 1) is the first step in a modelling process. However, there are still many grey areas around abiotic (physico-chemical conditions) and biotic (species interactions) factors that maintain coral systems in a healthy state. This makes it difficult to translate them into equations. Although they are necessary to statistically estimate the relationships between the various components of the ecosystem, there are very few datasets that simultaneously characterize the state of the environment and the health of the coral reef ecosystem.

It becomes even more complex when the health of the coral reef ecosystem is linked to socio-economic factors and coral reef-induced services (Fig. 2). We observe that, if the health of the coral reef ecosystem deteriorates, ecosystem services are affected and users are likely to act accordingly (fewer tourists, fewer fish, recreational activities are less attractive, etc.). If this happens, users will exert pressure on public authorities to implement protective measures. This therefore gives rise to the hypothesis of a dynamic system, structured by a feedback loop and self-regulation between users and the coral reef ecosystem.

This complex issue was recently addressed as part of the CORAIL research project, funded by the European program BEST and conducted in New Caledonia and French Polynesia, between 2013 and 2016. Research institutes, organizations and consulting agencies involved in this project worked in collaboration with local decision-makers and stakeholders to apprehend and co-construct methodological developments and public policy tools for the management of coral reef ecosystems. The study sites were the southern region (Grand Sud) and Hienghène for New Caledonia, and Opunohu and Moorea in French Polynesia.

Bayesian networks

A Bayesian network (KJAERULFF and MADSEN, 2007) is a probabilistic graphical model, representing random variables in the form of an acyclic oriented graph. Its networked architecture transcribes almost directly the models of knowledge representation such as those described in Figures 1 and 2. The cause-effect relationships between variables are not deterministic in this type of modelling, but probabilistic. Thus, the observation of a cause or several causes does not systematically lead to the effect or effects that it triggers, but only modifies the probability of observing them. Bayesian networks are particularly interesting because they simultaneously take into account the a priori knowledge of experts and the information contained in the data. Bayesian networks are mainly used for risk analysis and to support decision-making. Mathematically, the states of variables representing nodes in the Bayesian network are assessed using conditional probability calculation techniques and the Bayesian theorem (box. 34).

For example, a simplified Bayesian network can model interactions between coral reef ecosystems, induced ecosystem services, human pressures and natural disturbances (Fig. 3). Although this model has been successfully tested in other parts of the world, its application in New Caledonia is difficult due to a lack of data. However, one of the advantages of Bayesian networks is that a model can be built based on expert knowledge. It was possible to calibrate a model for targeted areas of New Caledonia using the knowledge of researchers,

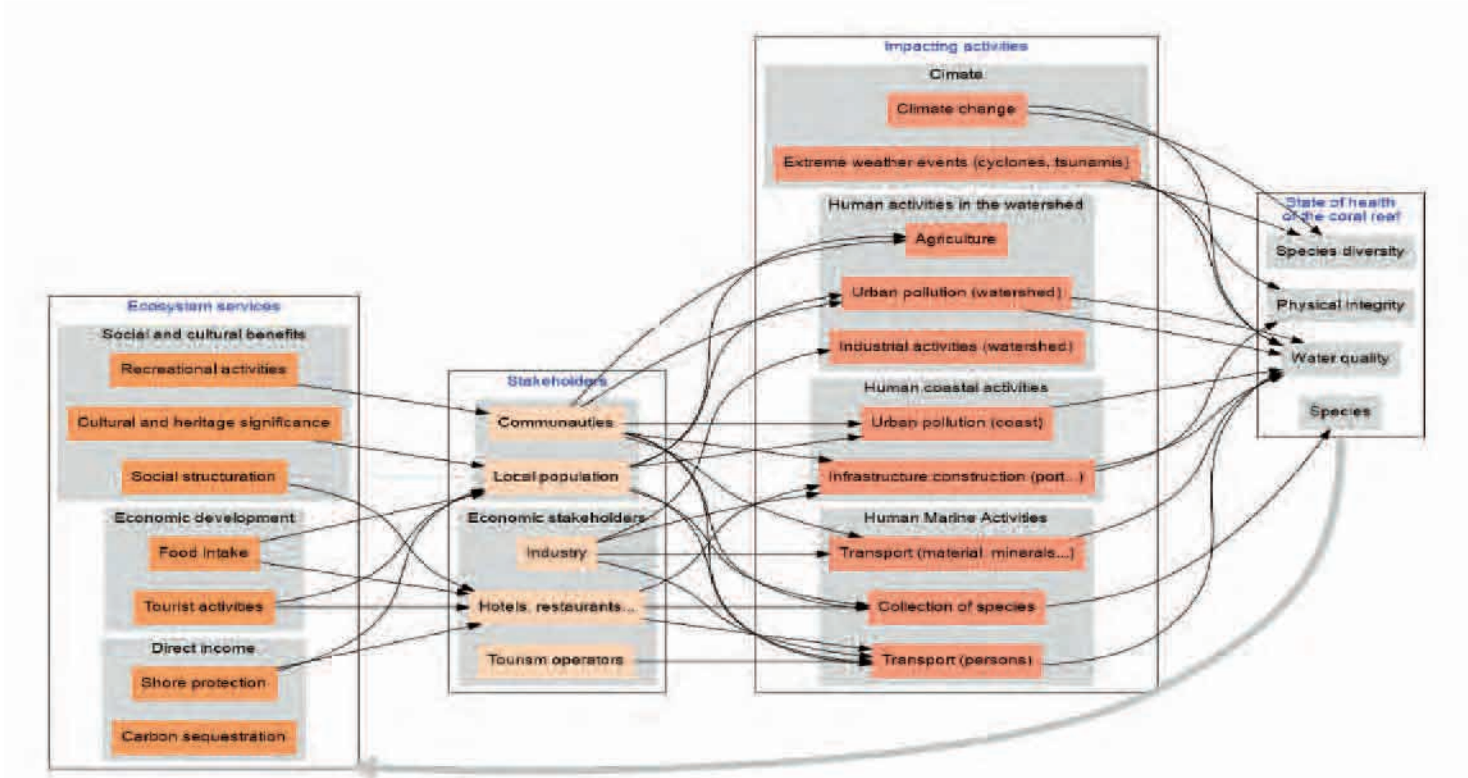


Figure 2: Interactions between users, ecosystem services, pressures on the coral reef ecosystem and potential impacts. The arrows describe the known relationships between these different elements. © IRD/M. Mangeas

inhabitants, lagoon users and stakeholders involved in environmental management.

Feedback modelling would require the use of a more complex model such as a Dynamic Bayesian Model (DBN). However, this simplified approach identified the main trends and proposed scenarios that can then be used to guide the management of coral reef ecosystems in the study area.

Study site

Yaté is a municipality of New Caledonia located in the south of Grande Terre, 80 km from Nouméa (Fig. 4). Its surface area is significant (ranked the 15th largest municipality of France) given the small number of inhabitants (less than 2,000). The population mainly inhabits the narrow coastline where traditional fishing is practiced on the reefs facing the municipality. However, since 2009, one of the world's largest nickel mining plants has been built and is operated by the Brazilian mining operator Vale. The lagoon and coral reefs of the municipality are subject to several forms of pressure yet still thriving, but the population has largely abandoned fishing for mining jobs. The situation in New Caledonia is a typical example of multi-stakeholder negotiations involving diverse issues (environmental risks, mining industries, food uses, etc.). Negotiations on environmental management and the offsetting of mining impacts are very active, sometimes conflicting and often mediatized. The available socio-economic data are provided by the ISEE (Institute of Statistics and Economic Studies of New Caledonia), spatial data by the geographical portal of New Caledonia (www.georep.nc) and biological data by l'OEIL (Environment Observatory in New Caledonia, www.oeil.nc).

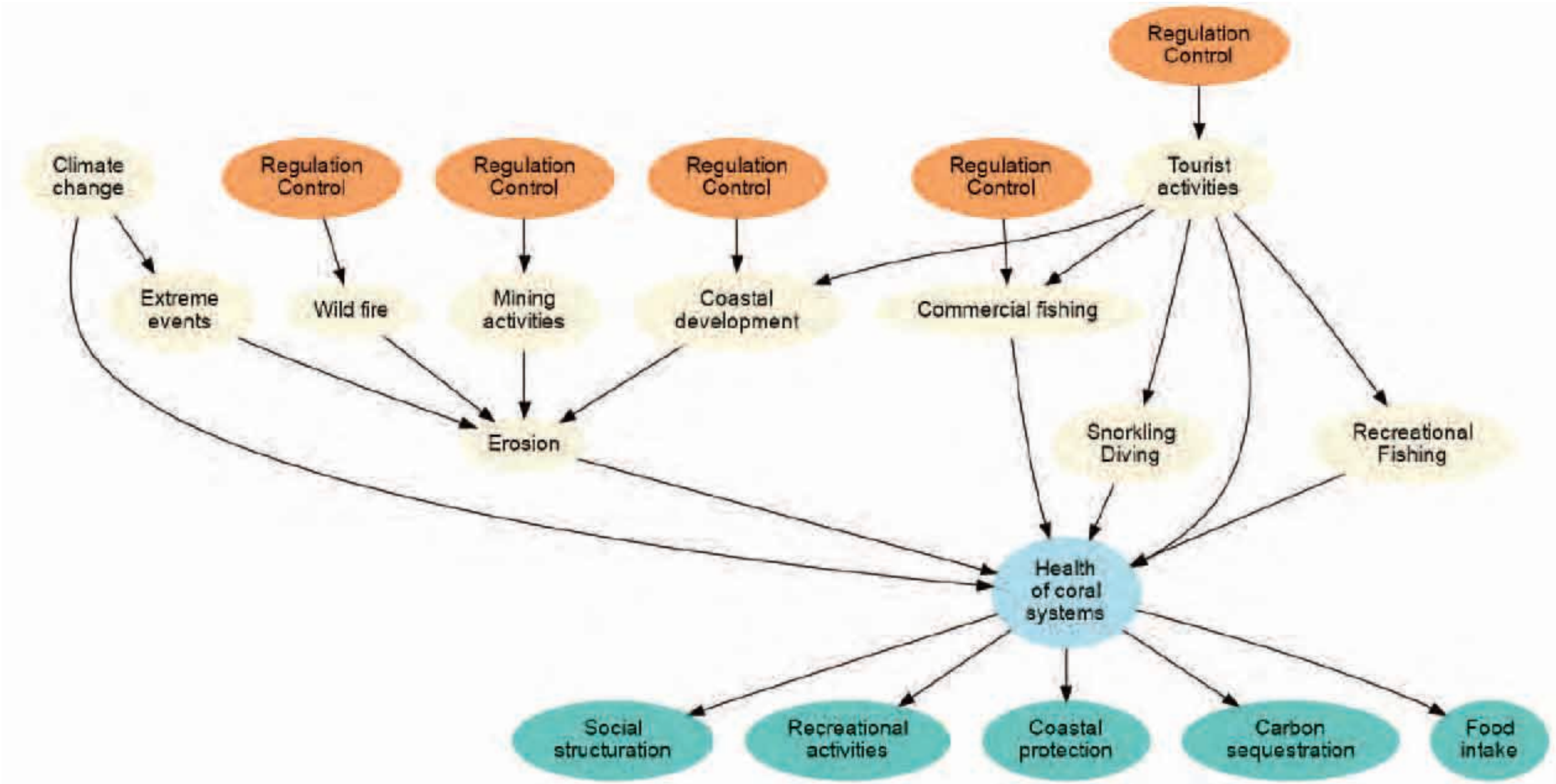
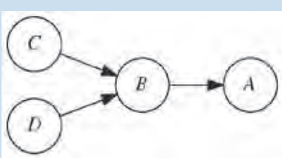


Figure 3: A simplified Bayesian network. © IRD/M. Mangeas

Box 34

The Bayesian theorem



Suppose that each of the four variables A, B, C, D evolves in a set of three states: "strong", "medium", "weak". Conditional probabilities are written as:
P(A = "strong" | B = "weak")

This literally means: probability that A is in the "strong" state, knowing that B is in the "weak" state. In a Bayesian network, if all the conditional probabilities associated with the relationships are known, either by statistical estimation or via an expert opinion, it is possible to calculate the probability that one of the variables is in a certain state according to the known states of the other variables. For example, it is possible to calculate by domino effect P(A = "strong" |C = "strong" and D = "medium") even if the state of B is unknown.

Note that it is possible to estimate the probability of a variable being in a certain state, even if it is a cause and the consequence is known. For example, P(B = "weak" |A = "strong") is calculated using the famous Bayes theorem that calculates P(B|A) from P(A|B), P(A) and P(B):
$P(B|A) = P(A|B)P(B)/P(A)$.

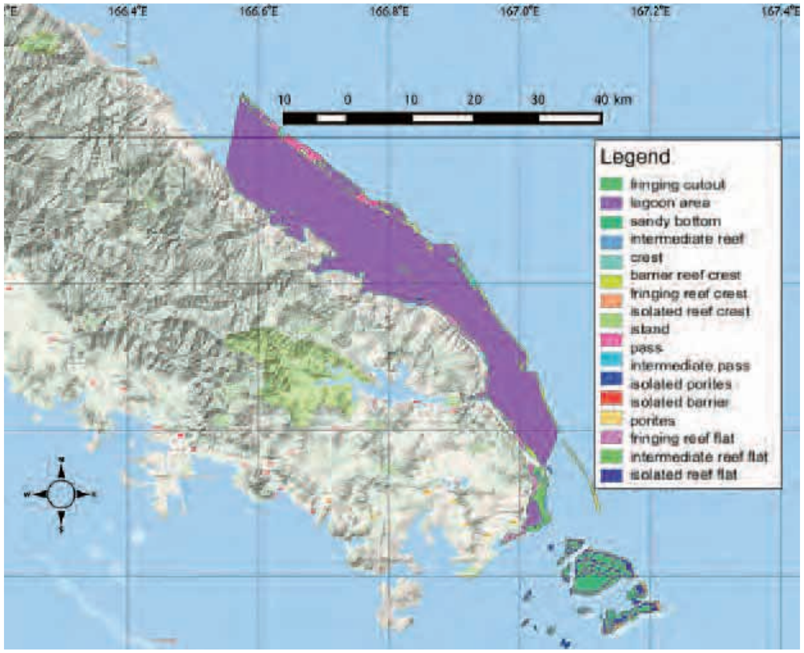


Figure 4: Study sites in the south of Grande Terre, New Caledonia. © IRD/M. Mangeas

The scenarios studied using modelling

The simplified Bayesian network was calibrated to provide satisfactory answers regarding the needs and the current state of health of the coral reefs in the municipality of Yaté. The various pressures were also assessed and the impacts estimated by experts. The aim is to use the model to provide trends for four specific configurations. The four scenarios, which correspond to contrasting but possible situations in this region, are as follows:

– 1: Current scenario: reef and ecosystem services under the human and natural pressures of recent years;
– 2: Establishment of a strict nature reserve in the intertidal and subtidal zone of the lagoon of the municipality of Yaté corresponding to the IUCN protection level I.a.;
– 3: Closure of the Vale plant: mining activity is interrupted, resulting in the dismissal of employees who have to move to new jobs;
– 4: Population growth in the surrounding villages (strong urbanization): massive influx of population into the area.

The coral reefs in the municipality of Yaté are currently considered to be in good health (scenario 1), particularly far from residential areas where the population is sparse. This indicates that regular human and industrial activities in the area have had little impact on the ecosystem to date. However, this does not take into account the possible occasional pollution that could be caused by an industrial spill; such as a malfunction of the nearby marine outfall, which drains the water coming out of the metallurgical plant from the port of Prony into the Havannah Channel. This outfall raises the majority of concerns regarding potential impacts on the ecosystems of the Yaté lagoon.

The resulting model projections for coral reef ecosystem health and recreational activities are shown in Fig. 5. In the case of scenario 2, the IUCN's protection level I.a. requires a ban on all harvesting in the area and the model predicts that ecosystem health will improve. In the event of plant closure (scenario 3), the model predicts that the ecosystem will deteriorate due to inhabitants returning to a more marine-oriented subsistence lifestyle. Lastly, in the event of accelerated urbanization of the area (scenario 4), the high recreational use of the lagoon, coastal development and pollution linked to a high density of inhabitants could have a significant impact on the reefs in the area. On the basis of the available data, the model therefore suggests that a significant increase in attendance would have a stronger impact than the current "ordinary" mining activities (excluding pollution events caused by industrial spill). However, this model was adjusted based on very fragmented data, particularly regarding the indirect and long-term environmental impacts of the mine and plant on all components of the coral reef ecosystem.

One of the major advantages of modelling is the possibility to analyze all situations resulting from the factors used in the model. It is possible to test scenarios combining the "establishment of a reserve" and "plant closure" or "plant closure" with "heavy urbanization". With Bayesian networks it is also possible to identify the most likely cause of an improvement or degradation of the ecosystem, depending on the area and the intensity of the event.

Modelling coral reef ecosystems and the pressures to which they are exposed is highly complex. Societal changes are particularly difficult to apprehend, much more than direct measurable impacts, and just as much

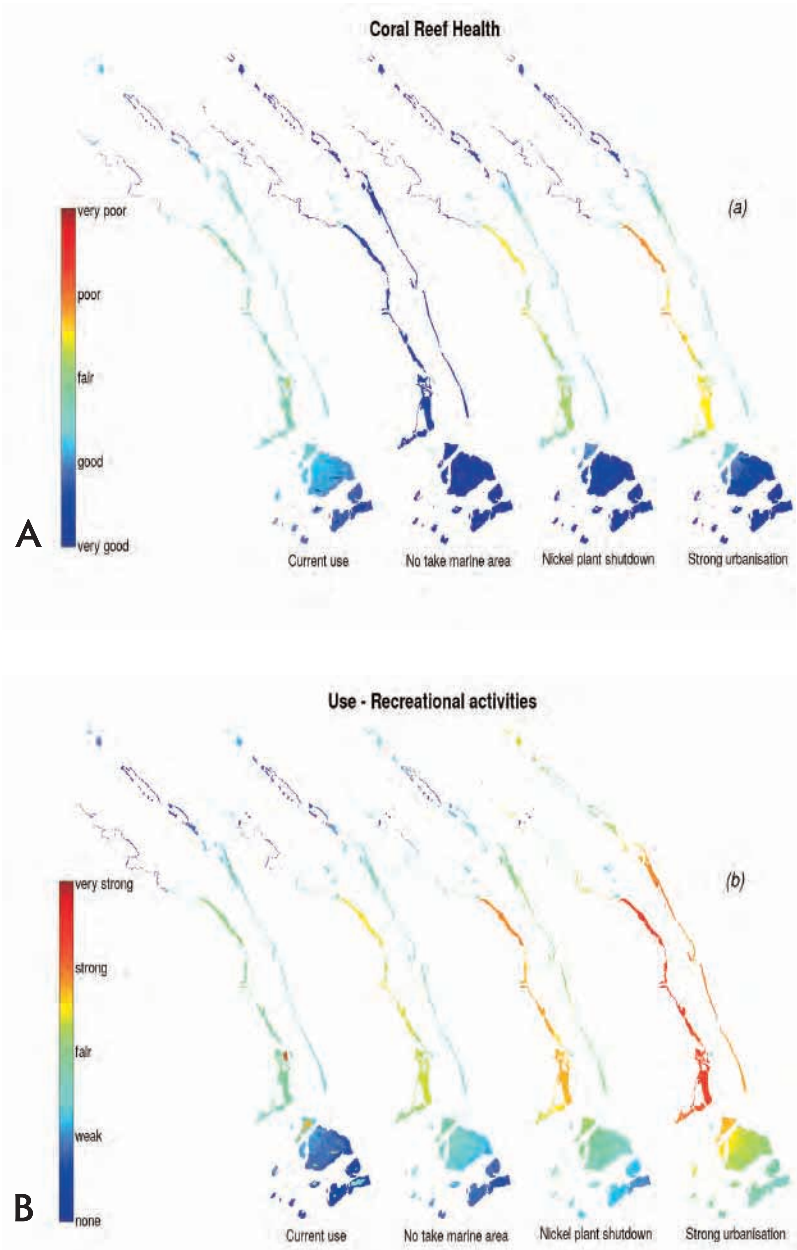


Figure 5: Municipality of Yaté, spatial assessment and evolution under the three scenarios studied.
A: Spatial assessment of coral reef ecosystem health.
B: Spatial assessment of recreational activities in the lagoon. © IRD/M. Mangeas

Mining processing plant, Vale, Prony. © P.-A. Pantz

as indirect impacts with their multitude of interactions between species and environmental variables. In the absence of a series of observations that are sufficiently long and accurate, modelling is highly dependent on expert knowledge. It also requires a multidisciplinary approach to determine the biological, societal and environmental interactions that influence the state of coral reefs and determine their ability to produce ecosystem services. In the case of the municipality of Yaté, because of the uncertainties surrounding the results, modelling is more suited as a tool for consultation and analysis than for prediction. In addition, modelling is not an end in itself; for it to be useful, it must become a user-friendly and efficient management tool so that stakeholders and decision-makers can use it in concerted decision-making processes.

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