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# Spatio-temporal variability of coral reefs at the global scale: causalities, idiosyncrasies and implications for ecological indicators.

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## FINAL REPORT

### I. Project identification

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**Project title:** Spatio-temporal variability of coral reefs at the global scale: causalities, idiosyncrasies and implications for ecological indicators

**[FR] Titre du projet:** Variabilité spatiale et temporelle des récifs coralliens du monde : causalité, idiosyncrasie et implications pour le développement des indicateurs écologiques

**Acronym:** SCORE REEF

**Co-funding organization** (if relevant):

**Principal Investigator:** Valeriano Parravicini (EPHE, CRIOBE) – Mehdi Adjeroud (IRD, ENTROPIE)

**Person who wrote this report:** Valeriano Parravicini (EPHE, CRIOBE)

**Starting date of the project:** sept 2019

**Finishing date of the project:** août 2023

**Scientific summary of project** (maximum of 300 words)

In the marine realm, coral reefs host the highest marine biodiversity and provide crucial services (e.g. edible biomass) that sustain 500 million people worldwide. However, reefs are degrading rapidly due to the overlap between climate-induced disturbance events and a backdrop of chronic stress (e.g. overfishing, increased nutrient load, sedimentation). While reefs are recovering from the most prolonged global coral die-off on record (2015-2016) the effect of multiple stressors is still hard to disentangle and managers or conservation practitioners are charged to take decisions in a context of high uncertainty. Solving this issue would require the development of a set of complementary indicators that evaluate the status of reef considering the taxonomic and the functional facets of biodiversity. These should be built using large-scale and long-term datasets to capture a wide range of environmental, biogeographical and anthropogenic conditions as well as the temporal dynamics of coral reef systems. In SCORE-REEF we merged and analysed global-scale spatial databases on coral reefs and long-term datasets deriving from monitoring programs running in the French Overseas Territories (French Polynesia, New Caledonia, Mayotte, Reunion Island, Eparses Islands, Martinique and Guadeloupe) and other regions (Hawaii, tens of Pacific islands, several sites South Western Indian Ocean, tens of sites in the Caribbean). We evaluated the quality, relevance and inter-operability of available datasets and assessed the temporal dynamics of coral reef benthic and fish assemblages using taxonomic and functional approaches with regard to impacts and to environmental variability. We then discuss the relevance and temporal stability of indicators used within the European Water Framework Directive, GCRMN, IFRECOR and MPAs monitoring, paving the way to the development of region-tailored indicators.

**[FR] Résumé du projet** (maximum de 300 mots)

Dans le domaine marin, les récifs coralliens abritent la plus grande biodiversité marine et fournissent des services cruciaux (par exemple, biomasse comestible) qui soutiennent 500 millions de personnes dans le monde. Cependant, les récifs se dégradent rapidement en raison du chevauchement entre les événements perturbateurs induits par le climat et un contexte de stress chronique (par exemple, surpêche, augmentation de la charge en nutriments, sédimentation). Alors que les récifs se remettent du plus long épisode mondial de mortalité des coraux enregistré (2015-2016), l'effet de multiples facteurs de stress est encore difficile à démêler, et les gestionnaires ou les praticiens de la conservation sont chargés de prendre des décisions dans un contexte d'incertitude élevée. Résoudre ce problème nécessiterait le développement d'un ensemble d'indicateurs complémentaires évaluant l'état du récif en tenant compte des aspects taxonomiques et fonctionnels de la biodiversité. Ces indicateurs devraient être élaborés à l'aide de jeux de données à grande échelle et à long terme afin de capturer une large gamme de conditions environnementales, biogéographiques et anthropiques, ainsi que la dynamique temporelle des systèmes récifaux coralliens. Dans SCORE-REEF, nous avons fusionné et analysé des bases de données spatiales à l'échelle mondiale sur les récifs coralliens et des ensembles de données à long terme provenant de programmes de surveillance menés dans les territoires d'outre-mer français (Polynésie française, Nouvelle-Calédonie, Mayotte, île de la Réunion, îles Éparses, Martinique et Guadeloupe) et d'autres régions (Hawaï, dizaines d'îles du Pacifique, plusieurs sites dans le sud-ouest de l'océan Indien, dizaines de sites dans les Caraïbes). Nous avons évalué la qualité, la pertinence et l'interopérabilité des ensembles de données disponibles et avons évalué la dynamique temporelle des assemblages benthiques et piscicoles des récifs coralliens en utilisant des approches taxonomiques et fonctionnelles en ce qui concerne les impacts et la variabilité environnementale. Nous discutons ensuite de la pertinence et de la stabilité temporelle des indicateurs utilisés dans la directive-cadre européenne sur l'eau, le GCRMN, l'IFRECOR et la surveillance des aires marines protégées, ouvrant la voie au développement d'indicateurs adaptés à la région

Key words (5): spatio-temporal variability, ecological indicators, water framework directive, Marine Protected Areas, GCRMN-IFRECOR Monitoring Network.

**Context and objectives** (around 1,500 characters including spaces)

Coral reefs are extremely dynamic systems, both across space and time. Across space, evolutionary history has shaped reefs so differently that their functioning may markedly change from one region to another. Across time, coral reefs have often shown dramatic variations due to both natural, climatic and anthropogenic stressors. Because of their importance from both an ecological and a socioeconomical point of view, reefs are presently the subject of several global (e.g. Global Coral Reef Monitoring Network; GCRMN) and national (e.g. French Initiative for Coral Reefs, IFRECOR, NOAA) monitoring programs with the specific goal of continuously assessing their status and eventually undertake conservation actions. However, the highly variable nature of reefs and the lack of comprehensive analyses of their temporal trajectories across a large range of environmental and anthropogenic conditions make it difficult to define 'reference' or 'desirable' conditions. Managers and conservation practitioners have to take decisions under high uncertainty and with the frustrating feeling that the resources and the time invested to surveys did not delivered the expected outcomes. This is, for example, the case of the indicators proposed within the context of the Water Framework Directive that should be implemented according to the EU legislation. Some well-known WFD indices (e.g. AMBI, M-AMBI, CARLIT) have proved themselves a powerful monitoring tool to achieve a good ecological status for coastal waters. Unfortunately, this is not the case for some marine ecosystems, where the implementation of reference indices is still disappointing due to the high ecological complexity. For example, WFD indices implemented for coral reefs in French Overseas Departments are mainly based on total coral cover or total algal cover, two variables that alone cannot capture the complexity of the system and that do not have the same meaning in different biogeographical contexts. In SCORE-REEF we took advantage of the scientific knowledge produced on coral reefs since

the beginning of the GCRMN, IFRECOR, WFD programs (~20 years). We critically reviewed the ecological indicators used, we analysed large datasets to propose novel approaches. We worked on the consolidated scientific evidence that disturbance may drive coral reefs through a vast set of trajectories that may greatly differ from the classical coral-algae shift. These trajectories may of course depend on the disturbance dynamics, but also on the context-dependency and region-specificity of coral reef functioning, with important consequences for indicators that need a reference condition.

**[FR] Contexte et objectifs** (environ 1 500 caractères espaces inclus)

Les récifs coralliens sont des systèmes extrêmement dynamiques, à la fois dans l'espace et dans le temps. Dans l'espace, l'histoire évolutive a façonné les récifs de manière si différente que leur fonctionnement peut changer considérablement d'une région à l'autre. Dans le temps, les récifs coralliens ont souvent montré des variations dramatiques en raison de stress naturels, climatiques et anthropiques. En raison de leur importance tant du point de vue écologique que socio-économique, les récifs font actuellement l'objet de plusieurs programmes de surveillance à l'échelle mondiale (par exemple, le Global Coral Reef Monitoring Network; GCRMN) et nationale (par exemple, l'Initiative française pour les récifs coralliens, IFRECOR, NOAA) dans le but spécifique d'évaluer en continu leur état et éventuellement d'entreprendre des actions de conservation. Cependant, la nature hautement variable des récifs coralliens et le manque d'analyses exhaustives de leurs trajectoires temporelles à travers une large gamme de conditions environnementales et anthropiques rendent difficile la définition de conditions 'de référence' ou 'désirables'. Les gestionnaires et les professionnels de la conservation doivent prendre des décisions dans des conditions d'incertitude élevée et avec le sentiment frustrant que les ressources et le temps investis dans les enquêtes n'ont pas produit les résultats attendus. C'est, par exemple, le cas des indicateurs proposés dans le cadre de la Directive-cadre sur l'eau qui devraient être mis en œuvre selon la législation de l'UE. Certains indices bien connus de la DCE (par exemple, AMBI, M-AMBI, CARLIT) se sont révélés être des outils de surveillance puissants pour atteindre un bon état écologique des eaux côtières. Malheureusement, ce n'est pas le cas pour certains écosystèmes marins, où la mise en œuvre d'indices de référence est encore décevante en raison de la haute complexité écologique. Par exemple, les indices de la DCE mis en œuvre pour les récifs coralliens dans les départements d'outre-mer français reposent principalement sur la couverture totale des coraux ou la couverture totale des algues, deux variables qui seules ne peuvent pas saisir la complexité du système et qui n'ont pas le même sens dans différents contextes biogéographiques. Dans SCORE-REEF, nous avons tiré parti des connaissances scientifiques produites sur les récifs coralliens depuis le début des programmes GCRMN, IFRECOR, DCE (~20 ans). Nous avons examiné de manière critique les indicateurs écologiques utilisés, analysé de vastes ensembles de données pour proposer des approches novatrices. Nous avons travaillé sur les preuves scientifiques consolidées selon lesquelles les perturbations peuvent conduire les récifs coralliens à travers un vaste ensemble de trajectoires qui peuvent différer considérablement du changement classique corail-algues. Ces trajectoires peuvent bien sûr dépendre de la dynamique des perturbations, mais aussi de la dépendance au contexte et de la spécificité régionale du fonctionnement des récifs coralliens, avec des conséquences importantes pour les indicateurs nécessitant une condition de référence.

## II. Project participants

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### List and attendance of project participants

NOM Prénom	Status	Affiliation	Country	Meeting1	Meeting2	Meeting3	Meeting4
Adjeroud Mehdi	PI	IRD	France	X	X	X	
Barneche Diego	Guest	Australian Institute of Marine Science	Australia			X	X
Bigot Lionel	Member	University of Reunion Island	France	X			
Brandl Simon J.	Post-Doc	University of Texas	USA	X		X	
Carlot Jérémy	Post-Doc	FRB, puis EPHE	France		X	X	X
Casey Jordan	Guest	University of Texas	USA			X	
Darling Emily	Member	Wildlife Conservation Society	USA	*	*	*	*
Delacambre Emily	Guest	EPHE	France			X	
Dirberg Guillaume	Guest	MNHN	France		X		
Donovan Guillaume	Member	University of Hawaii Manoa	USA	X			
Dornelas Maria	Member						X
Graham Maria	Guest	University of Lancaster	UK			X	
Guilhaumon François	Member	IRD	France	X			
Job Sandrine	Member	CORTEX	France	X	X		
Karkarey Rucha	Member	University of Lancaster	UK				*
Keith Sally	Member	Lancaster University	UK	X			
Maire Eva	Guest	Université de Montpellier	France			X	
Madin Joshua	Guest	University of Hawaii	USA				
Maréchal Jean-Philippe	Member	Marine Institute of Martinique	France	X	X		
McWilliams Mike	Guest	Hawaii Institute of Marine Biology	UK			X	X
Monnier Olivier	Guest		France	X	X		
Morais Renato A.	Guest	CRIOBE	France			X	
Mouillot David	Guest	University of Montpellier	France			X	
Obura David	Member		Kenya				
Parravicini Valeriano	PI	EPHE	France	X		X	X
Paul-Costesec Emma	Guest	EPHE	France			X	
Schiettekatte Nina	Guest	University of Hawaii	USA			X	
Strona Giovanni	Member	University of Helsinki	Finland	X		X	
Stuart-Smith Rick	Member	University of Tasmania	Australia	X			

Villéger Sébastien	Guest	CNRS	France			X	X
Wickel Julien	Member	MAREX	France	X	X		
Williams Ivor	Member	NOAA	USA				

### III. Activity report

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#### III.1 Description of the work conducted and scientific results obtained: for the scientific reader.

In the context of the SCORE-REEF project, the working group has set the ambitious goal of undertaking the most comprehensive analysis of the spatiotemporal variability of reefs ever attempted. The analysis of such variation is extremely important for various reasons, but considering the goals of SCORE-REEF, the most significant aspect is certainly related to ecological indicators. Not knowing the variability of a system's state is equivalent to not being able to determine whether the observed state corresponds to normal criteria or if it is an altered state that needs correction through conservation measures.

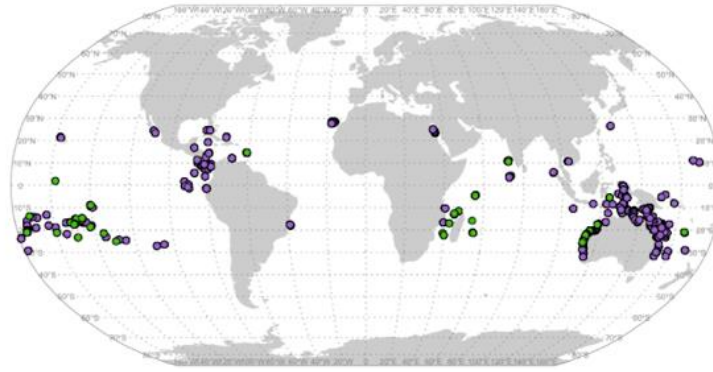
To undertake this ambitious work, we proceeded in successive steps:

1. Construction of the spatiotemporal database on a global scale;
2. Definition of ecological regions and reef status through simplified non-taxonomic indicators;
3. Extrapolation of species-specific functional traits for the analysis of ecological functions;
4. Development of techniques for studying the ecological functions performed by corals and fish;
5. Analysis of global spatiotemporal variability and discussion of implications for defining ecological indicators.

#### Construction of the global spatiotemporal database

We have built two databases: one primarily spatial and the other spatiotemporal (Figure 1). The spatial database covers 13,050 transects for fish and benthic community counts in 485 sites distributed across 14 biogeographic regions in all oceans. In addition to this, the database contains various information related to socio-economic variables (human population density, distance from reefs, protection through Marine Protected Areas) and environmental variables (temperature, salinity, pH, climatic stress).

The spatiotemporal database consists of time series on the composition of benthic communities and fish in 11 regions worldwide (Iles Eparses, Lakshadweep, Martinique, Mayotte, Mexico, New Caledonia, La Réunion, Seychelles, French Polynesia, western coast of Australia, Brazil).



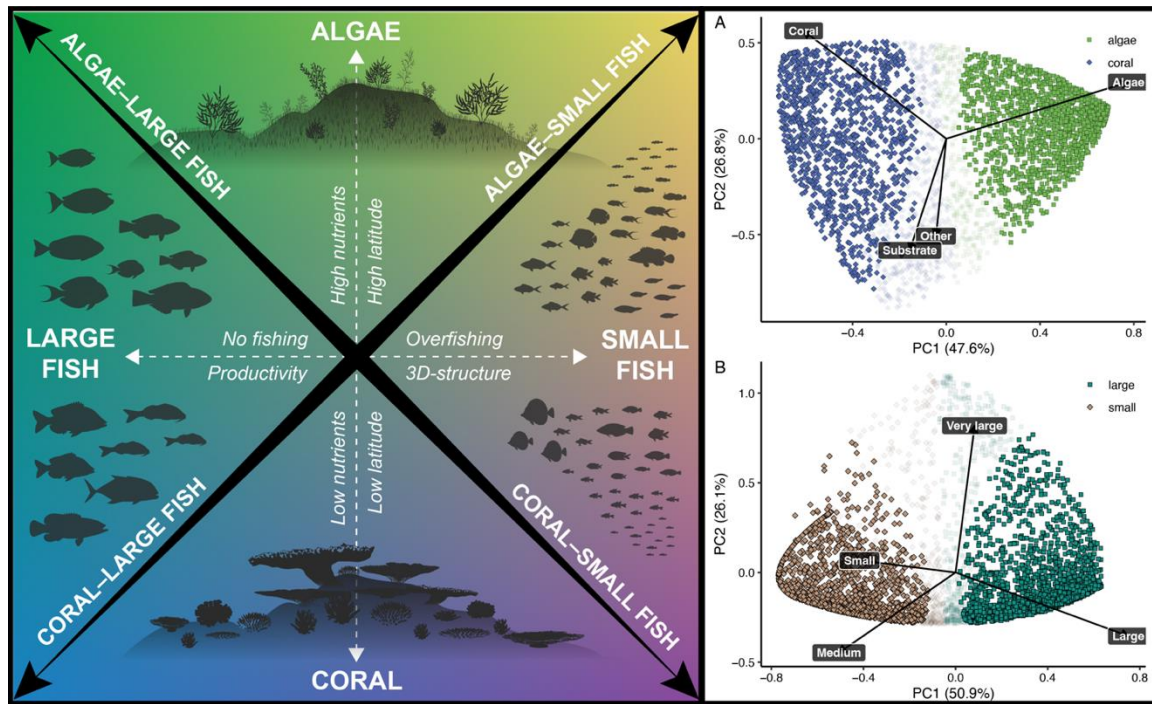
**Figure 1.** Spatio-temporal dataset built in the context of SCORE REEF. Purple dots represent spatial data while green dots are referred to sites where we obtained time series information for both benthic and fish communities.

### **Definition of ecological regions and reef status through simplified non-taxonomic indicators**

The compilation of databases in French overseas territories has highlighted substantial heterogeneity in the available data. Regarding benthic communities, some databases (French Polynesia) have good taxonomic detail concerning corals, which are identified at the genus level. However, they do not provide any information on other taxonomic groups (macroalgae, filamentous algae, coralline algae, detritus, sponges, ascidians, bryozoans, etc.). Most other databases, on the other hand, report information on coral and algae cover without providing further details. Similarly, for fish communities, some databases report the species and size of each individual, while others only report size and family or simply the abundance of a selection of families.

Given the significant heterogeneity of these databases, the first question we addressed is whether low-resolution information can be sufficient to describe the state of reefs. This work is part of a scientific article currently under review at the journal *Ecology Letters*.

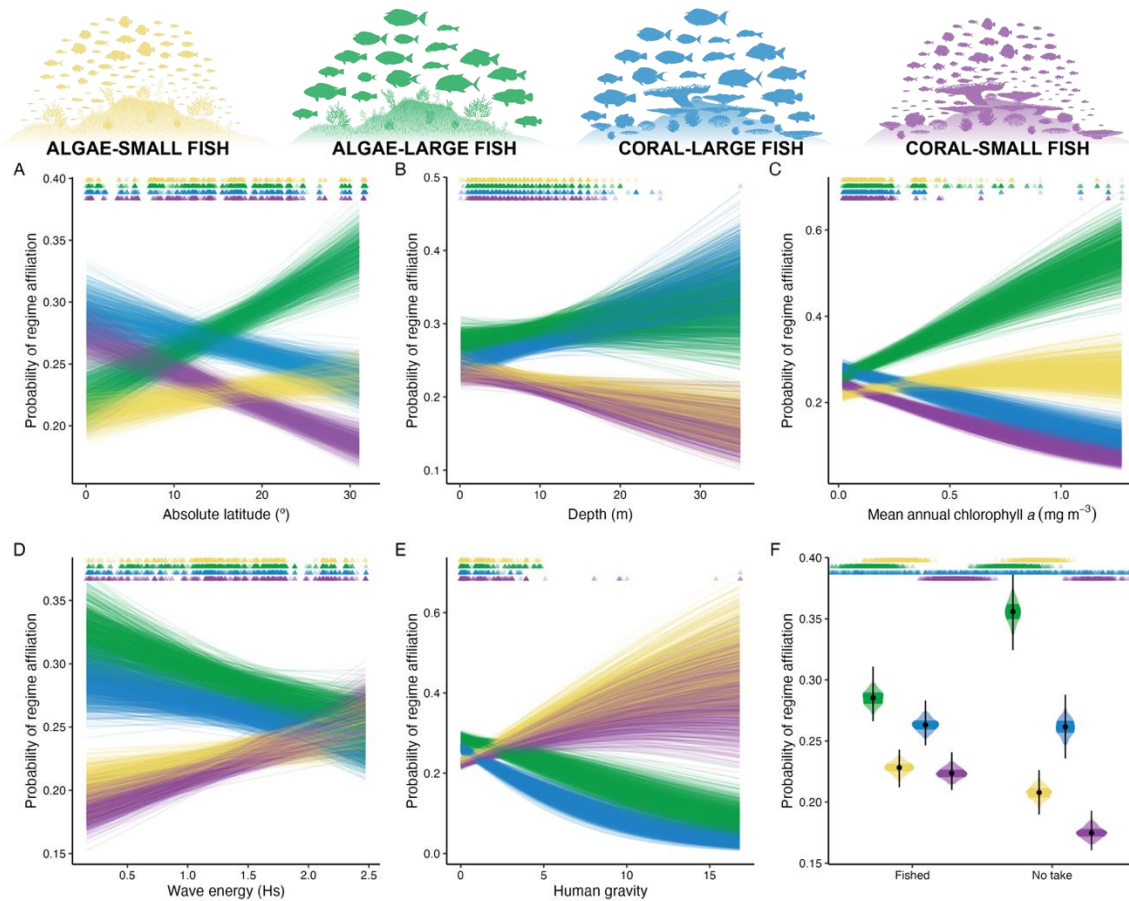
In general, we used extremely simple variables for both benthic communities (coral cover, bare substrate cover, algae cover, and the category "other") and fish communities (abundance of individuals corresponding to 5 size classes). We then identified two possible states for fish communities and two states for benthic communities, resulting in four possible states for the system (Figure 2).



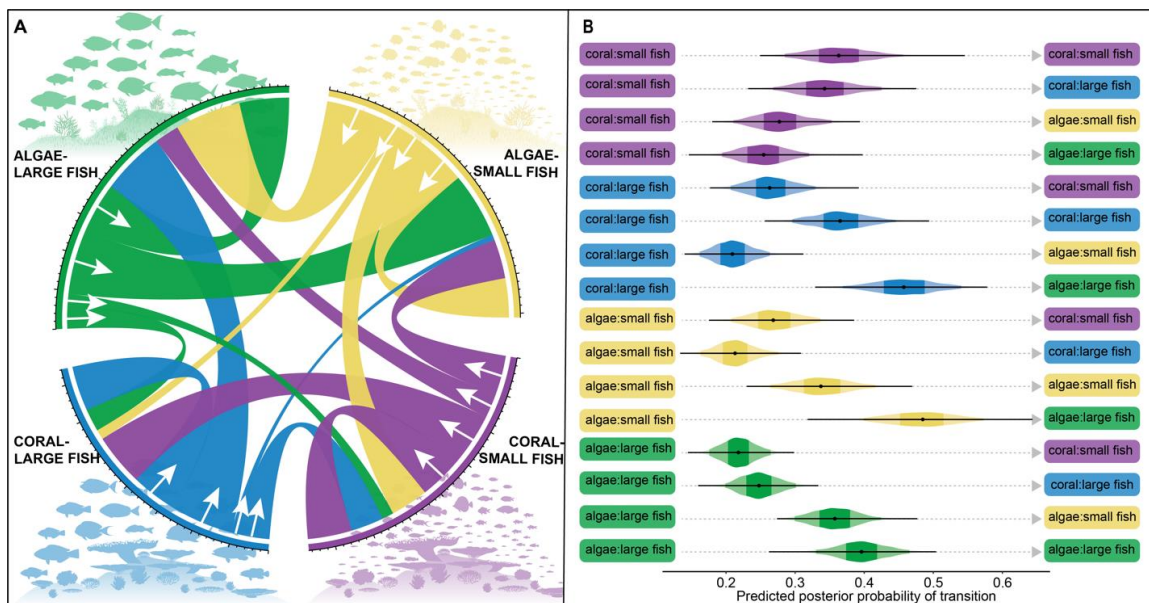
**Figure 2.** Definition of the 4 ecosystem states using a double-dicothomy approach. **A.** PCA showing the variability across the global dataset and the definition of the two clusters for benthic communities. **B.** PCA showing the variability across the global dataset and the definition of the two clusters for fish communities.

From a spatial perspective, we observed significant variation that is partially explained by both environmental and anthropogenic variables (Figure 3). This highlights that even highly aggregated variables, without taxonomic details, are capable of capturing a broad range of reef states that respond to both anthropogenic and environmental influences. It can be observed that an increase in local primary production (chlorophyll) corresponds to an increased likelihood of a reef being dominated by algae and large herbivores. Similarly, we can note that an increase in human influence corresponds to an increased likelihood of a reef belonging to states dominated by small-sized fish. We have thus hypothesized that monitoring these simple states could serve as an 'early alert' system, allowing the detection of significant changes that may warrant more high-resolution studies.





**Figure 3.** Relationship between environmental and anthropogenic variables and the probability that a reef belongs to one of the four states previously identified.



**Figure 4.** Transitions between states observed in the time-series dataset.

To verify if the spatial variability of this extremely simplistic approach corresponds to temporal responsiveness, we conducted an analysis to understand if there are transitions between one state and another in our temporal dataset. Our analyses highlight that on a global scale, temporal

transitions between the 4 states of the system are quite frequent. In particular, there is one transition that occurs particularly often, and it is the transition towards the state characterized by algae and large-sized fish. This tendency to shift from states dominated by corals to states dominated by algae and large herbivores is quite general and implies a rather clear global trend (Figure 4).

### **Extrapolation of Species-Specific Functional Traits for Ecological Function Analysis**

The approach based on non-taxonomic descriptors has the advantage of allowing the comparison of different data sets with limited standardization. At the same time, however, extremely generic non-taxonomic indicators, such as size in the case of fish, can lead to a lack of resolution in identifying ecological states. An extremely promising approach that allows the analysis of systems from different perspectives is functional ecology. Instead of focusing on static indicators (such as coral cover or total fish biomass), it involves quantifying relevant ecosystem processes, such as the calcification rate or biomass production rate. These indicators are multidimensional when working in the context of multiple functions and directly relate to the work done by the system, allowing for an extremely detailed analysis of community states.

Regarding the need for information, functional analysis requires knowledge of functional traits for each species studied. In the case of fish, fundamental functional traits include metabolic rate, diet, growth rate, elemental composition of the species (proportion of C, N, and P), and elemental composition of the diet. For corals, it involves morphological measurements, calcification rate, photosynthesis, and growth.

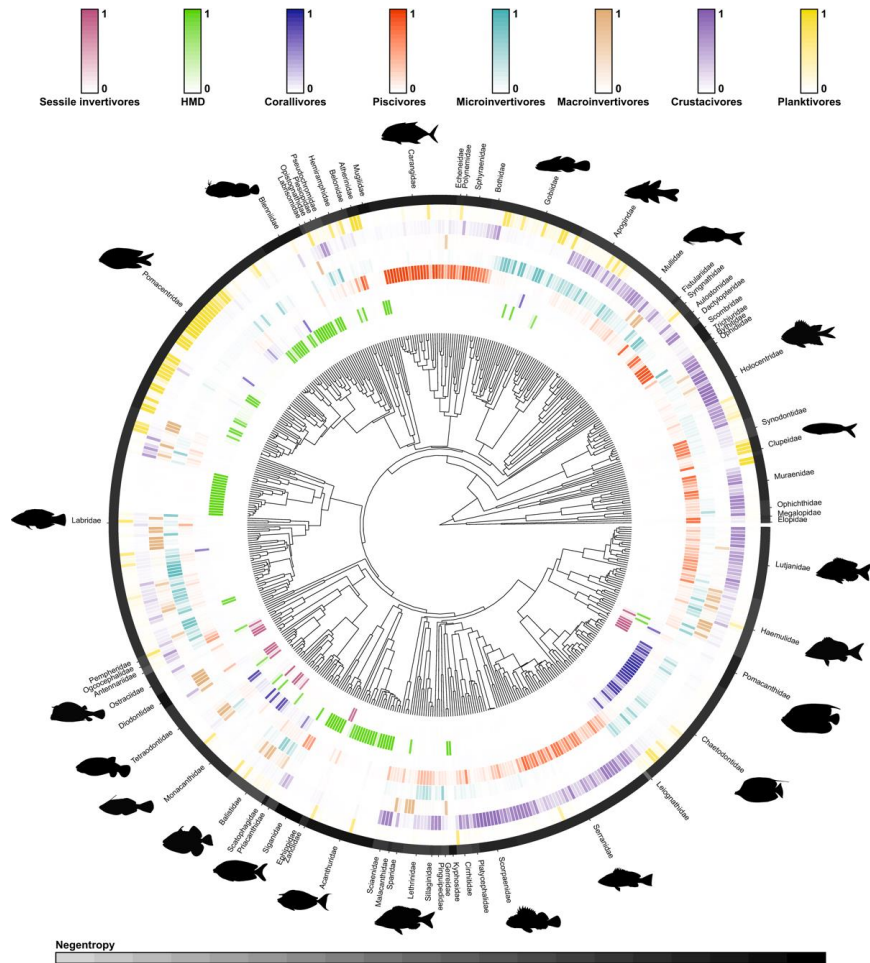
To obtain such information, we collected data in French Polynesia, established collaborations for species from other geographical areas, and conducted literature reviews. Subsequently, once information for a subset of species (ranging from 150 to 770 species) was obtained, we used the phylogenetic relationships between different species to impute data for all species in our datasets (~1800). As an example, the analysis of fish feeding habits highlighted the low reliability of currently used information in the literature and led to the development of a completely new classification (Figure 5). The same analysis, conducted for coral species, identified groups of species with similar characteristics, information that was incorporated into subsequent analyses.

### **Development of Techniques for Studying Ecological Functions Performed by Corals and Fish**

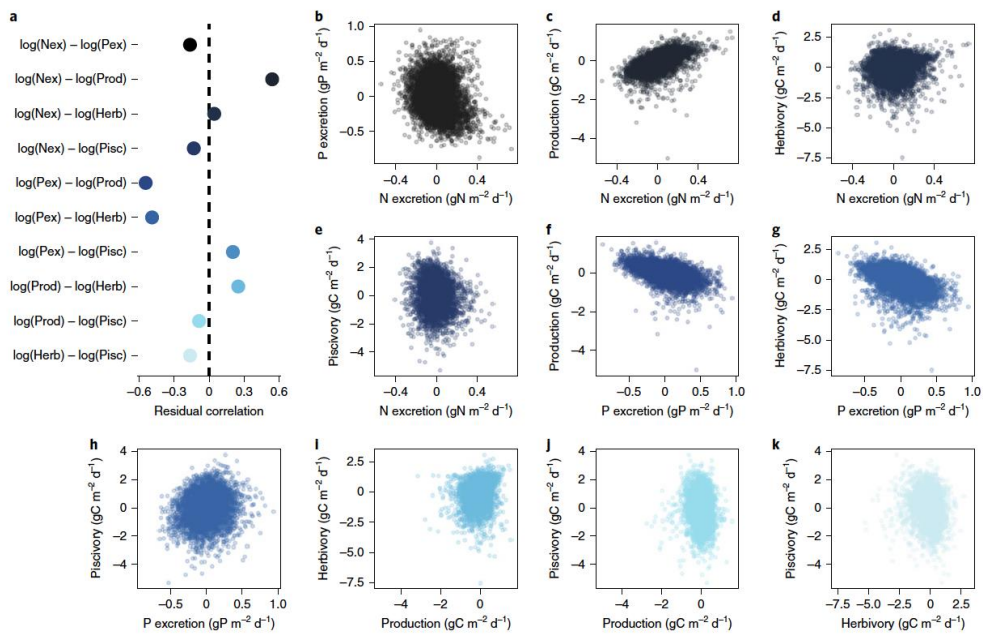
Functional analysis is traditionally conducted through the direct analysis of functional traits. However, in our case, we decided to focus on estimating actual ecological functions. Concerning fish, we identified the following functions: biomass production, biomass turnover, herbivory rate, piscivory, planktivory, nitrogen excretion, and phosphorus excretion. Regarding benthic communities, we quantified the following ecological functions: primary production, organic growth, inorganic growth, total growth, rugosity, three-dimensional space.

For fish, these analyses were carried out using bioenergetic models developed in the context of this work. In a preliminary phase, we focused on estimating fish functions globally to study the existence of relationships between these functions.

We were able to highlight significant relationships between ecological functions (Figure 6). This result implies that it is not possible to maximize all ecological functions simultaneously. Therefore, regarding reef management, weighted choices will need to be made to decide which functions can be maximized and which cannot



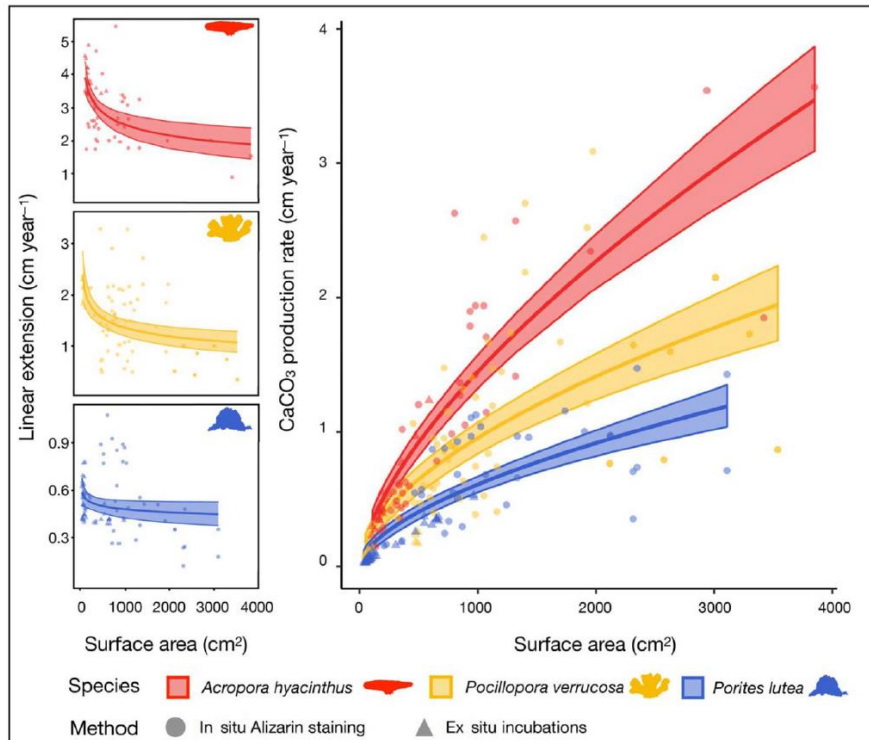
**Figure 5.** Example of phylogenetic extrapolation of diet data to infer the diet of species for which data were not available in the literature



**Figure 6.** Correlation between functions performed by reef fishes

Regarding the coral community, we tested our approach in a case study in French Polynesia. The local-scale test was necessary because there is less tradition in the use of bioenergetic models for benthic communities. We chose to conduct an initial test in a region for which there is significant data availability (Moorea).

Our analyses revealed allometric growth for corals (Figure 7). The direct implication of this result is that young corals grow faster. In the event of a disturbance, the recruitment of small colonies plays a much more significant functional role than was evident from the existing literature. In any case, our analysis allowed us to conclude that our approaches enable us to obtain reliable estimates and can therefore be applied on a larger scale.



**Figure 7.** Example of allometric growth for the dominant coral genera in Moorea

### Analysis of Global Spatiotemporal Variability and Discussion of Implications for the Definition of Ecological Indicators

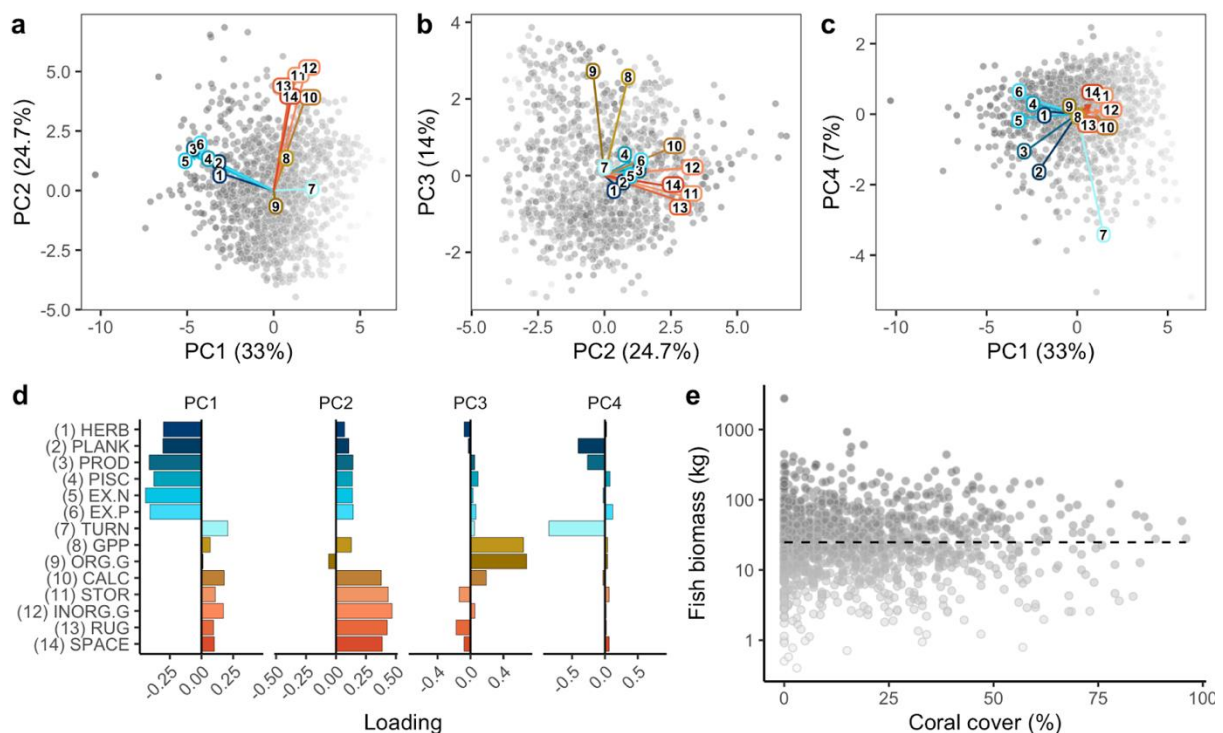
We subsequently estimated the 14 ecological functions on a global scale, thus conducting the first study of its kind on a global scale.

We charted the global spectrum of coral reef functions by projecting organismal rates of 14 essential ecosystem functions onto benthic and fish surveys from 1,100 reefs worldwide. In particular, we estimated 7 benthic functions — Gross Primary Production, Organic Growth, Inorganic Growth, Calcification, Carbon Storage, Rugosity, Branches Space — and 7 functions performed by fish communities — Herbivory, Planktivory, Piscivory, Biomass Production, Biomass Turnover, Excretion of Nitrogen and Excretion of Phosphorous (see Methods). Our multidimensional approach explicitly accounts for potential trade-offs among functions and allows us to explore the major axes of functional variation across biogeographical and perturbation gradients. Furthermore, we use time-series from several regions to show-case how ecosystem functions behave across temporal cycles of disturbance and recovery.

We see substantial variation in the 14 functional rates across the reefs examined, spanning three to five orders of magnitude for most functions. However, contrary to what might be expected for ecosystems considered to exist in alternate states, this variation is continuous and unimodal in all the functions examined. The continuous nature of reef functions is also apparent when looking at reefs in a multidimensional functional space as described by a Principal Component Analysis. There are continuous gradients across the functional space, which are partly associated with the biomass or relative abundance of different organisms rather than discrete clusters of reefs

Using the same PCA identified the major axes of coral reef ecosystem functioning. The high dimensionality of coral reef functional space can be collapsed into four main axes containing 78.9% of the global variation (Figure 8). As indicated by the PCA loadings, the first two axes are associated to the functions performed respectively by fish (PC1, 33.5% of variation) and benthic communities (PC2 24.5% of variation), which, between them, are orthogonal. The third axis (13.8% of variation) identifies functions performed by primary producers, as indicated by the high loadings of Gross Primary Productivity and Organic Growth. The fourth axis (7.1% of the variation), instead, runs from highly productive reefs with high planktivory rates to poorly productive reefs characterized by high biomass turnover.

Considering the substantial amount of literature supporting the idea of a large inter-dependence between fish and benthic communities, the orthogonality we found between fish and coral functions is surprising. However, this pattern is also reflected in how uncorrelated total fish biomass is to coral cover.



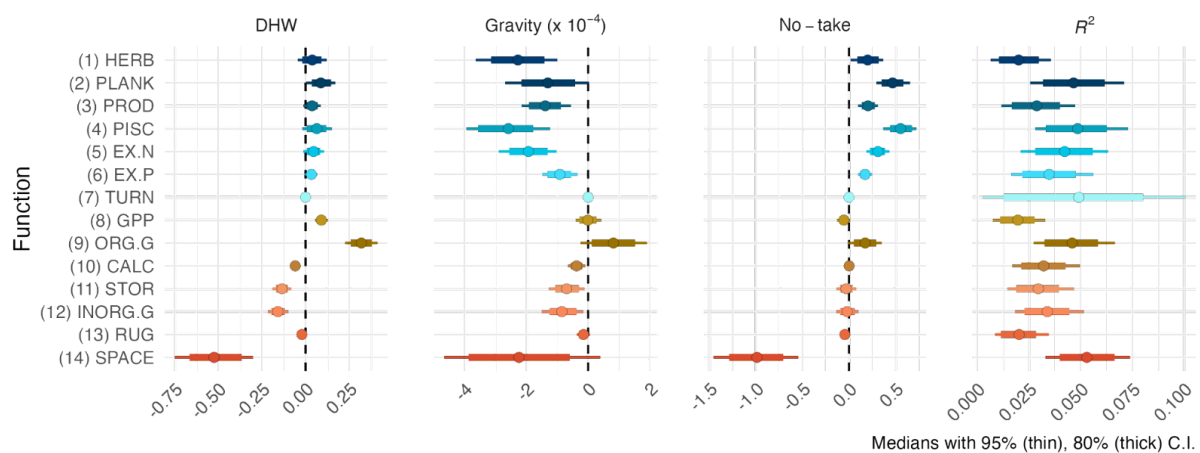
**Figure 8.** Global Principal Component Analysis for the 14 functions performed by coral reefs.

In our investigation, we delved into the potential of environmental and anthropogenic variables to elucidate the global variation in reef ecosystem functions. Specifically, we employed a Bayesian Linear Model to examine the associations between each function, environmental variables — Chlorophyll a, Net Primary Production, Salinity, Sea Surface Temperature, pH — and anthropogenic variables — Human Gravity, Degree Heating Weeks, and the presence of no-take Marine Protected Areas (see

Methods). To address collinearity among environmental variables, we incorporated the first two axes of a Principal Component Analysis (PCA) into the model. Human Gravity, following the approach by Cinner et al., served as a variable describing fishing effort and general proximity to humans. Degree Heating Weeks (DHW), referencing the year preceding the surveys, was included to account for the impact of heatwaves on coral reefs.

Consistent with prior literature, our analysis revealed discernible effects of DHW and Human Gravity on coral reefs. Specifically, DHW appeared to favor functions associated with primary producers (e.g., GPP and Organic Growth) while impacting functions linked to calcifiers (e.g., Branches Space, C storage, and Inorganic Growth). Simultaneously, Human Gravity influenced all fish functions, except biomass turnover, primarily affecting consumption rates (Piscivory and Herbivory) and nitrogen excretion. No-take Marine Protected Areas were associated with a general increase in fish functions (mostly Piscivory and Planktivory) but did not seem to improve any benthic functions. Interestingly, Branches Space tended to be lower within no-take MPAs, a counterintuitive association likely attributed to the larger DHW values observed within MPAs compared to other locations. While this result underscores the need for improved spatial planning of the global MPA network, it is unlikely that protection alone can reduce the three-dimensionality of benthic communities.

Our analysis confirms the significant impact of climate change and human proximity on coral reef functioning. However, we highlight that the variability around the mean effects is substantial, allowing reefs to exhibit almost any functional performance across the entire gradient of human impact. Our models seldom explain more than 20% of the global variation in reef functions, and without environmental variables, the explanatory power of anthropogenic variables alone drops to an average of 2% (see Figure 3). While we do not intend to minimize the well-known and concerning effects of these factors, our global-scale findings underscore a vast spectrum of functional configurations that cannot be solely explained by the shift between a few alternative states triggered by anthropogenic variables. Mapping DHW and Human Gravity onto the global functional space further demonstrates that the least disturbed reefs — comprising the 5% of reefs with the lowest Human Gravity — share a functional profile that largely overlaps with the most impacted reefs — encompassing the 5% of reefs with the highest Human Gravity.



**Figure 9.** Relationship between DHW, human gravity and MPAs and the 14 ecological functions performed by reefs.

### **III.2.1 Introduction (around 300 characters including spaces): for large audience**

SCORE-REEF, an innovative project, assesses the global health of coral reefs. Merging global databases with long-term data from French overseas territories and other regions, the project develops indicators to guide reef conservation amid multiple pressures.

### **III.2.2 [FR] Introduction (environ 300 caractères, espaces inclus): pour grand public**

SCORE-REEF, projet novateur, analyse la santé des récifs coralliens mondiaux. Fusionnant des bases de données mondiales et des données à long terme de territoires français d'outre-mer et d'autres régions, le projet développe des indicateurs pour guider la conservation des récifs face aux multiples pressions.

### **III.3.1 Methods and approaches used for your project (around 700 characters including spaces): for large audience**

The SCORE REEF project brings innovation to the table with its unique methods. By combining bioenergetic modeling, artificial intelligence, and vast global datasets, we're on a mission to understand and evaluate the well-being of coral reefs. Our approach is like a toolkit that uses simple, easy-to-understand descriptions and dives deep into 14 complex ecological functions tied to essential ecosystem services. Imagine it as a high-tech guide, blending the latest technologies with extensive data to shine a spotlight on the health of coral reefs worldwide.

### **III.3.2 [FR] Méthode et approches utilisées pour le projet (environ 700 caractères, espaces inclus): pour grand public**

Le projet SCORE REEF innove grâce à des approches méthodologiques uniques. En combinant la modélisation bioénergétique, l'intelligence artificielle et d'importants ensembles de données mondiaux, notre objectif est de comprendre et d'évaluer le bien-être des récifs coralliens. Notre approche est semblable à une boîte à outils utilisant des descripteurs simples et compréhensibles ainsi qu'une analyse approfondie de 14 fonctions écologiques complexes étroitement liées aux services écosystémiques essentiels. Imaginez-la comme un guide haute technologie, mariant les dernières technologies avec des données exhaustives pour mettre en lumière la santé des récifs coralliens à l'échelle mondiale. Cette approche multidimensionnelle nous positionne à l'avant-garde de la compréhension et de l'évaluation de la santé des récifs à l'échelle mondiale.

### **III.4 Access to data**

Describe any data and/or databases created or added to during the course of the project, and components of your data management plan:

(a) the types of data collected and used

- Global spatial dataset on benthic and fish assemblages
- Global temporal dataset on fish and benthic assemblages

(b) standards used to document the data

The meta-data are documented to insure the reproducibility of our analyses

(c) policy for access and re-use, short- and long-term storage and management

Spatial data are presently open access, but temporal data are not. We aim to release the data after publication

(d) people to contact after the end of the project.

Valeriano Parravicini, Simon Brandl, Jeremy Carlot

### III.5 Scientific outcomes of the project

#### In preparation

Adjeroud M, et al.

Coral reef health monitoring in French overseas: status, knowledge gaps, and improvements to meet national and European frameworks.

Parravicini V, et al.

The global spectrum of reef fish functions in a human dominated world.

Carlot J, et al.

How to define a quantitative coral reef health index.

#### 2023

Karkarey R, Maire E, Graham NAJ, Parravicini V, Brandl SJ, Carlot J, Arthur R, Alcoverro T, Wilson SK, Adjeroud M, Wickel J, Exton D, Keith SA.

Asynchronous population trends stabilize mesopredatory coral reef fish communities in the face of global change.

Submitted to Ecology Letters, 23 October 2023

Randrianarivo M, Gasimandova LM, Tsilavonarivo J, Razakandrainy A, Philippe J, Guilhaumon F, Botosoamananto RL, Penin L, Todinanahary G, Adjeroud M.

Assessing resilience potential of coral reefs in Madagascar and the effects of Marine Protected Areas.

Submitted to Regional Studies in Marine Science, 18 October 2023

Brandl SJ, Carlot C, Stuart-Smith RD, Keith SA, Graham NAJ, Edgar GJ, Wicquart J, Wilson SK, Karkarey R, Donovan MK, Arias-Gonzalez JE, Arthur R, Bigot L, Exton DA, Goetze J, Hoey AS, Holmes T, Maréchal JP, Mouillot D, Ross CL, Wickel J, Adjeroud M, Parravicini V.

Unifying coral reef states through space and time reveals a rapidly changing ecosystem.

Submitted Ecology Letters, 23 August 2023

Jouval F, Adjeroud M, Latreille AC, Bigot L, Bureau S, Chabanet P, Durville P, Elise S, Obura D, Parravicini V, Guilhaumon F, Brandl S, Carlot J, Penin L (2023)

Using a multi-criteria decision-matrix framework to assess the recovery potential of coral reefs in the South Western Indian Ocean.

Ecological Indicators 147: 109952 (<https://doi.org/10.1016/j.ecolind.2023.109952>)

#### 2022

Adjeroud M, Peignon C, Gaudiard C, Penin L, Kayal M (2022)

Extremely high but localized pulses of coral recruitment in the southwestern lagoon of New Caledonia and implications for conservation.

Marine Ecology Progress Series 692: 67-79 (<https://doi.org/10.3354/meps14073>)

Schiettekatte NMD, Brandl SJ, Casey JM, Graham NAJ, Barneche DR, Burkepile DE, Allgeier JE, Arias-González JE, Edgar GJ, Ferreira CEL, Floeter SR, Friedlander AM, Green AL, Kulbicki M, Letourneur Y, Luiz OJ, Mercière A, Morat F, Munsterman KS, Rezende EL, Rodríguez-Zaragoza FA, Stuart-Smith RD, Vigliola L, Villéger S, Parravicini V (2022)

Biological trade-offs underpin coral reef ecosystem functioning.

Nature Ecology and Evolution 6: 701-708 (<https://doi.org/10.1038/s41559-022-01710-5>)



Carlot J, Rouzé H, Barneche DR, Mercière A, Espiau B, Cardini U, Brandl SJ, Casey JM, Pérez-Rosales G, Adjeroud M, Hédouin L, Parravicini V (2022)  
Scaling up calcification, respiration, and photosynthesis rates of six prominent coral taxa.  
*Ecology and Evolution* 12: e8613 (<https://doi.org/10.1002/ece3.8613>)

Urbina-Barreto I, Elise S, Guilhaumon F, Bruggemann JH, Pinel R, Kulbicki M, Vigliola L, Mou-tham G, Mahamadaly V, Facon M, Bureau S, Peignon C, Dutrieux E, Garnier R, Penin L, Adjeroud M (2022)  
Underwater photogrammetry reveals new links between coral reefscape traits and fishes that ensure key functions.  
*Ecosphere* 13: e3934 (<https://doi.org/10.1002/ecs2.3934>)

## 2021

Ghilardi M, Schiettekatte NMD, Casey JM, Brandl SJ, Degregori S, Mercière A, Morat F, Letourneur Y, Bejarano S, Parravicini V (2021)  
Phylogeny, body morphology, and trophic level shape intestinal traits in coral reef fishes.  
*Ecology and Evolution* 11: 13218-13231 (<https://doi.org/10.1002/ece3.8045>)

Pozas-Schacre C, Casey JM, Brandl SJ, Kulbicki M, Harmelin-Vivien M, Strona G, Parravicini V (2021)  
Congruent trophic pathways underpin global coral reef food webs.  
*Proceedings of the National Academy of Science USA* 118: e2100966118  
(<https://doi.org/10.1073/pnas.2100966118>)

Strona G, Beck PSA, Cabeza M, Fattorini S, Guilhaumon F, Micheli F, Montano S, Ovaskainen O, Planes S, Veech JA, Parravicini V (2021)  
Ecological dependencies make remote reef fish communities most vulnerable to coral loss.  
*Nature Communications* 12: 7282 (<https://doi.org/10.1038/s41467-021-27440-z>)

Strona G, Lafferty KD, Fattorini S, Beck PSA, Guilhaumon F, Arrigoni R, Montano S, Seveso S, Galli P, Planes S, Parravicini V (2021)  
Global tropical reef fish richness could decline by around half if corals are lost.  
*Proceedings Royal Society B* 288: 20210274 (<https://doi.org/10.1098/rspb.2021.0274>)

Carlot J, Kayal M, Lenihan HS, Brandl SJ, Casey JM, Adjeroud M, Cardini U, Merciere A, Espiau B, Barneche DR, Rovere A, Hédouin L, Parravicini V (2021)  
Juvenile corals underpin coral reef carbonate production after disturbance.  
*Global Change Biology* 27: 2623-2632 (<https://doi.org/10.1111/gcb.15610>)

Urbina-Barreto I, Garnier R, Elise S, Pinel R, Dumas P, Mahamadaly V, Facon M, Bureau S, Peignon C, Quod JP, Dutrieux E, Penin L, Adjeroud M (2021)  
Which method for which purpose? A comparison of Line Intercept Transect and underwater photogrammetry for coral reef surveys.  
*Frontiers in Marine Science* 8:636902 (<https://doi.org/10.3389/fmars.2021.636902>)

Moritz M, Brandl SJ, Rouzé H, Vii J, Pérez-Rosales G, Bosserelle P, Chancerelle Y, Galzin R, Liao V, Siu G, Tairui M, Nugues MM, Hédouin L (2021)  
Long-term monitoring of benthic communities reveals spatial determinants of disturbance and recovery dynamics on coral reefs.  
*Marine Ecology Progress Series* 672: 141–152 (<https://doi.org/10.3354/meps13807>)

Perez-Rosales G, Brandl SJ, Chancerelle Y, Siu G, Martinez E, Parravicini V, Hédouin L (2021)  
Documenting decadal disturbance dynamics reveals archipelago-specific recovery and compositional change on Polynesian reefs.  
*Marine Pollution Bulletin* 170: 112659 (<https://doi.org/10.1016/j.marpolbul.2021.112659>)

2020

Brandl SJ, Johansen JL, Casey JM, Tornabene L, Morais RA, Burt JA (2020)  
Extreme environmental conditions reduce coral reef fish biodiversity and productivity.  
Nature Communications 11: 3832 (<https://doi.org/10.1038/s41467-020-17731-2>)

Parravicini V, Casey JM, Schiettekatte NMD, Brandl SJ, Pozas-Schacre C, Carlot J, Edgar GJ, Graham NAJ, Harmelin-Vivien M, Kulbicki M, Strona G, Stuart-Smith RD (2020)  
Delineating reef fish trophic guilds with global gut content data synthesis and phylogeny.  
PLoS Biol 18(12): e3000702 (<https://doi.org/10.1371/journal.pbio.3000702>)

## **IV. Principal conclusions (publishable)**

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### **IV. 1 Principal conclusions (around 1000 characters including spaces): for large audience**

Our findings unveil significant variability in coral reef functioning across space, time, and disturbance gradients. This unpredictability poses challenges for management, emphasizing the potential for ecological surprises. However, acknowledging the broad functional spectrum offers a wider operational space for effective management. While restoring reefs to a 'pristine' state may be unattainable, our results support redirecting efforts toward maximizing functions that sustain crucial services. This aligns with recent literature advocating a reevaluation of coral reef futures, recognizing ongoing changes and the difficulty of reverting to historical conditions. For example, our Seychelles case study highlights increased productivity despite coral loss, showcasing resilient benthic primary production. It is vital to note that this doesn't downplay the serious threats reefs face, such as climate change and overfishing, requiring urgent action. Yet, recognizing variability calls for adaptive strategies maximizing resilience rather than fixating on an idealized 'pristine' state. The future of coral reefs relies on embracing their dynamic nature and implementing strategies ensuring continued functionality amidst evolving environmental challenges.

### **IV. 2 [FR] Principales conclusions (environ 1000 caractères, espaces inclus): pour grand public**

Nos résultats révèlent une variabilité significative dans le fonctionnement des récifs coralliens à travers l'espace, le temps et les gradients de perturbation. Cette imprévisibilité pose des défis pour la gestion, mettant en évidence le potentiel de surprises écologiques. Cependant, reconnaître le large spectre fonctionnel offre un espace opérationnel plus vaste pour une gestion efficace. Bien que la restauration des récifs à un état "pristine" soit peut-être inatteignable, nos résultats soutiennent une redirection des efforts vers la maximisation des fonctions qui soutiennent des services cruciaux. Cela s'aligne avec la littérature récente préconisant une réévaluation des futurs des récifs coralliens, reconnaissant les changements en cours et la difficulté de revenir à des conditions historiques. Par exemple, notre étude de cas aux Seychelles met en évidence une productivité accrue malgré la perte de coraux, mettant en avant une production primaire benthique résiliente. Il est essentiel de noter que cela ne minimise pas les graves menaces auxquelles font face les récifs, telles que le changement climatique et la surpêche, exigeant une action urgente. Cependant, reconnaître la variabilité appelle des stratégies adaptatives maximisant la résilience plutôt que de se fixer sur un état "pristine" idéalisé. L'avenir des récifs coralliens dépend d'accepter leur nature dynamique et de mettre en œuvre des stratégies assurant une fonctionnalité continue face aux défis environnementaux en évolution.

## **V. Result's impact**

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### **V. 1 Anticipated (or actual) impact of theses results for science, society, public and private decision making (around 1500 characters including spaces): for large audience**

From a scientific standpoint, our results demonstrate that adopting a functional approach provides a nuanced and improved means of describing the status of coral reef ecosystems. Contrary to expectations, reefs with low coral cover and fish biomass can excel in certain functions, notably in fish biomass production—a crucial aspect for people. From a management perspective, this suggests that managers may not necessarily need to push the system towards a state of high coral cover and fish biomass. Environmental variables play a role in this pattern and should be considered in management strategies. Broadening the spectrum of desirable coral reef states has the potential to enhance our ability to establish realistic goals achievable through proper conservation strategies.

#### **IV. 2 [FR] Impact pour la science, la société et la décision publique et privé (environ 1500 caractères, espaces inclus): pour grand public**

D'un point de vue scientifique, nos résultats démontrent qu'une approche fonctionnelle offre une description nuancée et améliorée de l'état des écosystèmes de récifs coralliens. Contrairement aux attentes, les récifs présentant une faible couverture corallienne et une faible biomasse de poissons peuvent exceller dans certaines fonctions, notamment dans la production de biomasse de poissons, un aspect crucial pour les populations. Du point de vue de la gestion, cela suggère que les responsables n'ont pas nécessairement besoin de pousser le système vers un état de haute couverture corallienne et de biomasse de poissons. Les variables environnementales jouent un rôle dans ce schéma et doivent être prises en compte dans les stratégies de gestion. Élargir le spectre des états souhaitables des récifs coralliens a le potentiel d'améliorer notre capacité à établir des objectifs réalistes réalisables grâce à des stratégies de conservation appropriées.

### **VI Next steps – the legacy of the CESAB project**

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We had two post-doctoral researchers working on the project. One of them got a permanent position in the US. The other obtained a 3-years contract as a post-doc. They are both involved within a network of collaboration and we are doing our best to obtain funding to keep working together. We are presently submitting applications with the support of the Paris Sciences et Lettres University.

### **VII CESAB AFTER**

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We are really keen in organizing a CESAB after, especially in our case where the expectation from the community of managers is extremely high. We wish to invite managers and practitioners to present results and show how we can help obtaining better ecosystem indices.

### **IX Comments on the execution of the project**

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Honestly, the project was very smooth. The organization at CESAB was really excellent and all our partners were extremely impressed by the productivity of the workshop and the nice environment. I strongly believe that this project allowed us to strengthen existing collaboration and creating new collaborations that will really increase the overall productivity of the project.