



**HAL**  
open science

# Systematic spatial planning for the management of black pearl farming islands in the Pacific, with a multi-criteria approach (biodiversity, resources, uses, ciguatera)

Laure Vaitiare André

## ► To cite this version:

Laure Vaitiare André. Systematic spatial planning for the management of black pearl farming islands in the Pacific, with a multi-criteria approach (biodiversity, resources, uses, ciguatera). Ecology, environment. Sorbonne Université, 2021. English. NNT : 2021SORUS382 . tel-03884127

**HAL Id: tel-03884127**

**<https://theses.hal.science/tel-03884127v1>**

Submitted on 5 Dec 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## Sorbonne Université

Ecole doctorale ED129 Sciences de l'environnement  
Institut de Recherche pour le Développement, UMR Entropie

### **Planification spatiale systématique pour la gestion des lagons perlicoles dans le Pacifique selon une approche multicritère (biodiversité, ressources, usages, ciguatera)**

*Systematic spatial planning for the management of black pearl farming islands  
in the Pacific, with a multi-criteria approach (biodiversity, resources, uses, ciguatera)*



Par Laure Vaitiare ANDRE

Présentée le 3 Décembre 2021

Thèse de doctorat en Sciences de l'Environnement, Spécialité : Ecologie Marine

Sous la direction de Serge Andréfouët et Mireille Chinain

Devant le jury composé de :

Eric THIEBAUT	Professeur, Sorbonne Université, Roscoff, Président du jury
Hiroya YAMANO	Professeur, Nat'l Institute of Environmental Science, Japon, Rapporteur
Johann BELL	Professeur, University of Wollongong, Australie, Rapporteur
Kirsten OLESON	Assistant Professor, University of Hawaii, USA, Examinatrice
Serge ANDREFOUET	Directeur de Recherche, IRD Nouméa, Directeur de thèse
Mireille CHINAIN	Directrice de Recherche, ILM Tahiti, co-Directrice de thèse
Simon VAN WYNSBERGE	Cadre de Recherche Ifremer Nouméa, Invité
Vetea LIAO	Gestionnaire, Direction des ressources Marines, Tahiti, Invité



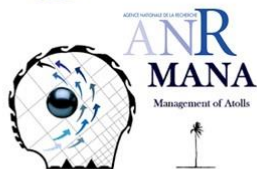
# Systematic spatial planning for the management of black pearl farming islands in the Pacific, with a multi-criteria approach (biodiversity, resources, uses, ciguatera)

LAURE VAITIARE ANDRE

Under the supervision of Serge Andréfouët and Mireille Chinain



Délégation à la  
Recherche de la  
Polynésie française



Laure Vaitiare André: *Systematic spatial planning for the management of black pearl farming islands in the Pacific, with a multi-criteria approach (biodiversity, resources, uses, ciguatera)*.  
October 2021.

**SUPERVISORS:**

Serge Andréfouët (thesis director) Researcher at Institut de Recherche pour le Développement (IRD), joint research unit: Entropie. (Tropical marine ecology of the Pacific and Indian Oceans)

Mireille Chinain (thesis co-director), Researcher at Institut Louis Malardé (ILM), joint research unit: EIO (Oceanian insular ecosystems)

Simon Van Wynsberge (co-supervision): Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), joint research unit: Entropie

**FUNDING:**

Délégation à la Recherche de la Polynésie française (DREC) – 50% of the doctoral grant  
Sorbonne University, ED 129 – 50% of the doctoral grant

MANA project (Management of Atolls, funded by Agence Nationale de la Recherche) – operating budget

Institut Louis Malardé (ILM) – operating budget

Direction des Ressources Marines de la Polynésie française (DRM) – operating budget

**LOCATIONS:**

New-Caledonia – hosting joint research unit: Entropie.

Address: 101 Promenade Roger Laroque, Anse Vata, BP A5 - 98848 *Nouméa, NC*

French Polynesia – fieldwork: Vairao, Takaroa, Raivavae and Mangareva.

**TIME FRAME:**

December 2018 – December 2021

## Foreword

This PhD thesis is the result of three years of work based at the IRD center in Nouméa (New Caledonia), where the UMR Entropie hosted me. The missions on the three studied islands in French Polynesia (Takaroa, Raivavae and Mangareva) were carried out with a team of ILM partners, and in Tahiti, I was hosted by the IFREMER center in Vairao.

The *Délégation à la Recherche de la Polynésie française* (DREC) and Sorbonne University - ED 129 *Ecole doctorale des Sciences de l'Environnement* have co-financed the PhD scholarship. The ANR MANA, the *Direction des ressources marines* (DRM) and the ILM financed the data acquisition missions.

This is a thesis by publications. The introduction is based on a publication and Chapters 2 to 5 have been the subject of articles, published, submitted or in review in peer-review journals. Therefore, this thesis is primarily written in English. However, an abstract (p. iii) and a synthesis (p. 1) are available in French.

## Avant-propos

Ce doctorat est le fruit de trois années de travail basées au centre IRD de Nouméa (Nouvelle-Calédonie), où l'UMR Entropie m'a accueillie. Les missions sur les trois îles étudiées en Polynésie Française (Takaroa, Raivavae et Mangareva) ont été menées en équipe avec les partenaires de l'ILM et à Tahiti, j'ai été accueillie par l'Ifremer de Vairao.

La Délégation à la Recherche de la Polynésie française (DREC) ainsi que Sorbonne Université – ED 129 Ecole doctorale des Sciences de l'Environnement ont co-financé la bourse doctorale. L'ANR MANA, la Direction des ressources marines (DRM) ainsi que l'ILM ont financé les missions d'acquisition des données.

Il s'agit d'une thèse sur articles. L'introduction s'appuie sur une publication et les Chapitres 2 à 5 ont fait l'objet d'articles, publiés, en revue ou soumis à des journaux de rang A. Cette thèse est donc principalement rédigée en anglais. Elle propose cependant un résumé (p. iii) et une synthèse (p. 1) en français.

## Abstract

Implementing conservation and sustainable resource management actions is crucial in the context of the current environmental crisis. In the field of conservation science, Systematic Conservation Planning (SCP) identifies areas that optimally meet the trade-off between conservation objectives and socio-economic costs to be minimized (i.e. opportunity cost: what could have been gained but become foregone opportunities when a reserve is implemented). Guided by spatialized and quantified data, SCP provides decision support to managers in a transparent manner. However, our state-of-the-art assessment of the marine SCP use in the Pacific Ocean Tropical Islands (POTIs) indicates a general tendency to SCP exercises disconnected from the concrete needs of managers. We have thus identified several orphaned themes that seem crucial for management of POTIs coastal spaces.

We therefore look at how to better integrate these identified gaps into spatial planning of island lagoons, particularly in French Polynesia. We break this down into four lines of research: 1) how to integrate **ciguatera** into SCP (a poisoning due to the consumption of certain seafood products, highly prevalent in the Pacific) and what is the impact of ciguatera risk areas for reef fisheries management? 2) How to respond to the spatial management needs of the **black pearl farming** at its various stages? 3) How could SCP make useful contributions to or help optimize **traditional marine resource management** (*rāhui*)? 4) How to plan for activity **diversification** in a given lagoon and measure the impacts associated to the different spatial configurations? Through four studies conducted on three islands in French Polynesia (Takaroa, Raivavae, Mangareva), this work demonstrates the SCP contributions made in response to local problems and stakeholder needs for optimal management of the coastal space.

This study produces original data adapted to the studied contexts and provides a new methodology for integrating, for the first time, ciguatera into spatial analysis to reduce the opportunity cost for fishers. In addition, this study illustrates how SCP can be mobilized to optimize a traditional scheme of fisheries spatial management integrating opportunity cost and ciguatera. Lastly, this method allows identifying suitable areas for restocking oysters and evaluates how to reallocate lagoon space in case of diversification activities. Although these applications are guided by site-specific needs and data, the topics addressed can be generalized to many POTIs. Finally, this thesis demonstrates that, in an international and regional context where commitments for conservation and sustainable management are multiplying, SCP constitutes a valuable tool in bridging the research-implementation gap by translating, in conjunction with managers, international ambitions into adapted local responses.

### Keywords:

Conservation science, systematic conservation planning, artisanal fisheries, black pearl oyster farming, aquaculture, biodiversity, coral reef, ciguatera, spatial management, Oceania, French Polynesia.



## Résumé

Mettre en œuvre des actions de conservation et de gestion durable des ressources est capital, dans le contexte actuel de crise environnementale. Dans le domaine des sciences de la conservation, la **Planification Systématique de la Conservation** (PSC) identifie des zones qui répondent de manière optimale au compromis entre objectifs de conservation et coûts socio-économiques à minimiser (ex. coût d'opportunité : ce qui aurait pu être gagné mais devient une opportunité perdue lors de la mise en réserve). Guidée par des données spatialisées et quantifiées, la PSC apporte ainsi un support de décision aux gestionnaires de manière transparente. Pourtant, l'état de l'art de la PSC marine dans les îles de l'océan Pacifique tropical (*Pacific Ocean Tropical Islands*, POTI) indique une tendance générale à des exercices de PSC déconnectés des besoins concrets des gestionnaires. Nous avons ainsi identifié plusieurs thématiques orphelines qui semblent pourtant cruciales pour les POTI.

Dans le but de mieux les intégrer dans la planification spatiale des lagons, notamment en Polynésie française, nous avons retenu quatre axes de recherche : 1) comment inclure dans la PSC, la **ciguatera** (une intoxication alimentaire due à la consommation de certains produits de la mer, hautement prévalente dans le Pacifique) et l'impact des zones à risque pour les pêcheries récifales ? 2) Comment répondre aux besoins de gestion spatiale de la **perliculture** dans ses différentes formes d'activités ? 3) Comment contribuer utilement à la **gestion traditionnelle** des ressources marines (*rāhui*) et aider à son optimisation ? 4) Comment planifier la **diversification** des activités dans un lagon et mesurer les impacts de différentes configurations spatiales ? A travers 4 études menées sur 3 îles de Polynésie française (Takaroa, Raivavae, Mangareva), ce travail illustre les contributions qu'apporte la PSC en réponse à des problématiques locales et aux besoins des parties-prenantes, dans une perspective de gestion optimale de l'espace côtier.

Cette étude a produit des données originales adaptées aux contextes étudiés et développé une nouvelle méthodologie afin d'intégrer, pour la première fois, la ciguatera à l'analyse spatiale afin de diminuer le coût d'opportunité pour les pêcheurs. De plus, cette étude illustre comment la PSC peut être mobilisée pour optimiser un schéma spatial de gestion traditionnelle de la pêche intégrant coût d'opportunité de pêche et ciguatera. Enfin, cette méthode a permis d'identifier des zones propices au réensemencement d'huitres perlières et évalué comment réallouer l'espace lagunaire en cas de diversification des activités. Bien que les cas traités se fondent sur des besoins et données spécifiques aux sites, les thématiques abordées sont extrapolables à de nombreux POTI. Finalement, cette thèse démontre que, dans un contexte international et régional où les engagements pour la conservation et la gestion durable se multiplient, la PSC constitue un précieux outil pour réduire l'écart entre recherche et action en traduisant, en lien avec les gestionnaires, les ambitions internationales en réponses locales adaptées.

### Mots clés :

Sciences de la conservation, planification systématique de la conservation, pêche artisanale, perliculture, aquaculture, biodiversité, récifs coralliens, ciguatera, gestion spatiale, Océanie, Polynésie française.



## Scientific contributions

### Publications – peer-reviewed article

#### *Accepted:*

**André, L. V.,** Van Wynsberge, S., Chinain, M., Gatti, C. M.iti, Dempsey, A., Andréfouët, S. (2021b). A framework for mapping local knowledge on ciguatera and artisanal fisheries to inform systematic conservation planning. ICES JMS International Council for the Exploration of the Sea Journal of Marine Science. <https://doi.org/10.1093/icesjms/fsab016>

**André, L.V.,** Van Wynsberge, S., Chinain, M., Andréfouët, S. (2021a). An appraisal of systematic conservation planning for Pacific Ocean Tropical Islands coastal environments. Marine Pollution Bulletin 165, 20. <https://doi.org/10.1016/j.marpolbul.2021.112131>

#### *Submitted:*

**André, L. V.,** Van Wynsberge, S., Chinain, M., Andréfouët, S. (*submitted*). Benefits of collaboration between indigenous fishery management and data-driven spatial planning approaches: the case of a Polynesian traditional design (rāhui). Submitted to ICES JMS.

**André, L. V.,** Chinain, M., Gatti, C. M.iti, Liao, V., Van Wynsberge, S., Tedesco, P., Andréfouët, S. (*submitted*). Identification of suitable pearl oyster restocking zones in Takarua Atoll following a mass-mortality event, using environmental and socio-economic data in a systematic prioritization approach. Submitted to Marine Pollution Bulletin.

**André, L. V.,** Van Wynsberge, S., Chinain, M., Gatti, C. M.iti, Liao, V., Andréfouët, S. (*submitted*). Spatial solutions and their impacts when reshuffling coastal management priorities in small islands with limited diversification opportunities. Submitted to Journal of Applied Ecology.

### Scientific and technical reports

**André L. V.,** Andréfouët S., Chinain M., Gatti C., Van Wynsberge S., Le Gendre R., Bourgeois B., Butscher J. Varillon D., Liao V. (2021). Premiers résultats et synthèse des informations collectées sur Mangareva et Iles Gambier, dans le cadre de la convention sur le fonctionnement hydrodynamique du lagon des Gambier (DRM-IRD), du projet doctoral Pangéa (IRD, ILM, SU, DRec), et du projet ANR Mana (IRD, Ifremer, DRM et autres). 32p.

**André L. V.** (2019) 3 rapports de mission, îles de Takarua, Raivavae et Mangareva, destinés à l'équipe encadrante de la thèse, à la Direction de la Recherche du Gouvernement de la Polynésie française (financeur) et aux mairies des îles concernées.

Benzoni F., Houlbrèque F., **André L. V.,** Payri, C.E. (2017). Plan d'action rapide et adaptatif, en cas de blanchissement corallien : Le cas de la Nouvelle-Calédonie, épisode 2016,

synthèse. Nouméa : IRD, novembre 2017. Sciences de la Mer. Biologie Marine. Rapports Scientifiques et Techniques, 90 p.

## Books

Meyer J.Y. (coord.), Letourneur Y. (coord.), Payri C. (coord.), Taquet M. (coord.), Vidal E. (coord.), **André L. V.** (collab.), Dumas P. (collab.), Gaertner J.C. (collab.), Gerbeaux P. (collab.), McCoy S. (collab.), Pauly D. (collab.), Rodolfo-Metalpa R. (collab.), Steven A. (collab.), Thaman R. (collab.), Van Wynsberge S. (collab.) (2019). Partie 1 : Biodiversité, services écosystémiques et activités socio-économiques basées sur les ressources naturelles. *In*: Payri Claude (dir.), Vidal Eric (dir.). Biodiversité en Océanie, un besoin urgent d'action. Nouméa : Presses universitaires de la Nouvelle-Calédonie, 17-29. Atelier Biodiversité en Océanie, Nouméa NC. ISBN 979-10-910321-1-7  
<https://www.documentation.ird.fr/hor/fdi:010078409>  
English version: <https://hal.ird.fr/hal-02539329v1>

Claude E. Payri, Francesca Benzoni, **Laure. V. André** et Fanny Houlbrèque (2018). Chapitre 25: Le blanchissement corallien de 2016. *In*: Payri, C.E. (dir.). Nouvelle-Calédonie, archipel de corail. IRD Editions/Solaris, Marseille/Nouméa, 288 p.

## International conference

**André L, V.**, Andréfouët S., Chinain M., Gatti C., Van Wynsberge S. (2020) A Tale of South Pacific Islands: Optimizing Biodiversity Conservation Plans Using Fisheries, Ciguatera and Pearl Farming. 27<sup>th</sup> Hawai'i conservation conference.

## Workshops

**André L, V.** (2020) Doctoriales of the New-Caledonia University, oral presentation.

**André L, V.** (2019) Doctoriales of the New-Caledonia University, poster presentation.

**André L, V.** (2019) Seminar for Entropie lab scientific animation



## Remerciements

L'expérience d'une thèse c'est un peu celle d'une longue navigation. Il y a d'abord le rêve, ancré depuis longtemps, nourri de complexité de M. Liscia, et du *¡ Hay pescaado !* vénézuélien. Puis on se décide et on déplie la carte : on choisit le bateau, la destination. Quels sont les vents dominants ? Maintenant, il faut préparer le navire, rassembler l'équipage, guetter la fenêtre météo.

Je tiens tout d'abord à remercier vivement Serge, pilote exigeant, à l'origine du projet. Moi qui souhaitais travailler en écologie marine, à l'interface entre sciences et société, ce sujet m'a motivée particulièrement. Je tiens également à remercier Mireille, qui m'a fait découvrir le volet scientifique de la ciguatéra, passionnant, encore plein de mystères. Thanks roa à tous deux pour votre encadrement au long cette thèse et toutes les connaissances transmises. Malgré les trains de houles on a gardé le cap, et finalement, on en a parcouru des milles. Merci Simon pour ton investissement dans cette thèse et tes conseils avisés. Māuruuru roa à Jean-Yves Meyer pour sa confiance accordée en m'octroyant la première moitié de bourse de thèse, point de bascule qui a mis le projet sur les rails.

On largue les amarres, le vent gonfle les voiles. Merci à Entropie pour son accueil sur ce beau site de Nouméa, en particulier à Claude, de tous les quarts, qui mène ce gros bateau avec un leadership impressionnant. Un regard complice pour Véro, dont l'énergie et les rires raisonnent par-delà les embruns. A bord, un équipage soudé est primordial, merci à mes co-bureaux pour les échanges, la bonne humeur et les astuces, Florian, Thomas et en intermittence Laëtitia, Julie, Laura et Mathilde. A tous les mousses du café pour égayer les quarts de veille, Nosh, Lucas, and co. C'est toute une flotte d'embarcations sympathiques, aux trajectoires parallèles ou qui ont ponctuellement croisé ma route, que je remercie : les amis à l'IRD, au loft, sur les îlots, à bord de Mangareva, au club Apnée, autour d'une aquarelle, d'un baudrier ou d'un pareu... ces chers compagnons de route se reconnaîtront.

Les oiseaux de mer, rencontrés en cours de navigation apportent parfois de bonnes surprises, un peu d'avitaillement. Un grand merci à Éric et Rodolphe pour les échanges et leur support déterminant. L'orage gronde, les conditions se durcissent. Je perds un ami en mer et ma pensée t'accompagnera toujours Nat. Mes grands-parents aussi. Les étoiles guident encore les marins.

Par mer belle à peu agitée, nous faisons escale sur trois îles de l'océan Pacifique : Takaroa, Raivavae, Mangareva. Brassage de découvertes mythiques, retour aux sources, et intense labeur. Māuruuru à tous les pêcheurs enquêtés, pour votre temps et le partage de votre passion, ainsi qu'à toutes les personnes impliquées dans le bon déroulement de ces missions, en particulier à Clarisse Teura Mahara, guide formidable, Clémence complice des enquêtes, Teapehu et Gaby pour les sorties pêche sur le platier ou la passe.

Enfin, la destination se rapproche, la silhouette de l'île se dessine clairement à l'horizon maintenant. Mais pour l'atteindre dans les meilleures conditions, la route tracée oblige à tirer de longs bords de près serré, rallonger les quarts, affiner les réglages. Je vérifie mille fois la carte et remercie mes guides Dimitri et Solène. Last but not least, merci Christophe, mes parents, ma sista, toujours solidaires et présents qu'importe la distance.

L'ancre est jetée, on peut maintenant savourer ce mouillage, se jeter à l'eau et nager vers d'autres projets. 'Ua reva !

## Table of contents

Foreword .....	i
Abstract.....	ii
Résumé.....	iii
Scientific contributions.....	iv
Remerciements .....	vii
Table of contents .....	viii
List of figures.....	x
List of tables.....	xii
Synthèse des travaux en français .....	1
General Introduction .....	30
1 Conservation science.....	30
2 Systematic Conservation Planning (SCP).....	32
3 Context of the Pacific Ocean tropical islands (POTIs).....	36
4 State of the art of SCP in the POTIs.....	44
5 Gaps and challenges for SCP in the POTIs.....	51
6 General objective and thesis outline.....	55
Chapter I – Study sites .....	60
1 French Polynesia.....	60
2 Rationale for site selection.....	64
3 Three contrasted islands in French Polynesia.....	67
Chapter II – Ciguatera risk .....	74
1 Introduction .....	76
2 Material and Methods.....	78
3 Results .....	90
4 Discussion.....	95
5 Conclusion .....	97
Chapter III – Mariculture management.....	102
1 Introduction .....	104
2 Materiel and method .....	106
3 Results .....	112
4 Discussion.....	115
Chapter IV – Traditional management .....	118
1 Introduction .....	120

2	Material and Methods.....	122
3	Results .....	127
4	Discussion.....	133
5	Conclusion .....	136
	Chapter V – Diversification options.....	140
1	Introduction .....	142
2	Study site context and specific objectives.....	144
3	Methods.....	147
4	Results .....	153
5	Discussion.....	160
6	Conclusion .....	162
	General Discussion.....	166
1	Synthesis of the contributions.....	166
2	Generalization to other POTIs.....	174
3	Perspectives.....	183
4	Conclusion – take home messages .....	186
	References.....	189
	Appendices.....	212

## List of figures

Figure 1 Conservation biology and conservation science.....	30
Figure 2. An example of Systematic Conservation Planning (SCP) exercise.....	33
Figure 3. Schematic view of the main methods to solve optimization problems applied to systematic conservation planning.....	35
Figure 4. Map of the study zone: the Pacific Ocean tropical islands (POTI).....	37
Figure 5. Importance of coastal fishing production for subsistence, compared to commercial fishing, for 14 countries among the POTIs in 2014 (Gillett and Tauati, 2018). ....	42
Figure 6. Trophic chain of ciguatera poisoning (Chinain et al., 2019).....	43
Figure 7. The study region and the POTI exclusive economic zones. ....	45
Figure 8. SCP trends in the POTIs.....	46
Figure 9. Summary of the SCP case studies organized according to their regions and the themes tackled. Themes are presented with key words here.....	50
Figure 10. Annual volumes, values and average price of raw black pearl from French Polynesian production (adapted from IEOM, 2020). ....	62
Figure 11. Schematic presentation of the pearl oyster farming infrastructures and their usual spatial organization (adapted from Gaertner-Mazouni and Rodriguez, 2017). ....	63
Figure 12. Maps of the study sites. (A) Map of the Economic Exclusive Zone of French Polynesia, location of its five archipelagoes and the three selected study sites. (B) Takaroa. (C) Raivavae. (D) Gambier.....	66
Figure 13. Illustrations of Takaroa Atoll.....	68
Figure 14. Illustrations of Raivavae Island. ....	69
Figure 15. Illustrations of Gambier lagoon.....	70
Figure 16. a. Location of Raivavae in French Polynesia; b. Satellite view of Raivavae Island .....	78
Figure 17. Illustrated definition of fishing polygon, fishing zone and fishing ground. ....	81
Figure 18. Location of the different geomorphological strata, on Raivavae Island.....	84
Figure 19. Procedure to refine fishing polygons according to geomorphological strata. ....	85
Figure 20. Cumulated fishing ground surface areas as a function of the number of interviews. ....	90
Figure 21. Examples of fishing grounds grouped by fishing gear and refined by geomorphological strata.....	91
Figure 22. Maps of opportunity costs to fishers.....	92
Figure 23. Maps of ciguatera: .....	92
Figure 24. The solutions from the nine scenarios comparing three targets (10, 20, and 30%) and three maps of costs used as inputs.....	94
Figure 25. Maps of the study site. ....	105
Figure 26. Hydrodynamic circulation modelling and connectivity matrices in Takaroa. ....	109
Figure 27. (A) Wild black-lipped oyster <i>Pinctada margaritifera</i> on a 'karena' in Takaroa lagoon. (B) Example of moderate amount of pearl farming waste accumulated in the Takaroa lagoon.....	110
Figure 28. Spatial layers used for the systematic prioritization analysis. ....	113
Figure 29. SCP solutions .....	114

Figure 30. Map of the study site.....	123
Figure 31. Ecological and socioeconomic features in Raivavae lagoon aggregated per PU. .....	128
Figure 32. Map of the Rairua south-west district, under different options of management. .....	129
Figure 33. Example of management options, all protecting the same stock of giant clam resource (red for closed areas, green for open))......	131
Figure 34. Incidental levels of ciguatera risk in the reserve designs. ....	132
Figure 35. Study-site characteristics.....	146
Figure 36. Graphical description of the three types of optimization scenarios.....	150
Figure 37. Spatial information on Gambier lagoon.....	154
Figure 38. The ‘Business as Usual’ (BAU) situation and the best solutions in term of zones distribution for each optimized scenario.....	155
Figure 39. Comparison of the generated impacts for each scenario and each zone. ....	157
Figure 40. Relative impacts of the scenarios.....	158
Figure 41. Sensitivity analysis of the optimization scenario solutions. ....	159
Figure 42. Update of the previous state of the art (Figure 9), summarizing the themes addressed by the SCP case studies across the POTI regions.....	169
Figure 43. The regions where ciguatera poisoning (CP) occurrences have been documented at a global scale (Chinain et al., 2021).....	175
Figure 44. Distribution of fishing grounds in the Gambier lagoon, according to the fishing gear used.....	181
Figure 45. Blue growth and blue justice display here ten challenges for the ocean economy that interconnect with marine spatial planning (adapted from Bennett et al., 2021). ....	185
Figure 46. Summary of the number of SCP case studies in the POTI, with the contribution from this thesis, as an update of Figure 7.....	188



## List of tables

Table 1. The IUCN categories of Protected Areas and their associated management objectives (Adapted from IUCN, 2017).....	31
Table 2. Definition of SCP key terms.....	33
Table 3. The POTIs main features.....	39
Table 4. Candidate islands, their status and available data, for this PhD potential study sites. ....	65
Table 5. Synopsis of the study sites.....	72
Table 6. Correspondence between fishing gears and geomorphological strata.....	83
Table 7. Coefficients of risk ( <b><i>rp</i></b> ) attributed to ciguatera zones, depending on their types..	86
Table 8. List of scenarios implemented to test the effect of ciguatera in conservation plans,	89
Table 9. Comparison of the costs for fishers .....	89
Table 10. Description of the three scenarios.....	114
Table 11. Levels of ciguatera risk considered, and PU distribution associated to each class of risk.....	127
Table 12. Gauge of rāhui and optimisation scenarios, and ratios of efficiency, when performed at the scale of each district <i>vs</i> the whole lagoon. ....	130



## Synthèse des travaux en français

### Introduction

*Ce chapitre introductif se base sur la publication suivante :*

André, L. V., Van Wynsberge, S., Chinain, M., and Andréfouët, S. 2021a. An appraisal of systematic conservation planning for Pacific Ocean Tropical Islands coastal environments. *Marine Pollution Bulletin*, 165: 112131.

#### 1. La science de la conservation

A l'origine, la conservation a été définie et étudiée dans le domaine de la biologie de la conservation afin de chercher comment réduire les taux d'extinctions biotiques et protéger la biodiversité restante, ou zones sauvages, des multiples pressions liées à l'homme (Saoulé, 1985). Ce paradigme a évolué vers la science de la conservation, englobant la conservation de la biodiversité ainsi que le bien-être humain, par la reconnaissance des interrelations entre les systèmes sociaux et naturels (Kareiva et Marvier, 2012). Cette approche interdisciplinaire prend en compte, entre autres, le développement durable, les politiques publiques et l'économie.

En effet, la Convention sur la diversité biologique et les objectifs du millénaire pour le développement ont fixé des lignes directrices internationales pour atteindre des objectifs de conservation de la nature, des écosystèmes et des ressources (CDB, 2010, 2019, 2020 ; ONU, 2015). Les mesures de conservation peuvent prendre plusieurs formes, notamment en se basant sur une dimension spatiale.

Dans le milieu marin, un certain nombre d'outils de gestion par zone sont utilisés, notamment les aires marines protégées (AMP), ou les aires marines gérées localement (LMMA) (Reimer et al., 2020). Comme les niveaux de protection peuvent varier, d'une réserve naturelle stricte à une réserve à usages multiples, l'IUCN a déployé une classification des niveaux de protection théorique (UICN, 2008).

Ces mesures de gestion font l'objet d'un débat sur l'équilibre entre conservation des systèmes naturels et inclusion des systèmes sociaux. Relever ce défi est inhérent à la science de la conservation. D'une part, une attention croissante est portée à la question de la capacité des AMP à contribuer à atteindre les objectifs globaux de conservation, étant donné leurs différentes classifications (Gorud-Colvert et al., 2021). D'autre part, des zones dont la gestion locale vise à exploiter durablement des ressources, peuvent également révéler des résultats positifs quant à la protection de la biodiversité, alors que ce n'était pas l'objectif premier, comme les OECM (*Other Effective area-based Conservation measures*). Ces zones contribuent à atteindre les objectifs mondiaux de conservation (UICN, 2019 ; Gurney et al., 2021).

Les lignes directrices internationales spécifient des objectifs quantitatifs : « préserver 10 % des zones côtières et marines », et intègrent une série de principes : « l'équité et l'efficacité de la

gestion ; des zones écologiquement représentatives ; la connectivité et l'intégration dans un paysage terrestre et marin plus vaste » (objectif 11 d'Aichi, CDB, 2010). Pour intégrer ces principes directeurs et mesurer les résultats atteints, il est nécessaire de mobiliser des méthodes et outils appropriés. Ainsi, des solutions numériques ont été élaborées à l'aide de méthodes quantitatives spatialement explicites, telles que la planification systématique de la conservation (PSC, ou SCP en anglais).

## 2. La planification systématique de la conservation (PSC)

Des approches systématiques ont été développées pour concevoir et délimiter spatialement des réserves afin que la biodiversité y soit correctement représentée, tout en prenant en compte les pressions et les services tirés des écosystèmes (Margules et Pressey, 2000). La planification systématique de la conservation (PSC) est une méthode d'optimisation fondée sur des données spatiales qui permet de guider les décisions de manière transparente et objective. La procédure se déroule ainsi : la zone d'étude est segmentée en un certain nombre de "petites" unités de planification (UP) et un outil numérique permet d'identifier la/les combinaison(s) de UP optimales et prioritaires pour la gestion, selon un certain nombre de critères. D'abord, des attributs de conservation (cf. le nombre d'espèces ou la surface d'habitat) et de coûts (cf. le coût d'acquisition monétaire ou socio-économique de chaque UP) sont affectés à chaque UP. Ensuite, on fixe des objectifs de conservation (que protéger), des cibles quantitatives (combien protéger) et on règle des paramètres complémentaires (par exemple la compacité de la solution), afin de mener la sélection et trouver une/des solution(s). Enfin, l'outil analyse systématiquement chaque UP quant à sa capacité à répondre aux conditions fixées, et sélectionne un réseau optimal de UP, qui minimise le coût global. La PSC repose sur des concepts clés pour la conservation tels que l'exhaustivité, la représentativité, la complémentarité, la vulnérabilité et l'efficacité du réseau de solutions (Kukkala et Moilanen, 2013 ; Margules et Pressey, 2000 ; Pressey et Bottril, 2009).

La sélection optimale des sites se fait par des méthodes mathématiques de résolution de problèmes afin d'explorer l'espace de recherche pour identifier la/les solution(s). Différents outils logiciels ont été développés, dont Marxan, Zonation, Prioritizr et ConsNet (Justeau-Allaire, 2020). En adéquation avec la question posée, le contexte spécifique local et les données disponibles, un certain nombre de choix méthodologiques doivent être effectués pour mener une analyse systématique. Ces choix concernent notamment les variables utilisées pour quantifier les attributs de conservation et les coûts associés à chaque UP. Le plus souvent, ces variables étant difficile à quantifier et à cartographier, des *proxies* (ou variables de substitution) sont utilisés à leur place. Par exemple la biodiversité est souvent représentée par des proxies d'habitats, chacun théoriquement associé un certain cortège de biodiversité. D'autres choix portent sur la taille et la forme des UP, les contraintes appliquées à la compacité du réseau et au compromis recherché entre atteindre strictement les objectifs et minimiser les coûts. Ces dernières décennies, les exercices de PSC ont eu tendance à gagner en complexité et à intégrer un nombre croissant de contraintes telles que la connectivité entre les populations marines, les continuum terre-mer, le changement climatique, etc. (Álvarez-Romero et al., 2018).

Au-delà de l'étape centrale de la priorisation des sites que représente la PSC, le processus de mise en œuvre de la conservation implique des étapes complémentaires, telles que l'engagement des parties prenantes, l'intégration des plans à travers les niveaux de

gouvernance, la mise en œuvre concrète des zones de conservation, leur maintien et suivi avec un engagement à long terme (Pressey et Bottril, 2009 ; Weeks et al., 2014a).

Le recours à la PSC est de plus en plus fréquent dans la région du Pacifique. Afin d'appréhender les questions et les défis en jeu, nous survolons tout d'abord les principales caractéristiques des îles tropicales de l'océan Pacifique (*Pacific Ocean Tropical Islands*, POTI), puis nous dressons un état de l'art de l'usage de la PSC dans les POTI. Leurs objectifs, forces, faiblesses et lacunes sont analysés au regard du contexte et des besoins des parties prenantes, gestionnaires et scientifiques. Nous en déduisons une problématique générale à laquelle va répondre cette thèse en suivant différents axes de recherche, selon le plan proposé ci-après.

### 3. Le contexte des îles tropicales de l'Océan Pacifique (POTI)

La région d'étude englobe les îles du Pacifique se situant entre les deux tropiques, incluant la Micronésie, la Mélanésie et la Polynésie. Les POTI se caractérisent par des socio-écosystèmes où les populations sont traditionnellement très liées à leur environnement.

Sur le **plan administratif**, les POTI sont gérées à un niveau national et/ou territorial : il s'agit soit de pays totalement indépendants ou autonomes, possédant leur propre gouvernement, soit de territoires qui restent fortement liés à leurs métropoles. Plusieurs pays disposent de lois coutumières fortes au niveau local, qui contrôlent souvent l'utilisation locale des ressources marines. Le mode de gouvernance dédié à la gestion des ressources environnementales varie considérablement entre les POTI. Certaines disposent de services techniques efficaces et spécialisés dans la gestion de l'environnement et des ressources marines, tandis que d'autres n'ont pas de services techniques actifs et s'appuient le cas échéant sur des programmes d'aide internationale, des ONG étrangères, et autres consultants privés. Ces diverses situations engendrent des niveaux contrastés de production de données y compris spatialisées, qui sont nécessaires à la planification.

Les POTI sont caractérisées par une **grande dispersion géographique**, par des surfaces terrestres restreintes, ainsi que par le vaste territoire océanique inclus dans leurs zones économiques exclusives (ZEE). Elles relèvent de différentes **formations géologiques**, allant de grandes îles continentales (Papouasie Nouvelle-Guinée ou PNG) à des îles volcaniques entourées de récifs frangeants (Vanuatu), ou à des atolls (Kiribati, Polynésie française). La variété des écosystèmes marins tropicaux qui les caractérisent en font des objets d'étude particulièrement intéressants pour la conservation de la biodiversité.

Bon nombre de ces îles éparses révèlent des **niveaux élevés d'endémisme**, mais aussi une biodiversité menacée, tant dans les systèmes terrestres que marins (Payri et Vidal, 2019). Les îles sont fragiles, de plus en plus exposées à ces menaces, et font face à des problèmes aigus de gestion et de conservation des ressources, affectant directement les communautés qui en dépendent (Kueffer et Kinney, 2017). De nombreuses **initiatives de conservation** existent pour atténuer les menaces d'origine locales ou globales quant à la diversité ou aux ressources marines. Dans certains cas, elles viennent en appui ou en complément de mesures locales qui sont menées pour protéger les ressources, avec différents niveaux de succès (Bartlett et al., 2010; Hamilton et al., 2019; Sangha et al., 2019). Les différents niveaux de protection (totale, partielle, temporaire), de gestion (locale, territoriale, gouvernementale, et / ou ONG) et de

forme se recoupant parfois (réserves de biosphère Unesco, zone de pêche réglementée, zones traditionnelles *tapu*, *rāhui*, *bul*, etc.) reflètent, d'une certaine manière, la richesse des liens entretenus avec l'environnement marin en Océanie (Friedlander, 2018; Gairin and Andréfouët, 2020; Jupiter et al., 2014a; Smallhorn-West and Gowan, 2018).

Les mesures de conservation prises ou envisagées au niveau national ou territorial sont influencées par les directives et agendas internationaux. D'ailleurs, plusieurs « très grandes AMP » (d'une surface > 100.000 km<sup>2</sup>) ont été déclarées dans les ZEE des pays du Pacifique pour atteindre rapidement ces objectifs, mais aucune n'a fait l'objet de planification systématique basée sur la conservation des écosystèmes, et ces vastes AMP manquent souvent de moyens effectifs de gestion et de contrôle (Ban et al., 2017 ; Devillers et al., 2015 ; Singleton et Roberts, 2014).

Les **densités de population humaines** sont contrastées entre les plus grandes villes et les zones rurales ou les îles reculées (Andrew et al., 2019). Les insulaires du Pacifique dépendent fortement de leur environnement marin pour leur **subsistance**, revenus, culture, identité, échanges avec les autres îles, et pour la protection des côtes (Bell et al., 2009 ; Friedlander, 2018). La pêche en milieu lagunaire et récifal est intimement liée au mode de vie insulaire océanien et d'autant plus pour les îles éloignées (Bell et al., 2009 ; 2011b ; Friedlander, 2018). Les moyens de subsistance des populations sont donc particulièrement vulnérables à tout changement qui affecterait la disponibilité en ressources, notamment dans le contexte du changement climatique, de la croissance démographique (+15% entre 2007 et 2014), de la surexploitation des ressources, ainsi que de la dégradation de l'environnement (Gillett et Tauati 2018 ; Hanich et al., 2018). Une gestion durable des réserves halieutiques fait donc partie des priorités fortes de tous les POTI.

Les ressources lagunaires peuvent être fortement affectées par le risque sanitaire dû aux **intoxications ciguatériques**. Largement présente dans les POTI, l'intoxication par la ciguatera résulte de la consommation de produits marins, poissons et invertébrés, ayant accumulé des ciguatoxines, et provoque une combinaison de symptômes gastro-intestinaux, cardiovasculaires et neurologiques (Darius et al., 2018 ; Gatti et al., 2008). Les ciguatoxines sont produites par des dinoflagellés benthiques (microalgues) des genres *Gambierdiscus* et *Fukuyoa*. Il est difficile d'estimer l'incidence réelle de cette maladie car seuls environ 10 à 20 % des cas sont signalés aux organismes de santé publique (Friedman et al., 2017). Dans l'ensemble des îles du Pacifique, le taux d'incidence réelle estimé atteint 12 000 cas par an (Chinain et al., 2020). Les occurrences de ciguatera sont dynamiques et un lien a été trouvé entre le développement de la microalgue toxique et les perturbations environnementales (cf. cyclones, élévation de la température et aménagements côtiers) (Bell et al., 2009 ; Chinain et al., 2010). Comme la ciguatera varie dans l'espace, elle pourrait influencer les possibilités de conservation et constituer une caractéristique spatiale d'intérêt pour la PSC.

La **mariculture** (ou aquaculture en mer) est promue comme une mesure permettant de limiter la pression de la pêche sur les écosystèmes côtiers (Bell et al., 2011a). La Polynésie française et la Nouvelle-Calédonie concentrent 90% de la valeur maricole des POTI produite et destinée au marché local ou à l'export, principalement concernant la production de perles noires et de crevettes, respectivement. En Polynésie française particulièrement, la pandémie Covid-19 a

fragilisé l'économie de la perle noire déjà en difficulté, ainsi que les îles dont l'économie en dépendait.

Enfin, les projections montrent que le **changement climatique** devrait affecter l'océan Pacifique de différentes manières, avec des trajectoires d'exposition exacerbées par les vulnérabilités socio-économiques mêlées aux des problèmes environnementaux (Andrew et al., 2019 ; Bell et al., 2011a ; 2011b ; Duvat et al., 2017). Le changement concerne les circulations océaniques et atmosphériques, la température de surface de la mer, la propagation d'agents pathogènes, les concentrations de CO<sub>2</sub> dissous etc. (Kleypas et Yates, 2009). L'élévation rapide du niveau de la mer pourrait particulièrement affecter les îles récifales et les environnements côtiers, avec des conséquences sur l'habitabilité des îles basses (Duvat et al., 2020), induisant potentiellement des migrations planifiées de populations vers des zones plus sûres (Weir et al., 2017). Alors que les connaissances s'accumulent sur les impacts du changement climatique déjà survenus ou projetés, concevoir des stratégies d'adaptation et d'atténuation basées sur la conservation, la gestion des ressources marines et la planification côtière à l'échelle locale, nationale ou régionale reste un défi critique pour les autorités de gouvernance (Hanich et al., 2018 ; Payri et al., 2019)

#### 4. Etat de l'art de la SCP dans les POTI

Afin de faire un bilan de la planification systématique de la conservation (PSC) dans les îles du Pacifique, nous avons passé en revue la littérature scientifique et la littérature grise pour répertorier les cas d'études de PSC et les analyser en termes de sites étudiés, d'objectifs, de méthodes employées et de principaux résultats obtenus (André et al., 2021a). Cet état de l'art a rassemblé 85 publications évaluées par des pairs et 10 rapports. Parmi ceux-ci, nous avons dénombré 34 cas d'études spécifiques de PSC sur des POTI. De plus, nous avons recensé 12 publications liées au contexte des POTI et 28 études de cas en PSC au-delà des POTI mais concernant des zones tropicales ou subtropicales et abordant des sujets qui auraient pu être pertinents pour les POTI.

Les principaux résultats des analyses montrent un fort potentiel des applications de la PSC malgré une adoption limitée dans les POTI (Cheok et al., 2018 ; Margules et Pressey, 2000). L'occurrence géographique et l'abondance des études varient dans le temps entre les trois régions, avec une forte polarisation par les Fidji, qui concentre 40% des études PSC.

Les tendances montrent que les scénarios de PSC ont souvent pour objectif la représentation de la biodiversité et des coûts de type coûts d'opportunité pour les pêcheurs<sup>1</sup>. Une gestion traditionnelle a rarement fait l'objet de PSC. Enfin, la PSC évolue vers des scénarios de plus en plus sophistiqués, intégrant les concepts de résilience et de connectivité afin d'atténuer les impacts liés au changement climatique. Cependant, pour un certain nombre d'études, les proxies et modèles utilisés ne sont pas validés, ce qui remet en question la qualité de l'information utilisée, et des scénarios de planification produits. Enfin, les études purement

---

<sup>1</sup>NB. Tout au long du texte, « pêcheur » est utilisé à titre générique et concerne aussi bien pêcheuses que pêcheurs. Dans le texte en anglais, la traduction adoptée est de genre neutre : « fishers ».

académiques dominant largement, souvent sans l'implication de gestionnaires locaux, et les problèmes traités, de plus en plus complexes, déconnectent les scénarios de PSC des préoccupations de base. Ces études concernent davantage les pêches à court ou moyen terme, la préservation des stocks halieutiques, ou l'équilibre entre maintien de la pêche pour la sécurité alimentaire locale et la gestion du développement d'autres activités telles que le tourisme, la mariculture, les aménagements côtiers etc.

En outre, plusieurs caractéristiques majeures des POTI n'ont jamais été prises en compte, dont la ciguatéra, la mariculture et l'importance de la ressource en invertébrés. Ces manques identifiés dans la littérature PSC sont abordés plus en détail dans les sections suivantes.

## 5. Objectif général et plan de la thèse

Les points relevés ci-dessus induisent la question de recherche :

**Q-0** : Dans quelle mesure et comment peut-on davantage prendre en compte les spécificités des POTI dans la planification systématique pour la gestion et la conservation de leurs espaces marins ?

L'état de l'art de la PSC dans les POTI montrant que bon nombre de spécificités locales ne sont pas prises en compte, nous avons axé notre approche sur la volonté de mieux les cerner et les intégrer à l'analyse systématique. Pour cela, la détermination des critères spécifiques à étudier dans le cadre de cette thèse a été réalisée en deux phases. Puisque le terrain de recherche est situé en Polynésie française (voir chap. 1 Sites d'étude), nous avons retenu en premier lieu des critères significatifs pour notre zone d'étude : le risque de ciguatéra et l'activité maricole, particulièrement la perliculture. Ensuite, utilisant ce filtre à double critère, et d'autres facteurs (voir chap. 1 Sites d'étude), nous avons examiné la zone d'étude pour identifier des sites pertinents. Puis nous avons décliné la question de recherche (Q-0) en plusieurs axes grâce aux observations empiriques et discussions avec les parties prenantes. Cette démarche a apporté des critères supplémentaires, pertinents localement et qui manquaient dans la littérature PSC.

Cette approche multicritères nous a permis d'englober, au final, un nombre accru de critères originaux pour la PSC et qui répondent à un besoin bien identifié par les populations et les partenaires. Elle fournit également des exemples concrets de problèmes de gestion qui peuvent être appréhendés avec des méthodes de PSC. A cet égard, notre question de recherche générale se décline en quatre axes de recherches spécifiques, également formulés ci-dessous sous forme de questions (Q1 – Q4) :

**Q-1** : Est-il possible de prendre en compte la ciguatéra dans la PSC et si oui comment?

**Q-2** : Comment la PSC peut-elle guider la gestion maricole, en particulier la perliculture dans ses différentes étapes ?

**Q-3** : Comment la PSC peut-elle contribuer utilement à la gestion traditionnelle ?

**Q-4** : Comment utiliser la PSC pour concevoir et mettre en œuvre des stratégies de diversification d'activités ?

La PSC, étape centrale de priorisation pour la conception de schémas spatiaux qui tiennent compte des besoins exprimés par les parties prenantes, est la pierre angulaire de cette thèse. Cet outil de priorisation spatiale a été exploré au-delà du strict objectif de conservation, et inclut une approche de gestion.

Le chapitre I présente le terrain de recherche, la Polynésie française et les 3 sites d'études : Takaroa, Raivavae et Mangareva.

Les chapitres suivants permettent d'examiner la question de recherche principale à la lumière des différentes questions spécifiques, parfois complémentaires. Chacun d'eux fait l'objet d'une publication revue par les pairs, actuellement au stade publié, en revue ou soumis à un journal de rang A.

## Chapitre I – Le terrain de recherche

Pour répondre à la question générale, le choix du terrain de recherche s'est resserré en fonction de l'ancrage géographique de nos partenaires impliqués dans ce projet : la Délégation à la Recherche en Polynésie française, l'Institut Louis Malardé (ILM), la Direction des Ressources Marines (DRM) et le projet de recherche *Management of Atolls* (MANA) financé par l'Agence Nationale de la Recherche.

### 1. La Polynésie française

En tant que territoire, la Polynésie française s'étend au sein d'une ZEE de 4,8 millions de km<sup>2</sup>. Elle compte 280.000 hab. (recensement 2019) et 118 îles totalisant 4200 km<sup>2</sup>, regroupées en 5 archipels : les Marquises, les Tuamotu, la Société, les Gambier et les Australes.

#### 1.1 Régime politique et économie

Actuellement, le régime politique de la Polynésie française est unique parmi les territoires français d'outre-mer. Ses institutions comprennent le gouvernement territorial, l'assemblée territoriale qui peut édicter des "lois de pays", et le Conseil économique, social et culturel. Depuis la loi organique de 2004 qui renforce le statut d'autonomie, le gouvernement territorial est compétent dans toutes les matières, à l'exception de celles expressément attribuées à la France.

L'économie de la Polynésie française a connu un boom dans les années 60 suite au programme d'essais nucléaires, et a depuis réduit quelque peu sa dépendance aux transferts publics de la métropole (Dropsy et Montet, 2018 ; Poirine, 1999). Elle présente les caractéristiques des petites économies insulaires d'un territoire isolé aux îles dispersées, ainsi que des facteurs de difficultés structurelles, dont un marché intérieur restreint et des coûts de production élevés.

La production de perles noires est le premier secteur d'exportation de la Polynésie française et représente, avec le tourisme à petite échelle, l'une des rares sources de revenus possibles pour de nombreux ménages des îles éloignées. Des revenus complémentaires de subsistance sont apportés par la pêche, l'artisanat et le coprah (issu de la noix de coco).



## 1.2 Perliculture

Bien que la perliculture reste la deuxième activité génératrice de revenus en Polynésie française après le tourisme, ce secteur connaît depuis 1993 une crise continue. Les perles noires sont produites depuis les années 80 et après des années d'expansion jusqu'à l'année record de 2000, les revenus générés par l'exportation de perles ont dramatiquement chuté (IEOM, 2020). Largement dépendant des marchés internationaux, notamment Hong Kong et le Japon pour 90% des ventes, l'équilibre entre l'offre et la demande a été exposé à plusieurs crises économiques ou instabilités politiques et à la concurrence directe des perles japonaises et australiennes. Mais ce sont principalement des facteurs internes qui ont affecté le secteur, comme la surproduction, l'adoption puis la suspension de mesures de contrôle de la qualité et la vulnérabilité environnementale.

Pour faire face à ces problèmes, le secteur bénéficie largement d'un soutien public dont des programmes de recherche et de formation. Les professionnels de l'huître perlière et le gouvernement ont tenté une réforme sectorielle pour améliorer la gestion de l'activité, avec une préoccupation croissante sur la pression exercée sur les écosystèmes lagunaires. Un service technique public, la Direction des Ressources Marines (DRM), compte une division spécifiquement dédiée à la gestion de l'activité perlicole.

En résumé, produire des perles de qualité prend 3 à 4 ans et repose sur deux activités distinctes : (i) le captage de naissains (juvéniles) et (ii) l'élevage d'huîtres (adultes). La récolte des huîtres adultes sauvages est interdite en Polynésie française, afin de protéger les stocks. Par conséquent, la perliculture nécessite d'abord le collectage de naissains grâce à des lignes de collectage. Le succès du captage des naissains est cependant irrégulier dans le temps et l'espace, et dépend de l'abondance des stocks sauvages reproducteurs dans le lagon, de la circulation hydrodynamique et des conditions environnementales appropriées (Sangare et al., 2020). Ensuite, la perliculture comprend : (i) la gestion de la croissance des naissains jusqu'à ce qu'ils atteignent une taille suffisante pour être greffés, (ii) la greffe d'un nucléus de perle, puis (iii) le suivi de la croissance des stocks greffés jusqu'à, finalement, (iv) la récolte de la perle. Les greffes se déroulent dans les « fermes », bâtiments sur pilotis au-dessus du lagon, qui sont le point de convergence du transport des naissains et des huîtres depuis et vers des zones de collectage ou d'élevage (concessions), à forte densités de lignes immergées et de paniers d'huîtres adultes. L'usage de l'espace lagunaire est donc critique pour cette activité. La DRM contrôle les zones d'élevage et délivre des concessions marines annuelles, soumises à redevance.

Face à la crise du marché de la perle et aux risques environnementaux tels que l'occurrence d'évènements de mortalité massive (Andréfouët et al., 2015), la DRM cherche à améliorer la durabilité du secteur : les revenus des perliculteurs mais aussi la qualité des écosystèmes. Cette stratégie se traduit par une réduction des surfaces exploitées, pour, à terme, diminuer la production et la vente de perles de mauvaise qualité, et réduire la pression sur les écosystèmes lagunaires exploités. Une mesure supplémentaire envisagée par la DRM est le réensemencement du lagon avec les huîtres d'élevage post-récolte, afin d'augmenter le stock de géniteurs. Un réensemencement à haute densité au sein de sanctuaires dédiés pourrait augmenter la reproduction et finalement assurer un collectage durable de naissains.

## 2. Choix des sites

Notre analyse des études de PSC dans le Pacifique ayant mis en évidence un manque d'adaptation des cas d'études aux spécificités des îles, le choix des sites de recherche a été guidé par leurs dimensions multicritères qui permettent de répondre aux axes de recherche. Nous étions particulièrement intéressés par l'activité perlicole, active au sein de 17 lagons (DRM, 2019), et par la ciguatéra, lacune importante dans la littérature de la PSC. De plus, les sites devaient incarner une certaine complémentarité dans l'aspect « multicritères » des îles afin de représenter des cas de figures contrastés. L'objectif était d'identifier deux ou trois sites répondant à ces critères, pour lesquels des données complémentaires étaient disponibles, ainsi que présentant des conditions d'accès compatibles avec le budget et le calendrier de la thèse pour y conduire des missions de collecte de données spatialisée et quantifiée sur les différents usages du lagon, la pêche artisanale et la ciguatéra.

Le choix s'est finalement porté sur Takaroa, Raivavae et Mangareva. Nous présentons ci-dessous chaque île en quelques lignes, et les axes de recherche développés.

### 2.1 L'atoll de Takaroa, aux Tuamotu

Takaroa est un atoll situé dans l'archipel des Tuamotu, par 145°O et 14,27°S, à près de 600 km. Il abrite environ 900 personnes (recensement 2019), vivant pour la plupart dans le village principal, de Teavaroa. Le lagon, de 85 km<sup>2</sup>, est semi fermé, c'est-à-dire qu'il ne communique avec l'océan que par une unique passe.

Takaroa fut l'un des atolls perlicoles les plus productifs dans les années 1990, avant de connaître des événements successifs de mortalité massive dans le lagon, qui ont affecté les stocks d'huîtres d'élevage et sauvages (2000 et 2001 et surtout 2014) (Andréfouët et al., 2015). Ce dernier épisode de mortalité massive a eu des conséquences sur le moyen/long terme puisque même cinq ans après, les taux de croissance et de recrutement des huîtres étaient toujours nuls ou anormalement faibles (Monaco et al., 2021). Les causes de ces épisodes pourraient être multifactorielles, impliquant possiblement maladies, efflorescence de microalgues, dépassement de la capacité de charge trophique du lagon, taux de microplastique trop élevés, hausse inhabituelle de température de surface de l'eau etc. (Andréfouët et al., 2012).

De récentes observations rapportent une certaine reprise de la croissance des huîtres d'élevage à Takaroa. Les conditions pourraient être à nouveau réunies pour la perliculture. Afin de booster le stock sauvage, la DRM envisage donc des mesures de réensemencement, en réintroduisant dans le lagon, des huîtres adultes post-récolte de perles. En effet, une fois le cycle de production terminé, à moins d'une « surgreffe » (seconde voire très rarement troisième greffe), les huîtres sont la plupart du temps consommées ou simplement rejetées sur place. Or ces huîtres, hermaphrodites protandres, pourraient avantageusement être relâchées dans le milieu naturel pour augmenter le stock sauvage et accroître les chances de production naturelle du lagon en naissains. C'est dans cette perspective que la DRM, en impliquant les perliculteurs, souhaite programmer des actions de réensemencement avec des huîtres issues des élevages de Takaroa-même, ainsi que de Takapoto, l'île voisine.

➔ Dans ce contexte, comment identifier les zones les plus propices au réensemencement d'huîtres perlières adultes dans le lagon, en tenant compte de paramètres socio-économiques et environnementaux ? C'est la question que nous allons examiner à l'aide de la PSC, en Chapitre 3.

## 2.2 L'île haute de Raivavae, aux Australes

Raivavae est une île de l'archipel des Australes, située à 147,67°O et 23,87°S, légèrement au sud du tropique du Capricorne, à 630 km de Tahiti. Les 900 habitants se répartissent tout autour de l'île en quatre districts. C'est une île haute de 16 km<sup>2</sup> culminant à 437m. par le mont Hiro, entourée d'un lagon de 86 km<sup>2</sup>. Un anneau de corail ceinture le lagon, sous forme de récif barrière et *motu*, entrecoupé de trois passes. A Raivavae, les habitants produisent une grande partie des ressources alimentaires qu'ils consomment, basées sur une agriculture locale et une pêche artisanale très répandue. Un potentiel perlicole existe, mais l'activité est peu développée, comptant seulement quelques projets de collectage de naissains. La pêche au bénitier est particulièrement pratiquée, pour la consommation locale et l'export vers Tahiti. La pêche locale a été marquée par un important épisode d'intoxication ciguatérique en 2007-2008 (Chinain et al., 2010), ce qui a donné lieu aux premiers signalements d'intoxications par bénitiers. La ciguatéra est donc une composante importante pour les pêcheurs dans le choix de leurs zones de pêche.

➔ Dans ce contexte, la ciguatéra a une réelle emprise spatiale dans le lagon ; comment la prendre en compte dans la PSC ? Le chapitre 2 bâtit une méthodologie pour intégrer dans la PSC le risque ciguatéra tel que perçu par les pêcheurs. Cette méthodologie est ensuite utilisée dans les chapitres 4 et 5.

Lors de nos enquêtes sur le terrain, les pêcheurs nous ont signalé l'existence d'un projet en cours : la mise en place d'un rāhui, c'est-à-dire d'une rotation de réserves traditionnelles gérées localement. Le rāhui aurait pour but de protéger le stock de ressources marines, que les habitants et pêcheurs ont le souci de préserver pour leurs besoins actuels et pour ceux des générations futures. Cependant, la configuration du rāhui était discutée car elle entraînait d'importantes restrictions d'accès. Il était en effet envisagé pour chacun des quatre districts, de séparer le lagon en deux parties égales allant de la côte au récif, et de mettre en rāhui alternativement l'une des deux sections, pour tous les districts en même temps, ce qui correspond à fermer à la pêche 50 % du lagon, répartis en quatre zones. Les pêcheurs rencontrés étaient en demande de conseils et une réunion a été organisée pendant notre mission par le comité local de l'environnement afin de permettre un échange, et des questions-réponses.

➔ Suite à cet échange, comment la PSC peut-elle proposer une optimisation du design traditionnel rāhui, pour la préservation d'un stock halieutique, tel que les bénitiers, tout en diminuant les contraintes spatiales engendrées ? Cette question a été traitée dans le chapitre 4, pour proposer des designs alternatifs afin de protéger le même niveau de stock de bénitiers mais de diminuer la taille des réserves, le coût d'opportunité pour les pêcheurs, et le risque ciguatéra.

### 2.3 L'île haute de Mangareva, aux Gambier

Les Gambier représentent un ensemble de petites îles hautes situées dans un même lagon, par 135°O et 23,20°S, à 1650 km de Tahiti. La majorité des 1430 habitants se regroupe au village de Rikitea et le long des baies de Mangareva, cette île de 15 km<sup>2</sup> surplombée par Auorotini, ou Mont Duff, culminant à 441 m.

Mangareva connaît une grande renommée qu'elle doit à la qualité de ses perles noires. Le dynamisme du secteur perlicole est porté par quelque 160 professionnels, travaillant sur toutes les étapes du collectage à l'élevage (IEOM, 2020b). Aux Gambier, la gestion de la production est spécifique car collectage et élevage sont réalisés uniquement localement, sans imports de naissains d'autres îles. Certains producteurs se sont associés pour valoriser le prix des perles lors des ventes aux enchères. Le lagon des Gambier est le plus productif en perles noires, avec 1,7 millions de perles en 2020 soit 25 % de la production polynésienne (DRM, 2020a), bien que celle-ci ait été fortement affectée par la crise Covid.

Peu d'autres activités sont pratiquées aux Gambier, une petite économie du tourisme s'y maintenait avant la pandémie, et une activité de pêche vivrière a lieu à petite échelle. Celle-ci est particulièrement attentive au risque de ciguatéra, qui a affecté fortement les Gambier par le passé, et représente toujours un risque aujourd'hui (Chinain et al., 2020). La découverte de la microalgue *Gambierdiscus toxicus* dans les années 1970, à l'origine de l'intoxication, doit d'ailleurs son nom à cet archipel (Yasumoto et al., 1977).

Afin de soutenir la filière perle et améliorer sa durabilité économique et environnementale, la DRM, en accord avec les perliculteurs, envisage de réduire les surfaces de concessions dans le lagon des Gambier et de mettre en place des zones de réensemencement.

➔ Dans ce contexte, il apparaît important d'évaluer si le lagon des Gambier se prête à une diversification des activités et de quelle façon. Des scénarios à différents degrés de diversification sont explorés dans le chapitre 5, recherchant l'optimisation d'arrangements spatiaux entre diverses activités, dont collectage, concessions, réensemencement au sein de sanctuaires placés selon des schémas de gestion traditionnelle, conservation des communautés remarquables, et pêche, avec ou sans le risque de ciguatéra.

Les chapitres suivants sont succinctement résumés ci-après, et nous encourageons vivement le lecteur à consulter les articles correspondants, les résultats et cartes associées.

## Chapitre II

### Développement d'une méthodologie pour prendre en compte le risque de ciguatéra dans la planification systématique de la conservation.

*Ce chapitre a fait l'objet de la publication suivante :*

André, L. V., Van Wynsberge, S., Chinain, M., Gatti, C., Dempsey, A., Andréfouët, S. 2021b.  
A framework for mapping local knowledge on ciguatera and artisanal fisheries to inform systematic conservation planning.  
ICES Journal of Marine Science, 78: 1357–1371.

Des millions de personnes tirent leur subsistance de la pêche artisanale. Cependant, dans de nombreuses régions, les pêcheurs sont de plus en plus confrontés aux intoxications dues à la ciguatéra, une maladie transmise par les produits de la mer. Cette toxine, produite par des dinoflagellés benthiques, peut se propager dans les réseaux alimentaires marins et atteindre les humains par consommation directe. Le risque de ciguatéra, et la manière dont ce risque est perçu par la population, peuvent jouer un rôle majeur dans les activités des pêcheurs, car ces derniers évitent de prélever des ressources dans les zones qu'ils considèrent à risques. En dépit de l'importance du facteur « ciguatéra » dans la distribution de l'effort de pêche, ce facteur n'a jusqu'à présent jamais été pris en compte dans les plans d'aménagement du territoire marin.

Pour combler cette lacune, nous avons examiné si la prise en compte de la ciguatéra dans les plans de conservation systématique pouvait modifier la sélection des zones optimales. Nous avons développé un nouveau cadre en sept étapes pour collecter et cartographier les connaissances locales sur le risque de ciguatéra et sur les activités de pêche, incluant deux points innovants : (i) une meilleure cartographie des zones de pêche qui combine l'habitat géomorphologique et les caractéristiques des techniques de pêche, et (ii) l'intégration du risque de ciguatéra directement dans des scénarios de planification spatiale systématique conçus pour maximiser la conservation de l'habitat benthique tout en minimisant les impacts pour les pêcheurs.

*Les sept étapes de la méthodologie proposée, sur laquelle s'appuient les chapitres suivants, sont détaillées ci-après:*

- **Etape 1 : Collecter l'information.** Pour mener les enquêtes auprès des pêcheurs les plus actifs, la stratégie d'échantillonnage a été guidée par des lieux-clés (mairies, places, quais, magasins), informateurs clés et effet boule de neige. Les enquêtes semi-directives (cf. Aswani and Hamilton, 2004) sont menées de façon à collecter des données quantitatives et spatialisées sur la pêche, ainsi que sur la perception du risque de ciguatéra. La technique suivie est celle du rappel à court terme des pêches récentes, suivie d'un rappel des pêches antécédentes en remontant dans le temps (Brennan et al., 1996). Elle est complétée par une approche dans l'espace, pour obtenir une représentation de la pêche à l'échelle de l'année. La personne enquêtée était invitée à décrire chaque type de pêche en termes d'espèces (en utilisant

la référence taxonomique illustrée du guide Bacchet et al. (2010)), de taille, de nombre et de zone en la traçant au feutre sur une carte de l'île par image satellite, imprimée au format A0 et plastifiée, où les couleurs font ressortir les différents types de récifs et substrats benthiques (Close et Hall, 2006). Concernant la ciguatéra, chaque pêcheur était invité à tracer sur la carte deux types de zones, celles à risque avéré, ayant donné lieu à une intoxication en précisant la date (une date plus récente impliquant un risque plus élevé), et les zones à risque supposé, évitées pour la pêche.

- **Etape 2 : Transcrire les zones de pêche sous format SIG.** Après homogénéisation de l'information quantitative et qualitative recueillie par extrapolation des prises à l'année (approche conservative), l'information spatiale des zones de pêche est saisie sous SIG (système d'information géographique) en y associant les attributs correspondants. La carte des pêches donne donc une estimation des volumes (en kg) pêchés par zone et par pêcheur.

- **Etape 3 : Préciser les contours des zones de pêche.** Certains contours tracés au cours des enquêtes sont apparus assez approximatifs, certains instruments de pêche (fusil sous-marin, filet, *pātia*, ligne du bord du bateau immobile, traîne etc.) ne pouvant être utilisés que dans certains types d'environnement (limite de profondeur, présence de massifs coralliens ou autre). A chaque technique de pêche est donc attribuée une typologie d'environnements favorables, eux-mêmes spatialisés dans une carte d'habitats géomorphologiques (Andréfouët et al., 2006). Pour chaque technique de pêche, les zones initialement tracées sont donc rognées par les limites des habitats favorables correspondants et le contour des zones de pêches gagne ainsi en précision.

- **Etape 4 : Transcrire les zones à risque ciguatérique perçu, sous format SIG** (système d'information géographique). De la même manière que pour les zones de pêche, les zones à risque de ciguatéra sont saisies sous format SIG. Cette fois, un coefficient de risque est affecté en fonction de la nature de l'observation (i.e. risque estimé ou avéré récent ou ancien), permettant de produire une carte quantitative du risque ciguatéra.

- **Etape 5 : Superposer aux zones de pêche un calque d'unités de planification.** Dans un même lagon, de nombreuses zones de pêche peuvent se superposer. Pour produire une carte synthétique des quantités totales pêchées (prises à l'échelle de la population), le calque des zones de pêche raffinées est intersecté par une grille d'hexagones constituant les unités de planification (UP) (procédure Goñi et al. (2008), également suivie par Léopold et al., 2014). Pour chaque fraction de zone de pêche découpée par la grille, les prises sont attribuées de manière proportionnelle à la surface des fractions. Pour chaque UP, les différentes fractions de volumes de pêche sont additionnées, afin de produire un indice des prises par unité de surface (suivant Walters (2003) et en adaptant Léopold et al., (2014)) et ainsi d'obtenir une carte du lagon représentant les volumes des prises annuelles.

- **Etape 6 : Superposer au risque ciguatéra le calque d'UP.** Concernant la ciguatéra, le risque n'étant pas proportionnel à la surface désignée, le coefficient de risque associé à chaque zone a été généralisé (propagé) à chaque UP concernée. La somme des coefficients de risque par UP permet ainsi de produire une carte de distribution du risque au sein d'un lagon.

- **Etape 7 : Produire un calque de coûts combinant pêche et ciguatéra.** L'hypothèse sous-jacente est que les zones à fort risque ciguatérique sont moins fréquentées pour la pêche. Dans un scénario de conservation, pour chaque UP, le coût d'opportunité pour les pêcheurs serait alors diminué par le risque de ciguatéra, d'autant plus s'il est élevé. Nous avons paramétré une couche de coût spatialement explicite intégrant à la fois la pêche et le risque de ciguatéra après avoir normalisé leurs valeurs pour qu'elles soient comparables. Un coefficient a été affecté à la ciguatéra afin de moduler son poids par rapport à la pêche.

Cette approche est ensuite reproduite pour l'intégration de la ciguatéra dans le calcul des coûts socio-économiques, utilisés pour construire les scénarios de PSC.

Cette démarche est illustrée pour l'île de Raivavae, en Polynésie française, dans l'océan Pacifique. Nous avons mis en évidence qu'intégrer une couche de donnée spatialisée reflétant le risque ciguatérique perçu par les pêcheurs, permettait améliorer les solutions de priorisation avec une diminution de 24 à 38% des coûts pour les pêcheurs par rapport aux scénarios basés uniquement sur les données de pêche.

Ce cadre a été conçu pour les scientifiques et les gestionnaires afin d'optimiser la mise en œuvre des plans de conservation et il pourrait être généralisé aux zones sujettes à la ciguatéra.

## Chapitre III

### Identifier des sites favorables au réensemencement d'huîtres grâce à la PSC.

*Ce chapitre fait l'objet de la soumission d'article suivant :*

André, L. V., Chinain, M., Gatti, C., Liao, V., Van Wynsberge, S., Tedesco, P., Andréfouët, S.  
Identification of suitable pearl oyster restocking zones in Takarua Atoll following a mass-mortality event, using environmental and socio-economic data in a systematic prioritization approach. *Submitted* to Marine Pollution Bulletin.

La perliculture pour la production de perles noires est une activité centrale en Polynésie française. Elle constitue la deuxième source de revenu du Pays et offre d'importantes possibilités d'emploi, notamment dans les îles périphériques. Cependant, ce secteur a été fragilisé par des crises successives, telles que des événements de mortalité massive des stocks d'huîtres à la fois sauvages et d'élevage, entraînées par des perturbations environnementales.

Dans l'hypothèse d'une amélioration des conditions environnementales, une des options possibles pour relancer l'activité consiste à réintroduire des huîtres dans des points stratégiques du lagon, de manière à maximiser la reproduction et la dispersion des larves dans l'ensemble du lagon, favorisant ainsi le captage de naissains pour l'élevage et la recolonisation.

Pour Takarua, un atoll des Tuamotu-Ouest récemment touché par une forte mortalité des huîtres, une stratégie de planification systématique a permis d'identifier les sites appropriés pour le repeuplement en huîtres, en tenant compte de critères environnementaux et socio-économiques tels que : l'emplacement des habitats appropriés pour la colonisation des huîtres, la connectivité du lagon estimée par un modèle de circulation hydrodynamique, l'accumulation des déchets d'élevage, et le coût d'opportunité pour les perliculteurs et les pêcheurs, s'appuyant sur la méthodologie développée au chapitre 2.

Les sites identifiés fournissent aux gestionnaires des solutions pour les mesures de réensemencement.



## Chapitre IV

### Les bénéfices d'une collaboration entre pratiques traditionnelles et PSC pour le design d'un rāhui.

*Ce chapitre fait l'objet de la soumission d'article suivant :*

André, L. V., Van Wynsberge, S., Chinain, M., Andréfouët, S.  
Benefits of collaboration between indigenous fishery management and data-driven spatial planning approaches: the case of a Polynesian traditional design (*rāhui*).  
*Submitted* to ICES JMS.

Les systèmes de gestion de la pêche traditionnels autochtones bénéficient d'une reconnaissance croissante dans le monde entier, pour le respect des pratiques culturelles anciennes, dont beaucoup sont encore ancrées dans les communautés actuelles malgré la mondialisation et les moyens de subsistance modernes. Ce renouveau est largement répandu et approuvé par les décideurs politiques, les scientifiques et les communautés elles-mêmes. Cependant, les contextes environnementaux et socio-économiques actuels ne sont pas semblables aux situations des temps anciens. Les bases de référence sont différentes.

Le rétablissement des systèmes traditionnels "tels quels" nécessite un suivi ; un ajustement efficace des pratiques traditionnelles peut être préconisé. Pour cela, l'apport des approches modernes d'évaluation quantitative et de gestion se révèlent utiles.

Ici, nous abordons le cas d'une île rurale polynésienne qui fait face à une forte pression sur les ressources marines. Récemment, les pêcheurs ont discuté de la mise en œuvre d'un système traditionnel (*rāhui*) pour préserver les ressources des lagons, basé sur la fermeture de 50% de la surface lagonaire, selon des subdivisions territoriales, et une rotation de ces réserves. À la demande des pêcheurs, nous avons utilisé des outils de planification systématique de la conservation pour explorer les voies d'optimisation potentielles. A objectifs égaux, la PSC a identifié des solutions présentant des tailles et coûts respectivement 7 et 5 fois plus faibles en moyenne.

La gestion traditionnelle fédère les communautés et est encouragée, et la PSC peut apporter des éléments quantitatifs bénéfiques, assurant une certaine efficacité du design des réserves. On peut s'attendre à des résultats similaires ailleurs dans le monde.

## Chapitre V

### Scénarios de diversification des activités : configurations spatiales et coûts relatifs des zones.

*Ce chapitre fait l'objet de la soumission d'article suivant :*

André, L. V., Van Wynsberge, S., Chinain, M., Gatti, C. M.iti, Liao, V., Andréfouët, S.  
 Spatial solutions and their impacts when reshuffling coastal management priorities in small  
 islands with limited diversification opportunities.  
*Submitted* to Science of the Total Environment

Dans le cas de petites économies développées sur un nombre restreint d'activités qui sont dépendantes de facteurs externes, tels les fluctuations des marchés internationaux ou les changements globaux, une des voies recommandées consiste à diversifier les activités. Pour les petites îles, où l'espace côtier est restreint, l'éventail des activités possibles est souvent limité et cette diversification doit augmenter la résilience des populations et permettre de maintenir la pêche artisanale pour assurer la sécurité alimentaire locale, tout en conservant les écosystèmes en bon état afin qu'ils maintiennent leurs fonctions essentielles.

La perle noire de Polynésie française connaît une renommée mondiale mais fait pourtant face à une profonde crise économique et environnementale, et les gestionnaires locaux souhaitent en améliorer la durabilité. Dans cette étude, nous avons utilisé un outil de priorisation systématique multi-objectifs pour explorer la faisabilité de scénarios à différents niveaux de diversification spatiale, dans le lagon des Gambier.

Différents scénarios ont permis de concevoir des options de diversification dans la gestion côtière, notamment une réaffectation optimisée des fermes, l'identification de zones de conservation pour le stock d'huîtres sauvages et pour les communautés coralliennes vivantes remarquables, tout en tenant compte de la zone de collectage des naissains (juvéniles d'huîtres perlières) et des zones de réensemencement des huîtres définies dans les zones de gestion traditionnelle. Différents types de coûts d'opportunité ont été utilisés pour minimiser les impacts de la zonation, notamment la surface des zones, et le coût d'opportunité de pêche artisanale. En outre, le risque d'intoxication par la ciguatera a également été pris en compte, car il est déterminant pour les pêcheurs dans le choix de leurs lieux de pêche. La robustesse des solutions a été analysée avec différents niveaux de pénalités de capacité et différentes informations de coûts d'opportunité. Les solutions de PSC issues des scénarios de diversification ont été comparées entre elles, et les impacts mutuels de chaque zone ont été quantifiés, ce qui permet de définir des bases quantitatives solides en vue de discussions ultérieures entre les parties prenantes et avec les entités de gouvernance.

L'étude de cas des Gambier montre que l'exploration des options de diversification dans les petites îles à l'aide d'outils de priorisation systématique est possible et peut fournir aux gestionnaires locaux des plans sur mesure adaptés à des questions de développement insulaire très spécifiques pour faire face aux défis de notre époque.

## Discussion générale

La planification systématique de la conservation est un outil scientifique mature qui a démontré une grande flexibilité dans la prise en compte d'une variété de données, de caractéristiques et de processus pertinents pour la conservation et le maintien des écosystèmes tout en minimisant les impacts pour les parties prenantes.

### 1. Synthèse des contributions

Cette thèse a abordé la question générale de comment et dans quelle mesure mieux intégrer les spécificités des îles tropicales de l'océan Pacifique dans la planification systématique de la conservation et de la gestion des zones côtières. Nous avons contribué à améliorer la PSC pour la conservation et la gestion des lagons de Polynésie française en proposant des approches originales pour répondre à différentes questions de gestion qui ont émergé dans de nombreux contextes de POTI. En outre, nous avons développé des méthodes pour mieux prendre en compte plusieurs facteurs et processus qui sont importants dans les îles du Pacifique mais qui n'avaient jamais été pris en compte dans les études de PSC précédentes. Plus précisément, les sections suivantes reprennent les principales contributions apportées à nos quatre axes de recherche : (1.1) La prise en compte du risque de ciguatera dans les scénarios de PSC ; (1.2) La planification pour une perliculture durable ; (1.3) L'intégration de la PSC dans la conception de la gestion traditionnelle de la pêche ; et (1.4) La planification de la diversification. Enfin, les contributions transversales et les limites de cette étude sont abordées.

#### 1.1 Prendre en compte la ciguatera dans les scénarios de PSC

Lors de son élaboration, le plan de gestion spatialisé doit tenir compte de toutes les principales caractéristiques de la zone marine. En effet, dans les régions touchées par la ciguatera, si le plan ne laisse finalement ouvertes aux pêcheurs que les zones sujettes à la ciguatera, ceux-ci ne l'approuveront pas. En revanche, les zones perçues comme étant à risque ciguatérique sont *de facto* évitées par certains pêcheurs. Par conséquent, elles représentent des zones candidates pour la mise en réserve stricte, en minimisant les coûts d'opportunité générés. Pour prendre en compte la ciguatera dans les scénarios de PSC, nous avons mis au point un cadre méthodologique intégrant cette information quantifiée et spatialisée et l'avons appliqué à Raivavae et aux Gambier, où nos résultats démontrent que les plans sont moins coûteux pour les pêcheurs lorsqu'ils prennent en compte la ciguatera (chapitres 2, 4 et 5). Néanmoins, il faut garder en tête que l'information collectée sur le risque de ciguatera provient des savoirs locaux, qui peuvent avoir différents degrés de fiabilité, mais s'avérer assez précis quant à la ciguatera (Lauer et Aswani, 2010 ; Chinain et al., 2020). Ce type d'information est adapté au cadre de la planification marine, mais ne saurait s'appliquer à des programmes pour la santé humaine, où des analyses écotoxicologiques seront plus fiables, bien que limitées spatialement et beaucoup plus coûteuses.

#### 1.2 Planifier pour la durabilité de la perliculture

Après un âge d'or où la perliculture en Polynésie française s'est développée de manière rapide et dense dans de nombreux lagons, le secteur a connu plusieurs crises. Pour faire face à certains problèmes et favoriser la durabilité de l'activité, la Direction des Ressources Marines (DRM)

souhaite prendre différentes mesures spatiales, telles que la réduction des surfaces allouées à l'élevage (concessions), la sanctuarisation des populations d'huîtres sauvages et des mesures de réensemencement pour augmenter le stock naturel d'huîtres sauvages. Les outils de planification systématique ont été utilisés pour gérer spatialement ces activités spécifiques de perliculture (chapitres 3 et 5). L'outil SCP s'est avéré utile pour envisager différentes dispositions spatiales des étapes de la perliculture aux Gambier, puisque la gestion durable touche à la fois les domaines environnementaux et socio-économiques (Chapitre 5). Par ailleurs, la pierre angulaire de la perliculture est l'approvisionnement en naissains d'huîtres, qui dépend du succès reproductif du stock sauvage et du succès du collectage des naissains. L'étude menée à Takaroa a permis d'identifier des sites prioritaires pour le réensemencement d'huîtres dans le milieu naturel, en tenant compte de caractéristiques environnementales, dont le potentiel de dispersion, et des contraintes socio-économiques (chapitre 3).

### 1.3 Intégrer la PSC au design de réserves traditionnelles

La renaissance de la gestion traditionnelle et communautaire du milieu marin est en cours dans toutes les POTI, y compris en Polynésie française. Lors de nos enquêtes sur la pêche et la ciguatéra à Raivavae, nous avons été informés d'un projet de rāhui. Alors que les pêcheurs se questionnaient sur le design même du rāhui, l'occasion s'est présentée de l'étudier à l'aide de la PSC pour trouver des moyens d'optimiser sa conception (chapitre 4). La question n'était pas d'évaluer le rāhui, mais bien de chercher le moyen de rendre ce design moins contraignant pour les pêcheurs. Pour cela, les principes majeurs du rāhui ont été gardés, à savoir, conserver les ressources marines (en particulier le stock de bénitiers) en évitant la surpêche, et partager équitablement les zones de lagon fermé entre chaque district. L'analyse s'est basée sur des données de distribution et d'abondance du stock de bénitiers ainsi que de coût d'opportunité pour les pêcheurs et le risque ciguatéra, issues des enquêtes. Les résultats de la PSC ont identifié différentes options de design bien moins restrictives en termes de surface et de coût d'opportunité, tout en atteignant le même objectif de protection des bénitiers. Loin de vouloir se substituer aux initiatives locales et processus de décisions traditionnels, qui ont une valeur dépassant le cadre de cette étude (Gurney et al., 2015; Smallhorn-West, 2019), une telle analyse PSC peut se placer en complément au cours du dialogue de gestion et apporte des éléments de comparaison quantifiés permettant d'éclairer/ajuster la décision.

### 1.4 Planifier pour de multiples activités

Dans un monde en mutation, les crises mondiales touchent même les îles éloignées, avec plus ou moins d'impact selon leur degré d'échanges et de dépendances avec le monde extérieur. Des stratégies de diversification sont classiquement encouragées pour atténuer les risques d'effondrement de l'équilibre socio-économique local (Barrett et al., 2001 ; Bowser et Nelson, 2012 ; Kasperski et Holland, 2013). Aux Gambier, la perliculture est une activité économique prépondérante, mais ce secteur déjà fragilisé a été encore plus touché par la pandémie de Covid-19 (IEOM, 2020). La PSC a comparé plusieurs scénarios dans un contexte de diversification et d'usages multiples, d'intérêts et de contraintes plurielles. Les résultats ont montré que la diversification était possible dans le lagon, avec différentes configurations spatiales et l'espace alloué à chaque activité et les coûts relatifs induits ont été mesurés, y compris en termes de coûts socio-économiques (Chapitre 5).

## 1.5 Contributions transversales des exercices de PSC

De manière transversale, les contributions de cette thèse à la PSC ont porté sur la **qualité de la donnée** en évitant de reposer uniquement sur des proxies trop généralistes qui n'auraient pas été adaptés aux petites îles. Elle a produit et utilisé de la donnée empirique collectée *in situ* pour des applications plus robustes de la PSC. Ensuite, elle a conçu des **scénarios sur mesure**, en s'efforçant de traduire le plus précisément possible les questions locales de conservation de gestion maricole ou halieutique vers le cadre de la PSC, mobilisant des paramétrages adaptés et des données originales, dont des cartes de concessions, d'abondance de stock d'huîtres sauvages ou de bénitiers, de coût d'opportunité local et de risque ciguatéra. Des **analyses de sensibilité** ont été menées pour appréhender la variabilité des solutions selon les données d'entrée, les niveaux d'objectifs fixés ou les choix de compacité. Au vu de l'importante sensibilité des solutions obtenues aux paramétrages des scénarios, il est recommandé d'impliquer les parties prenantes dès l'amont pour guider au mieux les choix méthodologiques (Cheok et al., 2017; Flower et al., 2020). Enfin, nous avons utilisé la PSC pour aborder des questions de conservation de la biodiversité ou bien de gestion des ressources et des activités, ou les deux. Comme un écho au débat des sciences de la conservation sur la manière d'équilibrer la conservation entre systèmes naturels et systèmes sociaux (Gurnay et al., 2021; UICN, 2019), nous avons exploré ici l'application de l'outil de conservation PSC aux domaines de la gestion des activités économiques et des espaces multi-usages. Serait-ce là une nouvelle perspective : de la planification systématique de la conservation, vers la planification systématique ? Quoiqu'il en soit, la reconnaissance de la part des programmes internationaux de l'intérêt de la planification spatiale marine et de l'outil Marxan (IPBES, 2021; MSPGlobal program ; NOAA, 2021) semble renforcer le rôle à venir de la PSC dans la gestion de l'espace marin.

## 1.6 Limites

**Les limites pratiques** que nous envisageons sont celles qui pourraient affecter la validité d'une transposition directe des résultats dans le monde réel, tout en restant contraint par les questions posées et les moyens disponibles. En premier lieu, la récolte de données aurait probablement été améliorée par des enquêtes menées sur un temps plus long et répétées. Ensuite concernant la méthodologie bâtie pour inclure à la PSC l'information sur le risque ciguatéra, l'étape suivante sera de trouver le moyen d'intégrer à cette information spatiale générique, une dimension sur les espèces à risque. En effet, les risques dépendent à la fois des zones et des espèces, qui varient d'une île à l'autre (Chinain et al., 2021). Enfin, le modèle de connectivité utilisé pour la dispersion larvaire des huîtres dans le lagon de Takaroa sera amélioré prochainement dans le cadre du projet MANA, pour inclure un plus grand nombre de sous-zones et de régimes de vents afin d'affiner les prédictions. Ces modèles de connectivité pourraient ensuite être couplés à d'autres modèles biologiques et également servir pour la planification de la conservation.

**Les limites conceptuelles** que nous décrivons ici concernent la PSC elle-même, la conservation et la planification en général. D'une part, le fait de ne pas pouvoir prendre en compte la dimension temporelle dans la planification nous semble être une limite structurelle de la SCP, à laquelle nous avons été confrontés au moment de simuler le design du rāhui.

D'autre part, il nous a semblé que la sélection des sites était très (trop ?) guidée par les coûts à minimiser, qui correspondent, dans notre contexte, aux coûts d'opportunité pour les pêcheurs et sont potentiellement concentrés près des villages. Or la pratique montre que de nombreuses réserves traditionnelles, sont justement placées près des villages (Cinner et Aswani, 2007; Smallhorn-West et al., 2019), donnant finalement la priorité à la facilité du contrôle collectif. Cette dimension complémentaire pourra être prise en compte dans de futurs projets de PSC, et en concertation avec la population. Ensuite, même si la PSC tente d'intégrer le mieux possible les dimensions socio-économiques et culturelles, elle se fonde sur une vision spatiale de la gestion, et par nature, n'est pas apte à prendre en compte tous les types de facteurs humains (conflits interpersonnels). Ceci rappelle que la sélection des sites par la PSC, qui peut déjà impliquer les parties prenantes, n'est qu'une étape au sein du processus de mise en œuvre d'une réserve, et que les étapes suivantes impliquent que les solutions PSC soient validées (Pressey and Bottril, 2009) mais elles peuvent également servir des jeux de négociation ou d'instrumentalisation. Par ailleurs, le design de réserves se focalise souvent sur le fait de supprimer la pression de pêche mais se soucie rarement de l'impact du report de l'effort de pêche sur les zones adjacentes (mais voir Babcock et al., 2005, Halpern et al., 2004). Enfin, les plans de réserve ne sont malheureusement que des plans. D'abord, la dimension spatiale des réserves ne les coupe pas de menaces telles des pollutions ou les conséquences du changement climatique comme l'acidification et le blanchissement, bien que des designs spécifiques puissent être conçus pour atténuer ces impacts (Cinner et al., 2020; Green et al., 2014). Pour finir, au-delà de la planification, l'efficacité d'une réserve dépend fortement de l'efficacité de sa gestion dont les pierres angulaires semblent converger vers une adhésion locale, suffisamment de moyens dédiés sur le long terme, et une bonne articulation entre les différents niveaux décisionnels impliqués (Ban et al., 2011 ; Gruby et Basurto, 2013 ; Weeks et Adams, 2018).

## 2. Généralisation à d'autres POTI

### 2.1 Pêche artisanale et information sur la ciguatéra

La pêche artisanale est largement pratiquée à travers les POTI (Gillett et Tauati, 2018) et dans la perspective d'un design SCP, la collecte et l'utilisation d'informations à jour et adaptées à l'échelle d'étude est recommandée pour tous les sites concernés par cette activité. La ciguatéra est largement répandue à travers les POTI, certaines connaissant des taux d'incidence très élevés. Prendre en compte la ciguatéra dans les exercices de planification pour la conservation et la gestion des ressources relève donc de la plus haute importance pour la plupart des POTI et le cadre méthodologique élaboré dans cette thèse pourrait servir à de nombreuses futures études. Cependant, certains aspects pourraient en freiner son usage dans d'autres contextes, par exemple si les pêcheurs ne sont pas enclins à partager aussi facilement qu'ici leurs habitudes de pêche et leur perception du risque ciguatéra, ou s'ils en ont une conscience moins aigüe (notamment dans certaines îles où la ciguatéra a moins d'incidence), ou encore s'ils sont moins à l'aise pour se repérer sur une carte, même issue d'image satellite. Dans ces cas-là, l'approche de cartographie développée au cours de ces travaux et basée sur des savoirs locaux serait moins fiable. Par ailleurs, en perspective l'ILM et la CPS travaillent actuellement au développement d'une plateforme en ligne de télé-déclaration d'intoxication ciguatérique, qui sera déployée sur tous les POTI. Si les habitants se l'approprient, cette

plateforme de science participative pourrait rassembler de précieuses informations et permettre un premier niveau d'évaluation du risque, avant de prévoir des enquêtes de terrain complémentaires.

## 2.2 Gestion traditionnelle

La gestion traditionnelle est largement pratiquée au sein des POTI et intégrer cette dimension à toute PSC, est donc vivement recommandée. Néanmoins, l'articulation de la gestion communautaire avec les cadres juridiques territoriaux ou nationaux reste un défi, car elle exige que la gouvernance soit partagée et partiellement décentralisée (Kuemlangan, 2004). La reconnaissance du droit coutumier dans les systèmes législatifs nationaux est en cours en Nouvelle-Calédonie, aux Iles Cook, aux Salomon et aux Vanuatu, entre autres (Graham et D'Andrea, 2021 ; FAO, 2020). La cogestion des ressources naturelles est un schéma de gouvernance désormais largement reconnu comme équitable et efficace pour gouverner des socio-écosystèmes complexes, comme le sont les pêcheries. Basé sur des niveaux de responsabilité flexibles entre les gestionnaires et les partenaires de gouvernance, cet arrangement soulève des défis institutionnels mais est prometteur pour appliquer les mesures de conservation locales et assurer la sécurité alimentaire (Cohen et al., 2021 ; Gruby et Basruto, 2013).

Il faut noter que la PSC repose sur un paradigme scientifique avec des normes, des méthodes et des informations mesurables, alors que la connaissance traditionnelle de l'environnement et les schémas de gestion peuvent inclure d'autres paradigmes, qui peuvent varier au sein de l'Océanie, y compris les pratiques culturelles, de valeurs, d'héritage coutumier, ainsi qu'une perception à long terme de l'environnement. La culture étant en perpétuelle évolution et adaptation, en contact avec la mondialisation et les influences des puissances mondiales (États-Unis et Chine), nous assistons à la fois à une hybridation des points de vue et à une prise de conscience accrue de l'identité culturelle, illustrée par le regain d'initiatives de gestion communautaire (Johannes, 2002). Alors que ces initiatives étaient à l'origine principalement motivées par la gestion des pêches, beaucoup tendent à s'adapter au contexte et aux attentes contemporaines, y compris aux principes de conservation, en s'hybridant parfois avec des programmes de recherche et/ou d'éducation.

En s'appuyant sur la valorisation croissante des initiatives communautaires dans le Pacifique (Johannes, 2002), leur reconnaissance par les institutions régionales et internationales, telles que la Communauté du Pacifique Sud (Déclaration de Vemööre (PIRT, 2020) ; IPBES Océanie (Payri et Vidal, 2019), ODD (ONU, 2015)), et leur potentiel à contribuer à la réalisation des objectifs de conservation mondiaux par le biais des OECM (Gurney et al, 2021 ; UICN, 2019), la PSC pourrait être placée au carrefour de ces différents acteurs comme un outil commun pour dialoguer et adopter des plans harmonisés.

## 2.3 Mariculture, diversification et approche adaptative

Dans cette thèse, l'intégration de la mariculture dans la PSC s'est illustrée par la perliculture, prépondérante en Polynésie française et également pratiquée aux îles Cook et aux Fidji, mais elle pourrait également s'appliquer à bon nombre de productions maricoles actives et/ou en cours de développement dans les POTI concernant crevettes, invertébrés comme holothuries

et bénitiers comme aux Tuamotu (Remoissenet and Wabnitz, 2012; UICN, 2021), ou encore algues comme aux Salomon et en PNG (Gillett et al., 2008 ; Singh and Lulu, 2021). Ces cultures peuvent concerner une production destinée à l'alimentation locale ou bien à l'aquariophilie.

Le développement de la mariculture peut également être considéré dans un contexte de diversification des moyens de production et ses implications spatiales devront être planifiées au regard des autres usages du lagon, présents ou à venir. La pêche peut elle-même faire l'objet de diversification, comme le suggère la promotion des dispositifs de concentration de poissons (DCP) proches du rivage pour faciliter l'accès des pêcheurs artisanaux à des espèces océaniques et ainsi diminuer la pression de pêche exercée sur les communautés lagunaires (Bell et al., 2015, 2018; Hanich et al., 2018). La PSC pourrait également contribuer à optimiser le positionnement de ces DCP.

Enfin, une approche adaptative est recommandée, au cours de l'élaboration du plan et régulièrement par la suite, pour intégrer de potentielles modifications en lien avec les parties prenantes ou avec l'environnement. Plus généralement, dans de nombreuses îles éloignées, les habitants font déjà preuve d'adaptabilité, souvent optimisée de manière empirique. Une bonne illustration en est la diversification extrême des moyens de pêche artisanale, par les instruments de pêche employés (fusil harpon, ligne, traîne, *pātia*, filet et collecte manuelle), les zones de pêche choisies en fonction de la météo, la saison, l'espèce désirée, ou de manière opportuniste (cf. nos résultats d'enquêtes sur les trois îles, et exemplifié dans Adams et al., 2011; Deas et al., 2014; Van Wynsberge et al., 2015). Dans le contexte des POTI, il apparaît donc essentiel de faire des plans de manière adaptative, mais aussi intégrer le besoin d'adaptabilité lors de la planification.

## 2.4 D'autres voies pour la PSC

De nombreuses autres activités à dimension spatiale peuvent tirer avantage d'une PSC, dans le cas de développement ou de redimensionnement, par exemple suite à des perturbations majeures telle que la pandémie Covid-19. Le tourisme est largement concerné, ayant drainé plus de 900.000 visiteurs aux Fidji en 2017, et plus de 200.000 aux Vanuatu ou en Polynésie française par exemple (Cheers et al., 2018, IEOM, 2020). Dans de nombreux POTI, la population se concentre sur la frange côtière induisant une forte pression sur les écosystèmes proches et le développement d'infrastructures côtières. Des plans de gestion tel le plan local d'urbanisme pourraient inclure un volet marin de PSC pour optimiser les usages et par exemple préserver l'accès des populations à des ressources marines saines, et à des zones de loisirs nautiques sécurisées. Cependant, la planification peut s'avérer très complexe et potentiellement longue à mettre en œuvre dans des cas compliqués d'îles très peuplées, d'usages multiples et d'acteurs aux intérêts divergents.

Enfin, la PSC peut être utilisée à large échelle, par exemple pour des exercices de conservation au niveau de l'ensemble de la haute mer (Vissalli et al., 2020), en appui à la négociation en cours du traité de haute mer par les Nations Unies. L'information utilisée doit alors être cohérente par rapport à l'échelle utilisée. A un niveau régional, une carte des biorégions côtières et océaniques à l'échelle de l'Océan Pacifique Sud-Ouest a récemment été publiée et



pourra guider de futurs plans de conservation à l'échelle régionale des POTI ou à l'échelle des ZEE.

### 3. Perspectives

#### 3.1 Mise en œuvre des solutions de PSC identifiées

Après l'étape de planification intervient le transfert des plans vers les partenaires, possiblement à de multiples niveaux de gouvernance et ce transfert peut être dynamique, avec plusieurs allers-retours entre cycles de discussions et réévaluation en PSC. Concernant nos cas d'études, nous espérons que les parties prenantes pourront s'approprier les résultats. L'implication de la DRM tout au long du processus a permis d'obtenir des informations importantes sur les besoins et les attentes relatives à la PSC, afin de guider la co-construction des scénarios à Takaroa et aux Gambier. Le maintien de cette collaboration sur le moyen terme pourra permettre d'affiner le raisonnement et de préciser les plans. L'interaction avec les pêcheurs de Raivavae a été plus ponctuelle, mais vu les résultats de la PSC, un partenariat ultérieur n'est pas exclu entre pêcheurs, scientifiques et DRM tant pour le lancement et la reconnaissance institutionnelle du rāhui que pour son suivi.

#### 3.2 Au-delà de l'horizon de la PSC

En plus de la PSC, d'autres outils existent pour la mise en place de réserves, comme la détermination *ad-hoc* à dire d'experts, largement pratiquée mais cependant critiquée (Keppel et al., 2012; Klein et al., 2014a). Au-delà des méthodes basées sur des zones, il existe tout un maillage de mesures de gestion, comme les quotas de pêche, limites de tailles, de techniques destructrices et de normes environnementales pour limiter les pressions sur les socio-écosystèmes. Cependant, les moyens institutionnels et financiers de régulation et de contrôle font souvent défaut, *a fortiori* dans les îles éloignées et malgré une forte pression dans les zones densément peuplées. Par conséquent, un effort complémentaire doit être orienté vers des mesures préventives d'information et de sensibilisation. Une communication active sur divers canaux, des programmes d'éducation dans les écoles, la promotion d'associations environnementales favorisant l'engagement dans la gestion et le suivi des ressources, etc. sont autant d'outils essentiels. En cohérence avec les développements exposés ci-dessus, responsabiliser les communautés en les impliquant dans les processus de mise en œuvre et reconnaître leurs rôles, sont des leviers essentiels pour promouvoir et soutenir une pêche durable et la conservation de la biodiversité.

### 4. Conclusion – Messages clés

Dans le domaine des sciences de la conservation, la Planification Systématique de la Conservation (PSC) est un outil basé sur des méthodes de résolution mathématiques utilisées pour identifier, parmi une myriade de combinaisons possibles, les zones qui répondront de manière optimale au problème posé. Classiquement, il s'agit d'atteindre un objectif de représentation en conservation tout en minimisant les coûts socio-économiques induits par la réserve. Cet outil a pour but d'apporter un support de décision aux gestionnaires.

Par un état de l'art de l'usage de la PSC dans les environnements côtiers des îles tropicales de l'Océan Pacifique (POTI), nous avons constaté une application variée des approches PSC, mais également certaines lacunes. En effet, bon nombre d'études de PSC se sont révélées orientées vers des questions de plus en plus complexes, recherchant l'originalité pour la science en premier lieu, tandis que les études de PSC répondant à de réels besoins pour des applications concrètes localement, afin de contribuer au processus de décision, sont moins nombreuses. Il existe plusieurs aspects communs à de nombreux POTI, qui n'ont pas ou peu été abordés dans les exercices de PSC menés jusqu'à présent. Cet état de l'art a permis de formuler la question principale (Q0) de recherche abordée dans cette thèse : « comment mieux intégrer ces spécificités des POTI dans la PSC pour la conservation et la gestion des espaces marins ? »

Travaillant en Polynésie française avec des partenaires locaux (DRM, DREC, ILM), nous avons identifié en particulier quatre axes de recherche en lien avec des caractéristiques faisant sens au niveau local, et les questions associées ont été élaborées en accord avec les parties-prenantes. Nous examinons ainsi comment utiliser la PSC pour répondre aux problématiques suivantes : (Q1) **la ciguatéra**, qui affecte d'autant plus fortement les populations en Polynésie française, qu'elles sont dépendantes de la pêche lagonaire pour leur sécurité alimentaire. Lorsqu'elles sont connues, les zones à risque ciguatériques sont évitées et agissent donc, en soi, comme des restrictions d'accès pour les pêcheurs à prendre en compte dans la planification spatiale des lagons ; (Q2) **la perliculture**, largement développée en Polynésie française, pilier économique qui contribue à maintenir une activité dans les îles éloignées, mais face à une crise multifactorielle, il est nécessaire d'identifier des options de gestion dans les lagons ; (Q3) **la gestion traditionnelle des ressources marines**, qui connaît un regain d'intérêt ces dernières décennies, mais fait face à des besoins d'optimisation et (Q4) **la diversification** des activités comme moyen de diminuer les risques liés à la variabilité de facteurs extérieurs, en particulier dans le cas de la perliculture lorsqu'elle est dominante dans un lagon et que d'autres options d'usage de l'espace sont envisagées.

Les principaux résultats issus de cette étude sont les suivants :

- 1) La ciguatéra peut bel et bien être intégrée dans le cadre de la PSC. Pour cela, constituer une base d'information via la collecte des savoirs locaux est une solution satisfaisante et à relativement bas coût, qui permet d'obtenir une représentation spatialisée et quantifiée du risque de ciguatéra au sein d'un lagon. Ensuite, nous avons proposé une méthode pour intégrer cette information au coût d'opportunité de pêche. Selon notre approche, ce dernier diminue d'autant plus que le risque de ciguatéra est élevé, privilégiant ainsi la mise en réserve de zones à haut risque et à faible pêche. La méthodologie ainsi bâtie a été appliquée au lagon de Raivavae, aux Australes et les résultats montrent que prendre en compte la ciguatéra conduit à une diminution de 24-38% du coût d'opportunité des solutions, pour les pêcheurs (Chapitre 2).
- 2) Les questions de gestion durable en perliculture, en particulier concernant le volet spatial, sont abordées avec succès par la PSC. Celle-ci a été utilisée pour identifier des zones propices à la réintroduction d'individus adultes reproducteurs afin d'accroître le stock naturel d'huitres perlières dans le lagon et ainsi redynamiser la collecte de juvéniles à Takaroa, aux Tuamotu. La sélection des sites a été menée en fonction de

paramètres socio-économiques et environnementaux spécifiques à la ressource en huîtres perlières dont habitat et connectivité lagonaire (Chapitre 3).

- 3) Le design de gestion traditionnelle qui apparaissait contraignant pour les pêcheurs à Raivavae, a été appréhendé sous l'angle de la PSC pour tester des solutions alternatives. L'optimisation numérique a été menée afin de répondre aux mêmes objectifs de préservation de la ressource en bénitiers et de refléter la répartition spatiale des réserves entre les quatre grandes zones constituant le lagon. Elle a, de plus, visé à minimiser les coûts d'opportunité pour les pêcheurs, tout en prenant en compte la ciguatera, dans ce lagon qui y a été fortement exposé (Chapitre 4). Les solutions identifiées par la SCP ont souligné des designs respectivement 7 et 5 fois moins étendus spatialement et coûteux pour les pêcheurs.
- 4) Enfin, les options spatiales de diversification d'activités ont été explorées avec la PSC dans le cadre du lagon de Mangareva, où la perliculture, activité dominante, est menacée par les difficultés économiques que connaît ce secteur. Les gestionnaires souhaitent diminuer l'emprise spatiale des concessions perlicoles pour laisser plus de place à la pêche, mettre en place des sanctuaires pour réintroduire des huîtres adultes selon un schéma de zones de gestion traditionnelle, et identifier des zones de conservation pour les communautés coralliennes remarquables. Des scénarios ont été conçus pour la répartition spatiale des activités à travers divers degrés de diversification et afin de maximiser les zones d'intérêt pour les pêcheurs, y compris selon le risque de ciguatera (Chapitre 5). La PSC a montré que des scénarios de diversification sont possibles dans le lagon des Gambier et la comparaison des solutions pourra servir de base de discussion pour la gestion.

Jusqu'ici, la PSC n'avait encore jamais intégré le risque de ciguatera pour les pêcheurs, ni abordé les enjeux de gestion et d'exploitation durable que soulève la perliculture. En étudiant comment la PSC peut répondre aux spécificités des POTI, en particulier le risque de ciguatera associé aux pêches artisanales, la gestion de la perliculture, la gestion de réserves traditionnelles et les stratégies de diversification dans un lagon, cette thèse a contribué à démontrer le potentiel des scénarios de PSC sur mesure. Elle illustre leur faculté à répondre efficacement aux besoins des gestionnaires tout en tenant compte des logiques et contraintes locales. Ainsi, cette thèse a contribué à développer le champ des applications possibles de la PSC et a démontré que cet outil pouvait répondre à des questions très pragmatiques, dans des cas concrets de gestion de l'espace côtier. Chaque exercice est unique, adapté aux contextes locaux et nécessitant des données adéquates, mais les problématiques sont généralisables, communes à de nombreux POTI.

En conclusion, les spécificités examinées ici dans le cadre de la Polynésie française sont extrapolables à de nombreux POTI. En effet, généraliser la méthodologie intégrant le risque de ciguatera sera utile pour guider des exercices de PSC dans l'ensemble des zones où la ciguatera représente un problème pour la pêche. Une telle information, issue des savoirs locaux, ne doit cependant pas être utilisée dans le cadre de mesures de santé publique, où des analyses toxicologiques environnementales sont préconisées. Par ailleurs, l'approche hybride de gestion traditionnelle et PSC peut avantageusement être extrapolée à l'ensemble des POTI, qui connaissent un regain d'intérêt pour la gestion traditionnelle. Une limite néanmoins

identifiée repose sur la difficulté de la PSC à intégrer une dimension temporelle, qui est pourtant souvent rencontrée dans les schémas de gestion traditionnelle. Il est à noter que les schémas traditionnels, aussi socialement bénéfiques soient-ils, n'intègrent généralement pas de principes d'écologie ou de résilience auxquels ils doivent pourtant faire face. L'intérêt d'une collaboration entre les deux approches est donc ici souligné, ainsi que celui d'associer les parties-prenantes dès la conception de la planification, comme illustré dans cette thèse.

La PSC peut finalement être considérée et utilisée comme un outil qui a le potentiel de rassembler, à différentes échelles spatiales et de gouvernance, dans la perspective d'un processus participatif multipartite afin de progresser dans la voie d'une protection de notre environnement et d'une gestion durable des bénéfices qu'en tire la société.



# General Introduction



## General Introduction

*This chapter was adapted from the published article “An appraisal of systematic conservation planning for Pacific Ocean Tropical Islands coastal environments” (André et al., 2021a).*

### 1 Conservation science

Conservation was primarily defined and examined through the field of conservation biology to study how to lower biotic extinction rates and secure the remaining biodiversity, or wildlands from the multiple human-related pressures (Saoulé, 1985). This paradigm has moved towards conservation science, encompassing biodiversity conservation as well as human well-being, by recognizing the interrelations between social and natural systems (Kareiva and Marvier, 2012). This interdisciplinary approach accounts for sustainable development, public policies and economics, among others (Figure 1).

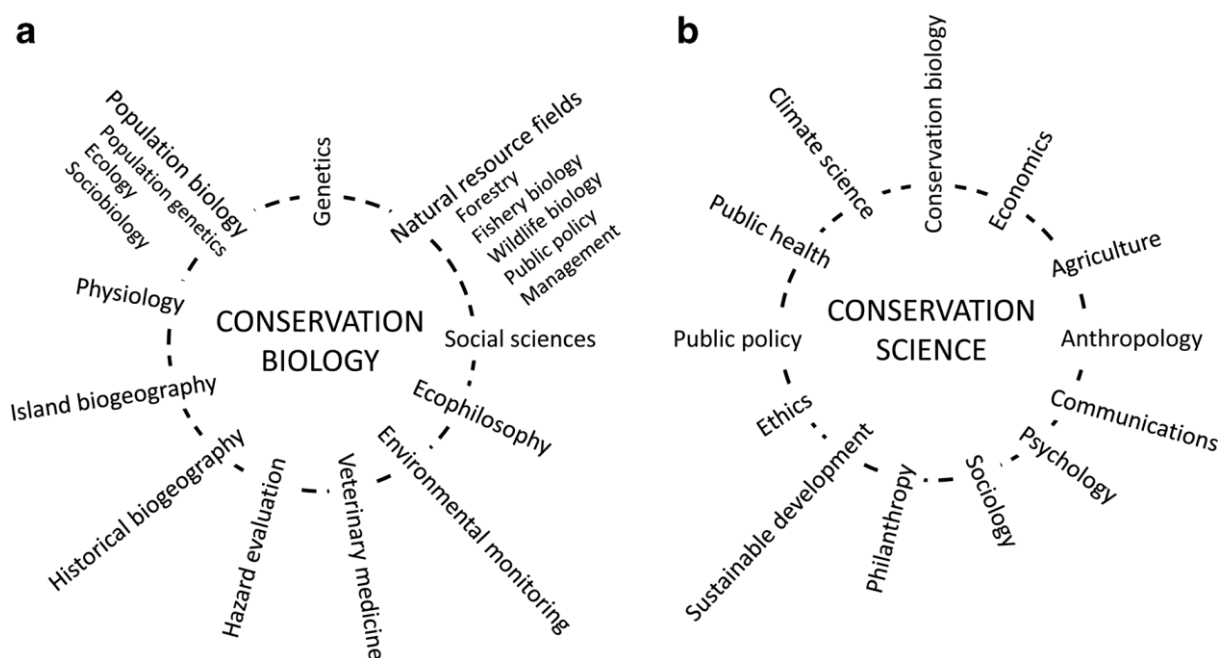


Figure 1 Conservation biology and conservation science.

(a) Fields contributing to conservation biology and (b) those contributing to conservation science. In panel (a) is Soulé’s (1985) depiction of the synthetic, multidisciplinary nature of conservation biology. Panel (b) depicts an updated view of conservation science, in which the many dimensions of conservation biology are part of a broader and more interdisciplinary endeavor to protect nature (Kareiva and Marvier, 2012).

To achieve biodiversity conservation, international guidelines were set by the Convention on Biological Diversity Aichi Targets (CBD, 2010) for the 2011–2020 period through time-bounded and measurable national targets. The post-2020 Global Biodiversity Framework (CBD, 2019, 2020) is currently elaborated for the next United Nation Biodiversity Conference,

the Kunming COP 15. Sustainable Development Goals (SDGs) (UN, 2015) also promote conservation and include ecosystem and resource protection (Goals 14 and 15).

Conservation measures can take multiple forms, including focusing on the most endangered species (IUCN, 2020), but conservation is often conducted through area-based measures, often within specific environmental or territorial frontiers.

This spatial lens also applies to the marine environment where a number of area-based management tools are used, including locally managed marine areas (Reimer et al., 2020) and marine protected areas (MPA). The International Union for Conservation of Nature (IUCN) has ranked theoretical MPAs' levels of protection from category Ia, as strict nature reserve, to VI, for sustainable use of natural ecosystems, including multiple-use MPAs (Table 1).

Table 1. The IUCN categories of Protected Areas and their associated management objectives (Adapted from IUCN, 2017).

Protected Area Category and International Name	Management Objectives
Ia – Strict Nature Reserve	Managed mainly for science
Ib – Wilderness Area	Managed mainly to protect wilderness qualities
II – National Park	Managed mainly for ecosystem protection and recreation
III – Natural Monument	Managed mainly for conservation of specific natural / cultural features
IV – Habitat / Species Management Area	Managed mainly for conservation through management intervention
V – Protected Landscape / Seascape	Managed mainly for landscape / seascape conservation and recreation
VI – Managed Resource Protected Area	Managed mainly the sustainable use of natural ecosystem

Such management measures are under debate on how to balance conservation between natural and social systems. This challenge is inherent to conservation science. The two following facets can be mentioned: 1) attention to discussing the ability of MPAs to reach global goals and 2) need to categorize, plan and evaluate MPAs (Grorud-Colvert et al., 2021). Besides, areas not primarily managed for conservation purpose can still reveal positive outcomes for biodiversity. These Other Effective area-based Conservation Measures (OECM) can include local indigenous management, and are suggested to be acknowledged as potentially contributing to reach the global conservation objectives (IUCN, 2019; Gurney et al., 2021).

Several levels of governance can overlap as well as stakeholders' intertests. They are often linked to the spatial extent of the reserves. For example, in New-Caledonia, the *Parc Naturel de la Mer de Corail*, measuring more than one million km<sup>2</sup>, is recognized at the international level by Unesco and governed by a management committee including multiple entities such as the local government, NGOs, territorial and civil society representatives, but it actually has low levels of protection. Additionally, each Province has its own Environment Code with varying degree of customary law influence and involvement of local committees. Lastly, at very local levels, some formal or informal fisheries management committees are also active, bound to tenure and customary rights (Deas et al., 2014; Deveze, pers. comm; Guillemot and Léopold, 2009).



Categories of protection are not specified in the international CBD guidelines, but other precise requirements are mentioned, for example, Aichi Target 11 focused on coastal and marine protection and sets specific quantitative target to preserve 10% of coastal and marine areas by 2020. It included “ecologically representative areas of particular importance for biodiversity and ecosystem services”, and integrates a series of principles such as “management equity and effectiveness; connectivity and integration into wider landscape and seascape” (CBD, 2010). Reaching such characteristics in a given spatial domain requires enhanced methods to help integrating these guiding principles and measuring the outcomes. To strengthen the planning of conservation actions and increase efficiency, numerical solutions have been developed using quantitative spatially-explicit methods, such as Systematic Conservation Planning (SCP).

## 2 Systematic Conservation Planning (SCP)

Systematic approaches were developed to locate and design reserves that represent and protect biodiversity, while accounting for anthropic pressures and needs (Margules and Pressey, 2000). Systematic conservation planning is a method that allows for area-based transparent, data-driven and objective decisions. The study area is segmented into a number of “small” planning units (PU) (small, related to the size of the planning area) and a prioritizing tool identifies optimal, or cost-effective, priority conservation PUs (Figure 2). To proceed, first, values of relevant feature(s) and cost(s) are assigned to each PUs. Then, the prioritization selects a set of PUs as a conservation solution that meets the objectives, which are quantitative targets on how much to protect, while minimizing the costs induced by conservation (see Table 2). The solution can be “minimum set covering”, if the aim is to minimize the cost, often resulting in a minimum number of PU; or “maximum set covering”, if the objective is to maximize the benefit for conservation but within a cost budget limit (ReVelle et al., 2002). The numerical prioritization and optimization can be repeated numerous times to identify at each new iteration, the most important PUs which are selected the most often. Although they can theoretically encompass a myriad of spatial information, the used features typically take the form of species abundance or habitat extent, while costs usually focus on monetary acquisition cost or opportunity cost (Table 2).

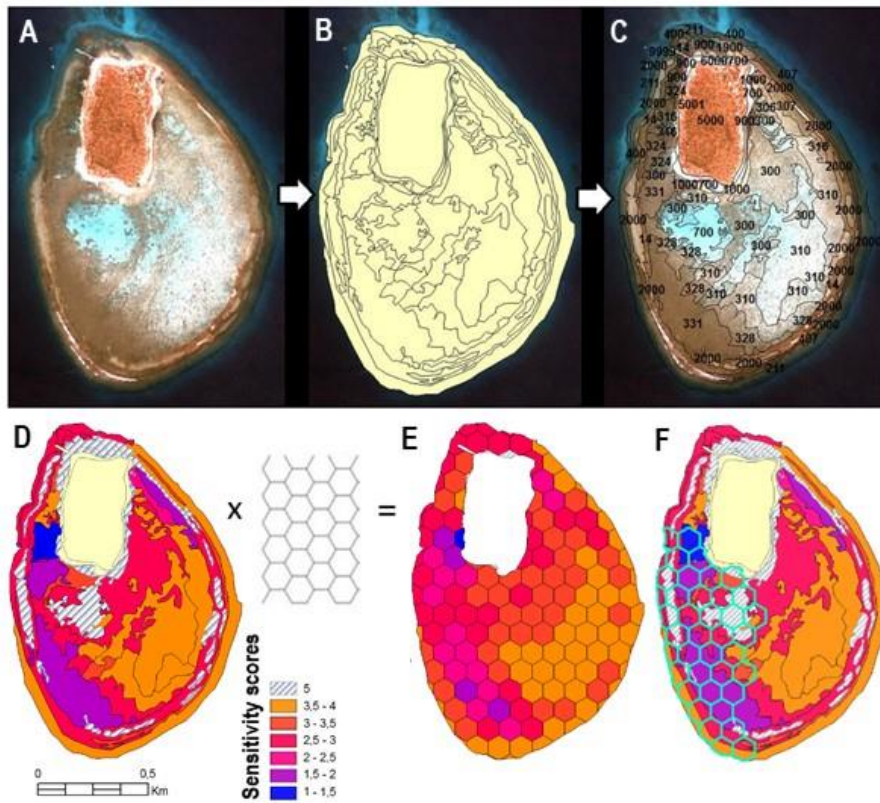


Figure 2. An example of Systematic Conservation Planning (SCP) exercise.

(A) a satellite imagery is used as a base to derive the different conservation features (B and C), here coral communities classified by their sensitivity to bleaching. The obtained feature map (D) is overlaid by a grid of planning units (PUs). Accordingly, a sensitivity score is then attributed to each PU (E). This SCP objective was to protect high sensitivity coral communities while minimizing the total surface area of the reserve. SCP optimization selected a set of PU as a solution (F) (Adapted from Deas, 2013).

Table 2. Definition of SCP key terms.

Term	Definition
Conservation objective	Qualitative goal, referring to general principles of conservation, such as international policy objectives, representativity objectives etc. It describes the kinds of features to protect (e.g., geomorphic habitats, mangroves...), as used by Margules and Pressey (2000).
Conservation target	Quantitative goal, to protect biodiversity. Often a percentage between 10% (Kool et al., 2010; Weeks et Jupiter, 2013) and 30% (Tulloch et al., 2016; Weeks et al., 2017) of the area of each feature that needs to be selected for conservation.
Cost	The resources needed to achieve the conservation objectives and targets, or the constraints expected to be generated. The design of SCP seeks to minimize the costs. Cost includes acquisition costs, management costs, transaction costs or monetary (or in any other value) (Naidoo et al., 2006). It is usually measured through the surface area or opportunity cost to fishers, but it could also be cultural or spiritual.
Opportunity cost	What could have been gained but become foregone opportunities when a conservation plan is implemented (Naidoo et al., 2006).

Spatial/planning domain	The total area considered by the analysis.
Planning Unit	The geometric division of the overall spatial domain into individual smaller spatial units where management decision are applied. Planning units are classically either regular square or hexagonal shape. Their size can vary from less than 1 km <sup>2</sup> to hundreds of km <sup>2</sup> , depending on the scale of the study.
Resolution	In SCP, it is used either as spatial resolution (minimum size on the ground of measured data), or thematic resolution (number of categories).
Scale	Can cover several meanings (see Cheek et al. 2016). Here, local-scale is used when the spatial domain includes one island or less; regional scale includes one or more archipelagos (which consist of at least two islands).
Scenario/problem	A combination of all of the above, which defines the specific context of a SCP case study. Numerical modelling information also defines the SCP scenarios when performed with planning software, such as the number of iterations.
Assessment	The design phase of conservation planning including spatial prioritization (Cheek et al., 2018).
Implementation	The translation of assessments into actions on the ground such as the implementation of protected areas (Cheek et al., 2018).

Conceptually, SCP relies on key notions such as adequacy, representativity, complementarity, connectivity, comprehensiveness, and efficiency of the solution network (Kukkala and Moilanen, 2013). SCP implements the overarching goals of, for instance, representativeness or connectivity of biodiversity features included in conservation areas, through a number of specific quantitative and locally relevant targets, which can be measured and monitored (Margules and Pressey, 2000; Pressey and Bottril, 2009; Kukkala and Moilanen, 2013).

Numerically, site selection is central to SCP and prioritization is expressed as mathematical problems that balance the objectives with the costs, accounting for a set of constraints, to provide sets of optimal and cost-effective trade-off solutions. Solving methods can be based on different type of heuristics, which are “the art of inventing, of making discoveries” (from ancient Greek *‘heuriskô’*, “I find”) by successive iterations to solve problems from incomplete knowledge. In practice, heuristics are numerical recipes that allow reaching optimal solutions in a limited time. They can also only attempt to search near-optimal solutions (meta-heuristics), or they can be very specific to a given problem (ad-hoc heuristic). This translates into different numerical optimization procedures. Solving methods can also rely on exact methods, which are mathematical methods that combine algorithms and mathematical reasoning to identify the ‘actual’ solutions, satisfying all constraints, rather than approximations.

The most used softwares in SCP rely on different solving methods (Figure 3):

- Prioritizr R package (Hanson et al., 2021) is based on integer linear programming, on exact methods;
- Zonation (Moilanen et al., 2005) is based on ad hoc local search heuristics;
- Marxan and its extensions (Ball et al., 2009) are based on simulated annealing from meta-heuristics;
- ConsNet (Ciarleglio et al., 2010) is based on *Tabu* search from meta-heuristics.

Integer linear programming provides an exact optimization solution that guaranties to satisfy all constraints, but may fail or exceed reasonable time processing with large problems, which are better studied with meta-heuristics (Beyer et al., 2016; Possingham et al., 2000). For simulated annealing, the solutions space is explored iteratively to generate near-optimal solutions. The number of iterations must be high enough to avoid local extrema, and enhance optimality between objectives, costs and constraints. For overly constrained problems, ad-hoc heuristics can find good solutions, but their lack of genericity cannot always guarantee constraints satisfaction and optimality (Justeau-Allaire, 2020). In the marine domain, Marxan software has been the most widely used and remains a reference. It is currently recommended by the Intergovernmental Platform for Biodiversity and Ecosystem Services as a policy support tool (IPBES, 2021).

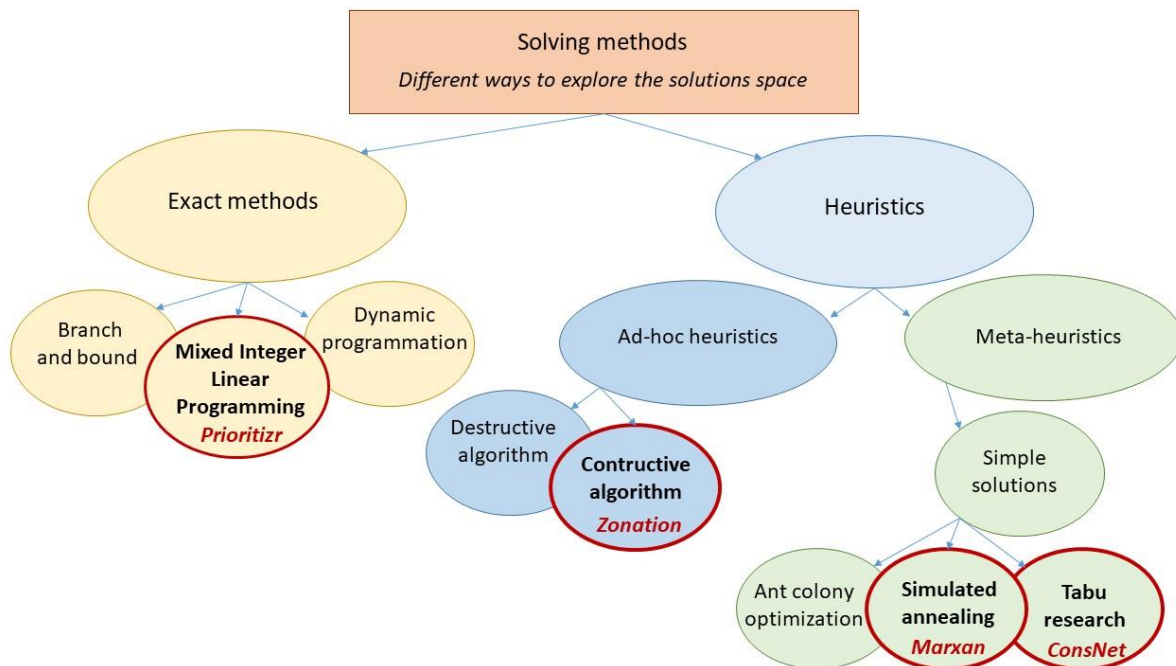


Figure 3. Schematic view of the main methods to solve optimization problems applied to systematic conservation planning.

The solutions provided by these tools can take the form of two main outputs:

- i) a ‘best’-case solution (a single solution with the lowest cost, or maximum benefit, depending on the approach);
- ii) a selection frequency (if Marxan), or priority rank map (if Zonation), showing how many times each planning unit is selected among the iterative runs, informing on its irreplaceability.

The best solution is not necessarily the only one to consider, as the overall portfolio of solutions can provide interesting alternatives for site selection. Additionally, a number of parameters can be set to fine-tune the solutions, including a penalty which is used to reach exactly the targets, and another type of penalty which is used to increase the compactness of the solution. PUs can also be locked out or locked in the selection, according to the design needed.

In the past few years, marine SCP studies have evolved in terms of complexity and have included a wide variety of objectives and socio-economic costs, as well as new criteria related to climate change, ecological connectivity between marine populations, and linkages within broader island-scapes through land and sea connections (Álvarez-Romero et al., 2018).

Beyond the core SCP prioritization step, additional stages in the conservation process take place such as involvement of stakeholders, integration of plans across governance levels, implementation of conservation actions, maintaining and monitoring conservation areas with long term commitment (Pressey and Bottril, 2009; Weeks et al., 2014a).

The resort to SCP is increasing in the Pacific region. To encompass the issues and challenges at stake, we first present the main features of the Pacific Ocean Tropical Islands (POTIs) as background information and then we draw up a state of the art of how SCP has been used in the POTIs. We identify the objectives, strengths, weaknesses and especially the gaps in SCP applications that could raise the interest of managers, stakeholders and scientists.

### **3 Context of the Pacific Ocean tropical islands (POTIs)**

The study region we name Pacific Ocean tropical Islands (POTIs) encompasses all groups of islands spread over Polynesia, Micronesia and Melanesia, extending from the Tropic of Cancer to the Tropic of Capricorn, longitude 23°26' North and South, respectively (Figure 4). The POTIs are characterized by their high geographical dispersion and small sizes, and socio-ecosystems with populations traditionally linked to their environment. The scattered islands reveal high levels of endemism and endangered biodiversity, both across terrestrial and marine systems (Payri and Vidal, 2019).

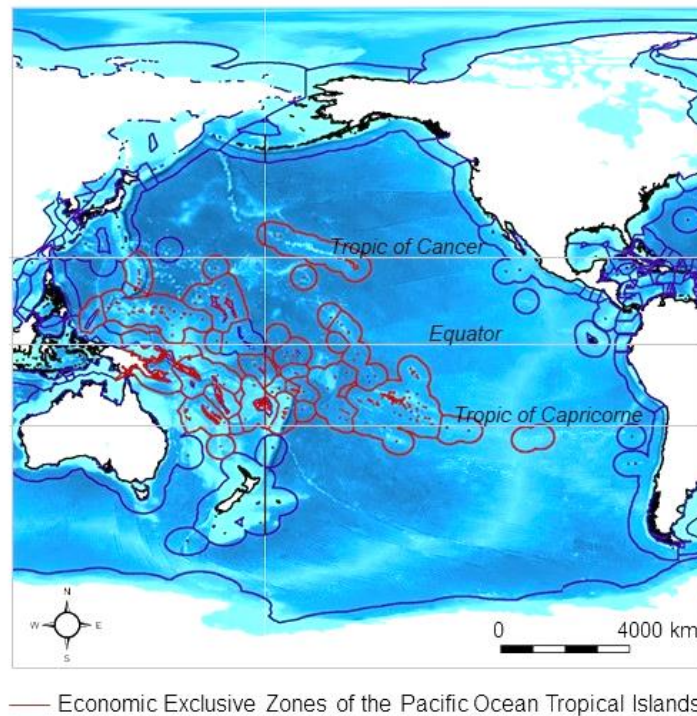


Figure 4. Map of the study zone: the Pacific Ocean tropical islands (POTI)

Pacific Ocean region and the countries' economic exclusive zones. Source of Ocean bathymetry: ETOPO1 (2011).

As of 2019, contrasted population densities are found between the largest cities and the most remote islands or rural areas (Andrew et al., 2019). Pacific islanders rely strongly on their marine environment for subsistence, income, culture, identity, exchanges with other islands, and coastal protection (Bell et al., 2009; Friedlander, 2018). The livelihoods and incomes of local populations are thus particularly vulnerable to any change in the availability of these marine resources, notably with respect to climate change, shifting weather patterns, demographic growth and overexploitation, and degradation of the environment due to economic development (Hanich et al., 2018). Islands are fragile, increasingly exposed to these threats, and face acute resource management and conservation issues (Kueffer and Kinney, 2017).

### 3.1 Geographical dispersion and physical diversity

In the tropical and sub-tropical Pacific Ocean, the Islands are first characterized by their geographical isolation with vast ocean territories included in their economic exclusive zones (EEZ). The countries and Islands have jurisdiction over natural resources within their EEZ, which typically stretches from the shoreline to 200 nautical miles. The boundaries of our study area expand from 32°N (Northern Hawaii EEZ) to 35°S (Southern Kermadec Islands EEZ) and from 130°E (Palau) to 105°W (Easter Island). Our focus is primarily on tropical islands. We included several high latitude sub-tropical islands because they already harbor some tropical species in their waters, and this trend is likely to increase with global warming (Payri and Vidal, 2019). POTIs are characterized by their physical diversity, ranging from large

continental islands with complex and extensive coral reef formations (e.g., New-Caledonia), to geologically recent oceanic volcanic islands surrounded by a narrow fringing reefs (e.g., Vanuatu), partially subsided volcanic land masses surrounded by a lagoon and a barrier reef, and atolls (e.g., French Polynesia). These tropical marine ecosystems of coral reefs and related are of particular interest for biodiversity conservation.

### 3.2 Political status and governance

Administratively, the POTIs are managed at national and/or territorial levels: they are either fully independent or autonomous countries, or territories that remain strongly linked to their overseas metropolises, several of those nonetheless have their own governments (Table 3). Several countries also have strong customary laws at a local level, which ultimately often control the local use of marine resources. Pacific countries and territories, their privileged metropole counterparts, and Pacific superpower countries also often promote regional cooperation to enhance sustainable development.

Some POTIs economies largely rely on the fishing rights sold to foreign companies to catch pelagic species, mainly tunas and billfish in their EEZ (Bell et al., 2021). To sustainably and equitably manage the exploitation of this transboundary mobile resource, and additional interests they share, many POTIs take part into regional organizations to coordinate their actions and increase their negotiating influence (Table 3).

Governance and enforcement required to managing environmental, marine, coastal and reef resources vary widely across POTIs. Some have efficient and dedicated technical services managing the environment and marine resources, while others lack active technical services, relying on international aid programs, foreign NGOs, private consultants, and frequent training and monitoring via external funding often managed by international organizations (Table 3). Some Islands have developed innovative multi-level governance models, such as Palau where resource users, the national government and NGOs, all take part to the management process (Gruby and Basurto, 2013). However, the lack of local available data and GIS facilities can make it difficult to compile local demography, environment and resource information (Table 3), and ultimately, can affect requirements for SCP.

The small size of most islands implies that communities may have limited opportunities to replace any loss and damage to their natural resources, thus emphasizing the need for integrated management and conservation (Payri and Vidal, 2019; Wenger et al., 2018).

Table 3. The POTIs main features.

SPC: South Pacific Community, FFA: Pacific Islands Forum Fisheries Agency, WCPFC: Western and Central Pacific Fisheries Commission (Y\* for Participating territory, not member), Environmental/fishery technical services (Y\* for existing services but few/no specific information available), SCP: Systematic conservation planning, MPA: Marine protected areas, VLMPA: very large MPA, WHS: UNESCO World Heritage Site, MAB: UNESCO Man and Biosphere Reserve. NC: New Caledonia, NZ: New Zealand; USA: United States of America; UK: United Kingdom. MPA: all categories, including IUCN ones.

Group	Countries or territories	Political levels			Status	Env/fishery technical services	National marine GIS database	SCP case studies	MPA, VLMPA, shark/marine mammal sanctuaries (sanct.), UNESCO WHS and MAB (area in km <sup>2</sup> )
		Regional level							
		SPC	FFA	WCPFC					
<b>Melanesia</b>	Papua New Guinea	Y	Y	Y	Independent	Y*	N	4	MPA; Whale sanctuary
	Solomon Isl.	Y	Y	Y	Independent	Y*	N	3	MPA; WHS: East Rennell (370)
	Vanuatu	Y	Y	Y	Independent	Y	N	0	MPA; Marine Mammal sanct.
	New Caledonia	Y	N	Y*	French overseas territory	Y	Y	1	VLMPA: Natural Park of the Coral Sea (1,368,806); WHS: Lagoons of NC (15,740); Shark sanct.; Whale sanct.
	Fiji	Y	Y	Y	Independent	Y	N	14	MPA
<b>Micronesia</b>	Palau	Y	Y	Y	Independent	Y*	N	1	MPA; VLMPA: Palau Nat'l Marine Sanct. (475,000); MAB: Ngaremeduu (137); WHS: Rock isl Southern Lagoon (1002); Shark sanct.; Marine Mammal sanct.
	Federated States of Micronesia	Y	Y	Y	Independent	N	N	4	MPA; VLMPA: Micronesia MPA (184,948); MAB: Utwe (18); And Atoll (10); Shark sanct.
	Guam	Y	N	Y*	Unincorporated territory of the USA	Y	Y	0	MPA
	Commonwealth of the Northern Mariana Isl.	Y	N	Y*	Unincorporated territory of the USA	Y	Y	0	MPA; VLMPA: Marianas Trench Marine Nat'l Monument: (250,000); Shark sanct.
	Marshall Isl.	Y	Y	Y	Independent	Y	N	1	MPA; Shark sanct.



GENERAL INTRODUCTION

	Nauru	Y	Y	Y	Independent	N	N	0	N
	Kiribati	Y	Y	Y	Independent	Y	Y	0	MPA; Shark sanct.; VLMPA-WHS: Phoenix Island protected area (408,250)
-	USA Minor Outlying Isl.	N	N	Y	Unorganized territories of the USA	Y	Y	0	VLMPA: Pacific Remote Isl. Nat'l Monument, (1,270,000)
<b>Polynesia</b>	Tuvalu	Y	Y	Y	Independent	Y*	N	0	MPA
	Wallis and Futuna	Y	N	Y*	French overseas collectivity	Y	Y	2	N
	Tonga	Y	Y	Y	Independent	Y*	N	0	MPA; Whale sanct.
	Samoa	Y	Y	Y	Independent	Y	N	0	MPA; Whale, Turtle and Shark sanct.
	American Samoa	Y	N	Y*	Unincorporated territory of the USA	Y	Y	0	MPA; Shark sanct.; Whale and Turtle sanct.
	Tokelau	Y	Y	Y*	Realm of NZ	Y	Y	0	Shark sanct.; Whale sanct.
	Niue	Y	Y	Y	Independent	Y*	N	0	Whale sanct.
	Cook Isl.	Y	Y	Y	Independent	Y	Y	0	VLMPA: Marae Moana, (1,900,000); Shark sanct.; Cetacean sanct.
	French Polynesia	Y	N	Y*	French overseas Country	Y	Y	2	MPA; MAB: Fakarava Reserve (15,948); Shark sanct.; Cetacean sanct.
	Pitcairn Isl.	Y	N	N	UK overseas territory (Non self- governing)	N*	Y	0	VLMPA: Pitcairn Island Marine Reserve (834,334)
	Easter Island	N	N	N	Special territory of Chile	Y	N	0	MPA; VLMPA: Motu Motiro Hiva Marine Park (150,000)
	Hawai'i	N	N	N	USA State	Y	Y	3	MPA VLMPA: Papahānaumokuākea Marine Nat'l Monument (1,508,870)
Polynesia subtropical	Kermadec Isl.	Y	Y	Y	NZ outlying Isl.	Y	Y	0	MPA; VLMPA: Kermadec Benthic protected area (620,000)

### 3.3 Conservation

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IBPES) emphasized that the Pacific Islands are an epicenter of the global biodiversity crisis. A pressing need for protecting biodiversity in Oceania region has been stressed again during the Biodiversity in Oceania Workshops held in Noumea in 2019 (Payri and Vidal, 2019). Conservation initiatives to mitigate various local and global threats are increasing. In some cases, they complement the customary management that is traditionally used to protect lagoon and reef areas as well as targeted species, with various levels of success (Bartlett et al., 2010; Hamilton et al., 2019; Sangha et al., 2019). National conservation initiatives are now also influenced by international guidelines and agendas (c.f. above).

MPAs are important instruments for conservation and for sustaining marine resources for food security, particularly as POTIs have experienced considerable loss of biodiversity (Jupiter et al., 2014b; Payri and Vidal, 2019). In the POTIs, MPAs are subject to diverse levels of management, from institutional government-level with international registries of the MPAs (listed in Table 3), to NGOs', including measures of fisheries management such as locally managed marine areas (LMMAs), community-based fisheries management (CBFM) and territorial use rights for fisheries (TURFs), based on traditional marine tenure (such as village-based, customary, and sometimes hybrid management). The different levels of protection and diverse forms that traditionally managed MPA can take, such as nursery areas, rotating closures, *tabu* zones and *rāhui* zones (Friedlander, 2018; Gairin and Andréfouët, 2020; Jupiter et al., 2014a; Smallhorn-West and Gowan, 2018), likely reflect the rich Oceanian practices and ties to the marine environment.

At a wider scale, the number of very large MPAs (VLMPAs, defined here as >100,000 km<sup>2</sup>) has increased in the past decade, allowing, on paper, a quick convergence towards the Convention on Biological Diversity Aichi target 11 on protected areas. Eight of the world's current thirty-five VLMPAs are located in the tropical Pacific Ocean (Table 3) (MPAtlas, 2020). The POTIs' considerable EEZ areas offer solutions to satisfy the political engagements, but the pros and cons of these engagements have generated important debates, about the relevance of EEZ to represent, for instance, species and ecosystems (Ban et al., 2017; Devillers et al., 2015; Singleton and Roberts, 2014). There is considerable differences in how POTIs manage their MPAs, several VLMPAS with official designation can have limited management plans and control means whilst others already have much stricter policies, such as no-take area, like the Phoenix Island Protected Area in Kiribati (Rotjan et al., 2014), or the Papahānaumokuākea marine national monument in Hawaii.

### 3.4 Coastal and reef fisheries, and mariculture

Most countries and territories rely heavily on their local coastal small-scale fisheries for food security, revenues, and job opportunities (Figure 5). In this thesis, the terms 'artisanal fisheries' and 'small-scale fisheries' are both used to refer to these subsistence fisheries. In addition, many urban centers harbor commercial fisheries infrastructures, and longline, coastal and FAD fisheries (Fish Aggregation Devices). Islander livelihoods often depend on coastal fishing, particularly from coral reefs (Bell et al., 2011b; Friedlander, 2018). Overall, sustainable fishing (including finfish and invertebrates) is a cornerstone of current protein

supply and future food security of Pacific Ocean Islanders, particularly in the outer Islands (Bell et al., 2009). For example, fish consumption is twice as much as the level recommended by the World Health Organization in Tuvalu, Samoa, Niue, Wallis and Futuna, French Polynesia and the Federate States of Micronesia. Therefore, the populations are vulnerable to changes in the status of these resources. Gillett (2016) underlined a 6 % drop of the coastal fisheries production per capita in the 2007-2014 period, which is a sharp decrease in such a short period. This suggests decreased stocks and unsustainable fishing by an increasing human population (+15.8 % over the period, and reaching nearly 11 million inhabitants in 2014, including 7.6 in PNG (Gillett, 2016)). Management of fishing stocks to achieve long-term sustainability is hence among the top priorities for many local governments and communities. Strategies of climate change adaptation include shifting fish consumption towards abundant oceanic species like tunas (Bell et al., 2018).

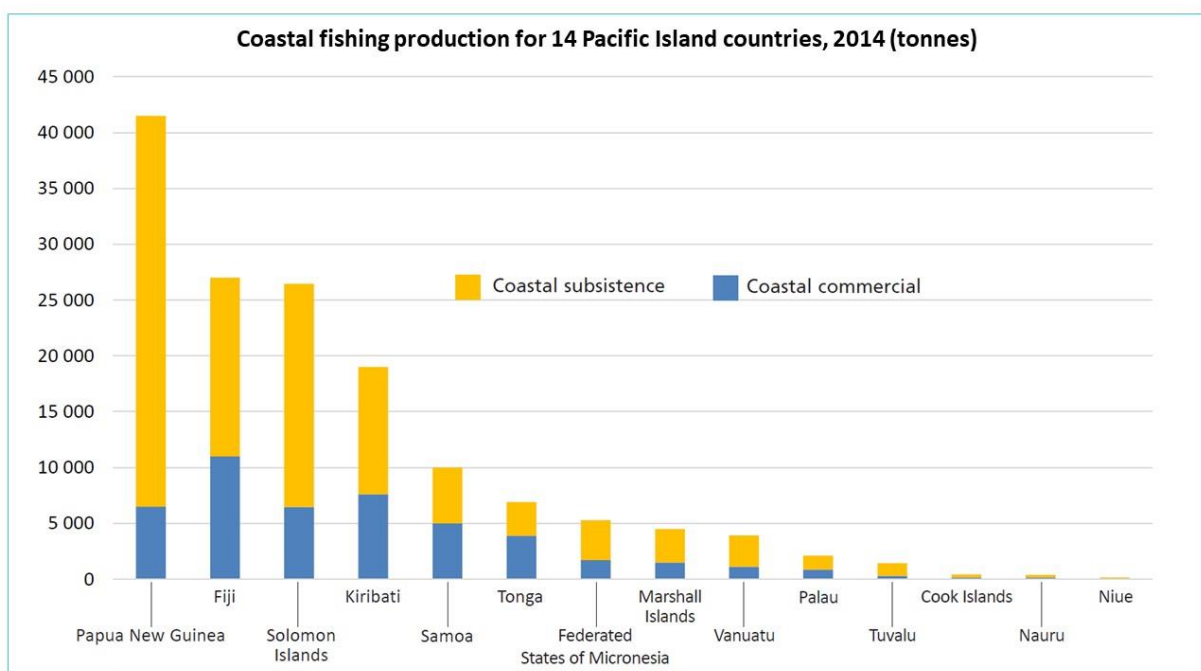


Figure 5. Importance of coastal fishing production for subsistence, compared to commercial fishing, for 14 countries among the POTIs in 2014 (Gillett and Tauati, 2018).

Mariculture production presents low levels compared to other regions bordering the Pacific Ocean, especially Asia or South America (Oyinlola et al., 2018). At this time, 93% of the mariculture production value, both for local and international markets, comes from only two countries (Gillett, 2016). In French Polynesia, mariculture is dominated by pearl oyster farming for the jewellery market, with 8,456 ha of pearl farms in 2019, of which 72% located in the Tuamotu Archipelago (DRM, 2019). The Covid-pandemic has considerably affected this sector, with international economic disruption, and threatens some islands where small economies were only or mostly based on this activity (IEOM, 2020a, 2020b). In New Caledonia, production is dominated by shrimp farming with 1,430 t. produced in 2015 (DAM, 2020). Mariculture remains a limited source of proteins for the local populations but is present in many places, often conducted at a small scale and at various development stages. Developing this activity throughout the POTIs is recommended as a climate change

adaptation and a way to mitigate reef-fisheries pressure and to respond to urban centers demand for fish (Bell et al., 2011a). Further, IUCN provides guidelines to articulate sustainable mariculture with conservation measures (IUCN, 2017).

### 3.5 Ciguatera poisoning

Widely present in the POTIs, ciguatera poisoning results from the consumption of marine products that have accumulated lipid soluble toxins known as ciguatoxins (Figure 6). Ciguatoxins render catches unsuitable for consumption, causing a combination of gastrointestinal, cardiovascular and neurological symptoms (Gatti et al., 2008). Yet, many fish species but also invertebrates highly prized by island communities such as bivalves (e.g. giant clams), echinoderms (e.g. sea urchins) and gastropods (e.g. trochus) have been found to be potential vectors (Darius et al., 2018). Ciguatoxins are produced by benthic dinoflagellates in the genera *Gambierdiscus* and *Fukuyoa* that grow preferentially within mixed algal turfs covering degraded coral substrates. Estimating the true incidence of this disease is difficult because it is believed that only 10-20% of cases are reported to public health organizations or other authorities (Friedman et al., 2017). Across the Pacific islands, the estimated true incidence rate reaches as much as 12,000 cases annually in the POTIs (Chinain et al., 2020), with the highest rates for Tokelau and Cook Islands between 1998 and 2008 (1,576 and 1,437 cases per 100,000 inhabitants, respectively) (Skinner et al., 2011). Ciguatera poses an immediate threat to human health, but also to islander livelihoods in the long run in the case of jeopardized access to safe local resources. Indeed, ciguatera occurrences are dynamic and a link was found between the toxic microalgae development and environmental disturbances, such as coral reef damage due to cyclonic waves, elevation of sea surface temperature, and coastal development (Bell et al., 2009; Chinain et al., 2010). As ciguatera varies spatially, it might influence opportunities for conservation and be an interesting spatial feature for SCP.

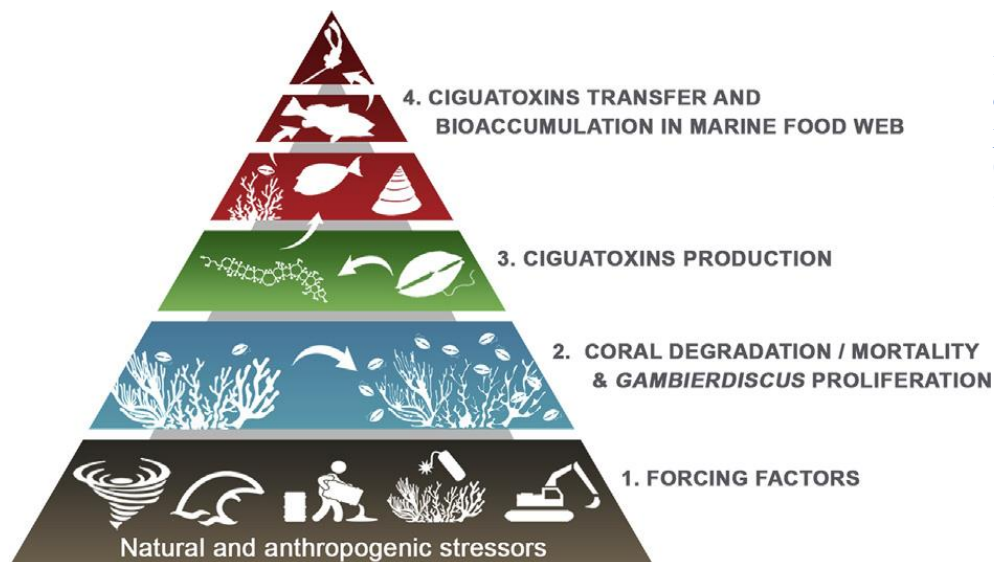


Figure 6. Trophic chain of ciguatera poisoning (Chinain et al., 2019).

### 3.6 Exposure to climate change

Climate change is expected to affect the Pacific Ocean itself in different ways, and to have great impacts on islanders, with trajectories of exposure exacerbated by intertwined socio-economic vulnerability and environmental issues (Andrew et al., 2019; Bell et al., 2011a; 2011b; Duvat et al., 2017). Many threats arise due to changes in oceanic and atmospheric circulations, which are expected to affect marine and coastal ecosystems. Increased sea surface temperature can cause more frequent coral bleaching, spread of pathogens, and mass mortality events. Increased dissolved CO<sub>2</sub> concentrations can lead to a more acidic ocean with altered capacity of calcifying organisms to build skeletons and shells (Kleypas and Yates, 2009). Mariculture can also be impacted by these changes and requires adaptation strategies, such as changing locations of the exploitations, and diversification of the production (Bell et al., 2011a). Rapid sea level rise could particularly affect reef islands and coastal environments, when the natural sediment production and dynamics are unable to compensate for the increased erosion of the soft-sediment coastlines (Garcin et al., 2016; Tuck et al., 2019). Sea level rise could also have serious implications on low lying islands habitability (Duvat et al., 2021), including planned migrations being required to move people to safer areas (Weir et al., 2017). Climatic migrations, inducing land use change, could have important implications for conservation and could require spatial planning to manage this shift.

As knowledge is building on climate change impacts already occurring or projected, conceiving adaptation and mitigation strategies on conservation, marine resource management and coastal planning at local, national or regional scales remain critical challenges for policy and governance (Hanich et al., 2018; Payri et al., 2019).

## 4 State of the art of SCP in the POTIs

### 4.1 SCP case-studies

To build the state of the art on when, where, how and for what purpose systematic conservation planning has been used in the Pacific islands, we reviewed scientific and gray literature to itemize SCP case studies and screen them to extract further details regarding study objectives and locations, methods and results (André et al., 2021a). This review collated 85 peer-reviewed papers and 10 reports. Among them, we found 34 studies describing POTI SCP case studies (Figure 7) (Appendix 1). We also identified and short-listed 12 POTIs context papers and 28 SCP case studies for tropical or sub-tropical areas beyond POTIs, non-exhaustive but focusing on topics that were relevant for the POTIs (detail in André et al., 2021a).

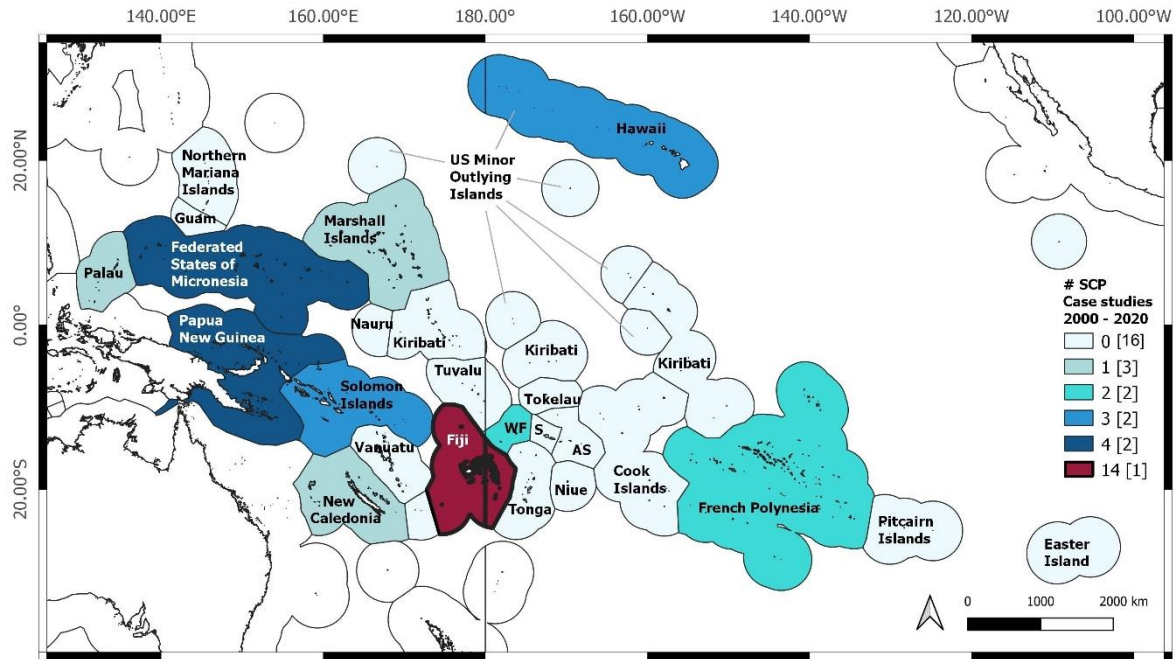


Figure 7. The study region and the POTI exclusive economic zones.

Colors reflect the census of reviewed systematic conservation planning case studies conducted for each one, from 2000 to 2020. For each value, the number of contributing POTIs is provided in brackets.

## 4.2 Trends

This review of SCP applications to the POTIs shows strong potential despite limited uptake in the POTIs (Cheok et al., 2018; Margules and Pressey, 2000). The geographical occurrence and abundance of studies vary over time between the three regions (Figure 8). The number of case studies per year grew since the beginning of the 2000s and tends to remain consistent with two to five new case studies yearly in the last ten years, but these levels seem very low compared to the potential needs for sustainable planning and management, in the numerous territories.

Regarding geographic scope, there is a great discrepancy in country coverage. Specifically, while many POTIs have no identified studies ( $n=16/26$ ; 47%), particularly in the Polynesia sub-region, where 77% of the countries had no SCP case studies (Figure 8a), Fiji is by far the most represented country with  $n=14/34$  SCP case studies (40% of all the studies). Melanesia thus accounts for 60% of studies (Figure 8b). In terms of geographic polarization, the present analysis is consistent with the conclusions from Álvarez-Romero et al. (2018): studies are concentrated within few areas; particularly in Fiji, at the POTI's scale analysis. In the other countries, there might be shortage of technical competences and initiatives from international NGOs and donors as those found in Fiji.

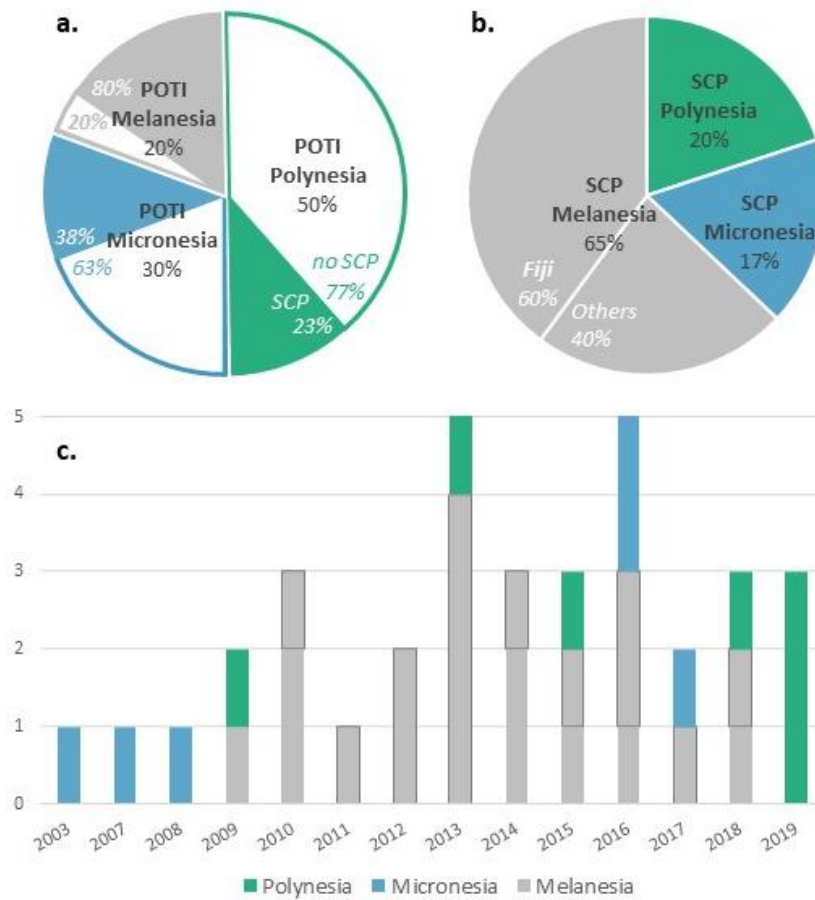


Figure 8. SCP trends in the POTIs.

a. All the Pacific Ocean tropical Islands (POTIs) classified by region (POTIs in Polynesia reaches 50% since as many as 13/26 POTIs that are located in Polynesia), and the proportion of POTIs that have been subject to SCP are indicated in colour, POTIs not subject to SCP in blank; b. All the reviewed POTI SCP case studies classified by regions; c. Number of SCP case studies through time, with a colored indication for each region, and case studies concerning Fiji highlighted by a gray frame.

We categorized the themes tackled by each POTI SCP case study (Appendix 2). The main ones are presented below, ranked by number of occurrences, keeping in mind that more than one topic could be found in any given study:

- **Identification of low cost marine conservation areas using SCP designs (n=13).** Planners aim to minimize costs and a number of POTI studies have explicitly addressed this issue in their designs, particularly reports aimed for implementation jointly with government entities (Government of PNG, 2015; Hinchley et al., 2007; Reimaanlok National Planning Team, 2008). Where cost reduction was not explicitly addressed, many studies simply used the notion of "equal cost," which means minimizing the size of the resulting network area (Tulloch et al., 2013; Weeks, 2017).
- **Importance of socio-economic costs and proxies in SCP design efficiency (n=12).** Costs are always recognized to greatly influence SCP outputs (Cheok et al.,

2016; Deas et al., 2014; Gurney et al., 2015), and their choice is not free of incidental consequences (Weeks et al., 2010b). Here, costs have most often been defined as fishery opportunity costs, using proxies such as population density or travelling distance (Cheok et al., 2016), with the exception of Deas et al. (2014) who used a rare atlas of artisanal fisheries. Using proxies is the only option when no resources are available to acquire spatially explicit socio-economic data (Mills et al., 2010; Weeks et al., 2010a). Nevertheless, the value of the socio economic proxy chosen is a key question (Hamel et al., 2018; Maina et al., 2015), although its relevance and precision is rarely evaluated or put to the test. Besides, costs are more often defined with fishers in mind, but the use of the marine domain in a variety of ways is a hallmark of POTI societies.

- **Ridge to reef approach for integrated land and sea planning (n=9).** “Ridge to reef” logic takes into consideration that land has an impact on streams, rivers, shores and the surrounding marine ecosystems and some studies based on coastal watershed, rivers, and forest cover or types (Comeros-Raynal et al., 2019; Klein et al., 2012; Lipsett-Moore et al., 2010; Tsang et al., 2019). Studies compared SCP without connectivity and with different types of connectivity, including land-sea connectivity in Fiji (Makino et al., 2013a) and in Hawaii (Tsang et al., 2019). At further implementation stages, the success of integrated land-sea management is largely subject to the type of governance, as demonstrated for three islands in the POTIs (Jupiter et al., 2017).
- **Integration of resilience and connectivity factors in SCP designs (n=7).** Resilience and connectivity, along with representativity are fundamental principles in conservation. Although representativity has been used early as a core concept in SCP, resilience and connectivity have been considered more recently in SCP, including for the POTIs, to refine scenarios and represent key dynamic ecological processes and functions in a network. **Resilience** is the capacity of an entity to resist to disturbances or recover and bounce back after disturbances (O’Leary et al., 2017). POTI examples of resilience-based SCP networks exist in Papua New Guinea (Green et al., 2009) and Fiji (Weeks and Jupiter, 2013). In Indonesian Islands, Torres-Pulliza et al. (2013) also built on these principles and ensured that coral reefs, mangroves and seagrass beds would be enough replicated at close distance. In practice, the application of resilience-based principles on any given site is strongly limited by the lack of knowledge, even for the most studied sites. **Connectivity** is a core process of landscape ecology and population dynamics as it depicts how populations are linked, with the movements of larvae, recruits, juveniles or adults (Pinsky et al., 2012). Connectivity is seen as a key factor of resilience and recovery, mitigating the impacts of stressors in the long term, such as climate change. Within marine ecosystems, there is a considerable degree of functional and spatial connectivity depending on species, locations, and scales (Rees et al., 2017). It is however, difficult to set general parameterization for connectivity considering there are often many species of interest with varying dispersal patterns (Magris et al., 2016).



- **Socio-economic and cultural aspects in conservation plans (including equity) (n=7).** The use and management of marine areas often have cultural dimensions in the POTIs. Preserving areas of significant cultural heritage was highlighted along with conservation objectives in some studies such as in the Marshall Islands (Reimaanlok National Planning Team, 2008), Fiji (Klein et al., 2014; Wendt et al., 2016) and the Solomon Islands (Lipsett-Moore et al., 2010). Additionally, taboo closures that are periodically harvested for the cultural purpose of providing abundant resources for an event of social importance such as evoked in Fiji and Vanuatu (Weeks and Jupiter, 2013). Another aspect is that treating the stakeholders as multiple groups rather than a single group, influences considerably the distribution of the costs induced by a reserve among the communities, and thus better accounts for equity of socio-economic costs (Gurney et al., 2015; Kabbadj et al., 2018; Weeks et al., 2010b).
- **Comparison of solutions between SCP and other approaches (n=6).** Many approaches to conservation and especially fisheries management exist in the POTIs, such as LMMAs, taboos, no-take areas and community-based fisheries measures. Some studies compared these ad hoc reserves with SCP for a gap analysis to fulfill conservation targets or include them as lock-in areas within the SCP network (Government of PNG, 2015; Klein et al., 2014; Mills et al., 2012; Wendt et al., 2016). Many studies suggest that local ad hoc designs are usually too small to meet biodiversity representation objectives or to maintain ecological processes that could effectively protect marine resources, considering fish home-range for example (Weeks et al., 2016).
- **Influence of habitat resolution/thematic richness of maps on SCP designs (n=5).** For representativity purpose, habitats are used for most scenarios as a baseline surrogate of biodiversity. Therefore, mapping habitat information, and understanding what is this information, should be critical. The quality, and the relevance of a habitat map for a given conservation problem, is related principally to its thematic resolution (i.e., the number of habitats considered), thematic information, spatial resolution, coverage, and accuracy. Different habitat map characteristics are shown to influence SCP solutions (Andréfouët et al. (2009), Deas et al. (2014), Hamel et al. (2013) and Mills et al. (2010)) such as an increased fragmentation of the solution network when using high thematic resolution, which can limit management effectiveness (Deas et al., 2014).
- **Benefits of integrating local knowledge into SCP (n=5).** In Oceania, local knowledge has been recognized as a reliable source of information to design reserves (Aswani and Lauer, 2006) and some studies combined SCP concepts with indigenous knowledge (Baker et al., 2011; Weeks and Jupiter, 2013) or based the acquisition of socio-economic information on local knowledge through surveys on fisheries (Adams et al., 2011; Deas et al., 2014) or on the value of fishing grounds as perceived by the communities (Hamel et al., 2018).
- **Conservation gap analyses (n=4).** Conservation and data gap analyses aim to identify the areas where data are needed and conservation activities are lacking. Various POTIs have been the subject of such assessments since 2000, including for

instance the Marshall Islands, Solomon Islands, Papua New Guinea, and Fiji, often with the goal of generating SCP scenarios (Government of Papua New Guinea, 2015; Jupiter et al., 2010; Kool et al., 2010; Reimaanlok National Planning Team, 2008).

- **Benefits of integrating a variety of stakeholders in SCP designs (n=3).** Integrating the stakeholders to the planning process can bring important positive outcomes such as in the Solomon Islands (Lipsett-Moore et al., 2010) or in Fiji (Wendt et al., 2016). Some studies emphasized the importance of involving a variety of practitioners and stakeholders along the SCP process, to identify conservation and research priorities in the Solomon Islands and in FSM (Lipsett-Moore et al., 2010; Weeks and Adams, 2018; Weeks et al., 2016).
- **Scaling-up conservation networks between local and regional scale (n=3).** ‘Scaling’ reflects the dynamic two-way relationship that may exist between local and regional scales in terms of assessment and implementation. Scaling-up addresses for instance MPA network extension from ad-hoc local solutions to regional solutions (Mills et al., 2012), the frequency at which regional priorities need to be updated as local actions are implemented (Cheok et al., 2017), or how conservation costs vary locally for a collection of local scenarios *vs* an overarching regional scenario (Kabbadj et al., 2018).
- **Integration of climate change information on SCP designs (n=3).** Principles to include climate change projections in SCP designs in the POTIs have been first discussed by Levy and Ban (2013) at regional scale. They used sea surface temperature historical patterns, a coupled atmospheric-ocean general circulation model (CAOGCM) and an emission scenario to infer future anomalies and vulnerability to climate stress. However, this pilot study needs to be enhanced. In particular, CAOGCM models are notoriously inaccurate for the central Pacific, so specific approaches are needed to meaningfully downscale and characterize anomalies for islands (Andréfouët et al., 2015; Duthiel et al., 2019). These precautions are required to identify suitable robust areas with SCP. It is critical to understand capacities to adapt over present ranges of environmental conditions (Kleypas et al., 1999). The location of possible refugia might be also a key resilience question. POTIs are highly vulnerable to climate change. While some island examples of climate change-driven SCP scenarios emerge from this review (Hawaii, French Polynesia and Fiji, respectively with Chung et al., 2019; Kabbadj et al., 2018; Weeks and Jupiter, 2013), their number is not congruent with the threats that represent warming, changes in cyclone activities and potentially sea level rise (Payri and Vidal, 2019).
- **Adaptive management and SCP designs (n=2).** Finally, adaptive planning is a relevant concept for islands facing climate change, resource collapse or socio-economic changes (Mills et al., 2015). Adaptive planning means that new data, socio-ecosystem changes, consequences of natural disasters and so on may call for new decisions, assessment and implementation. In the POTIs, adaptive planning has been emphasized for Fijian coral reefs (Weeks and Jupiter, 2013) but not all the challenges could be overcome in this case (Mills et al., 2015). On the ground, there are several POTIs examples of zoning plans that have been revisited in the past although without

using SCP (e.g., Moorea lagoon in French Polynesia, about 15 years after the first zoning).

Several of these topics also emerged in a global review of the recent marine SCP literature (Álvarez-Romero et al., 2018), which highlights that the same issues are of concern worldwide. However, there are POTI's specific issues. Although the relatively limited number of case studies in this region impedes robust quantitative analysis, several patterns emerge (Figure 9). Among the analysed themes, most of them have been tackled mainly in Melanesia, and either in Micronesia or Polynesia, or both. For example, adaptive management has been discussed only for Melanesia, precisely in Fiji.

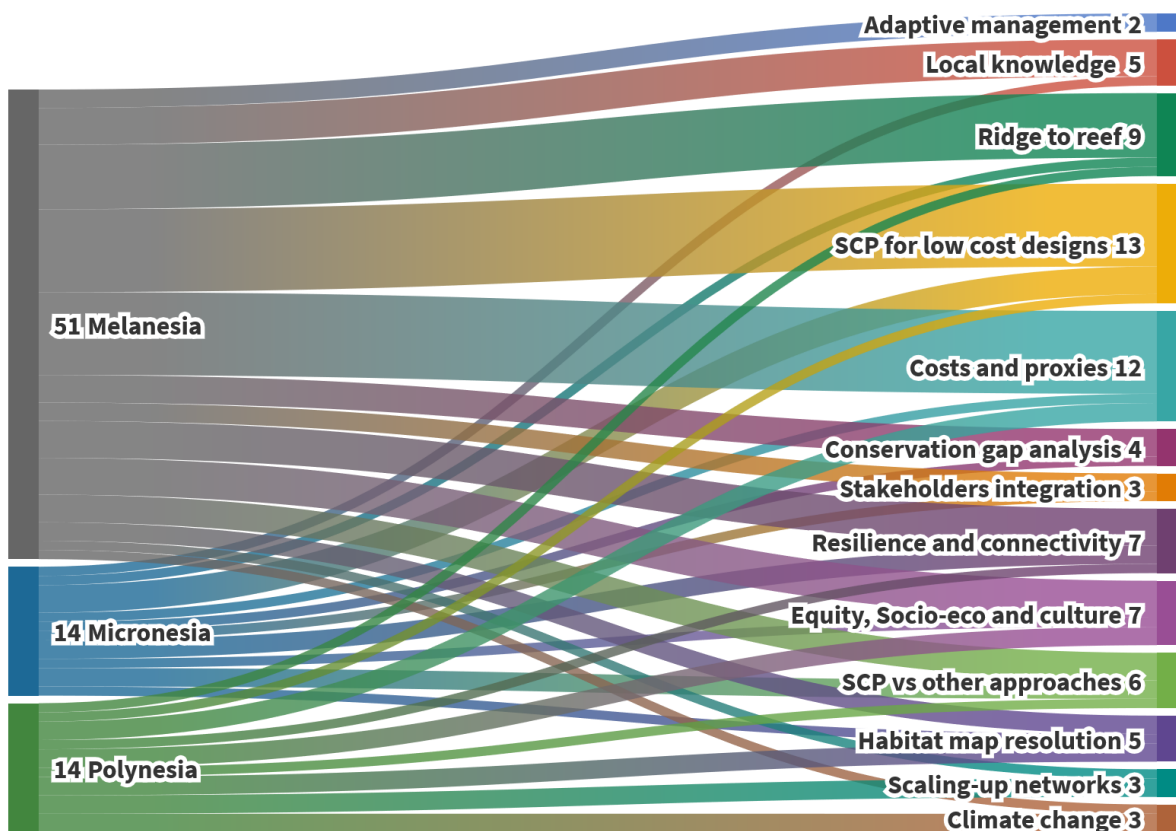


Figure 9. Summary of the SCP case studies organized according to their regions and the themes tackled. Themes are presented with key words here.

Overall, academic-driven studies are dominant without much of a manager involvement, which seems to push SCP towards more complex scenarios and challenges, to integrate new constraints and paradigms (adaptive planning, climate change, resilience, ridge-to-reef continuum, genetic models, etc.)

The simpler types of applications, which are more in line with the founding SCP concepts of evaluating conservation gaps and comparing objectives *vs* cost trade-offs, better match the main basic priorities often put forward by island managers regarding fishery or stock

conservation. Indeed, they often primarily have to deal with balancing marine resource management and food security with other types of activities (tourism, coastal development, mining, etc.). As such, it is likely that the simplest types of SCP scenarios will continue to be used to provide a sound foundation for decision making in partnership with various stakeholders.

While all themes were thoroughly presented and discussed in André et al. (2021a), we focus here on island-specific gaps and challenges relevant to enhance the use of SCP in the POTIs. Some aspects have already emerged in SCP scenarios but remain understudied or underrepresented; others have never been addressed in POTIs' SCP while they could define future additional roadmaps for POTIs scenarios.

## 5 Gaps and challenges for SCP in the POTIs

### 5.1 Diversifying the conservation criteria, and ensuring data quality

The first main findings were that the primary objective from which all results will depend on is often an Aichi 11 representation target. Indeed, most plans (83%) were designed to target a given percent representation of habitats. Second, many case studies relied on proxies (or surrogates) and modelling (80%), and very few have specifically collected new *in situ* data or validated models for their investigations. We develop these two main points below.

We found that biodiversity criteria (either as objectives, as costs of exploitation, or as biological processes) are often limited to habitats or biased towards finfish fisheries. Yet, from the POTIs context, there is a wider variety of potential relevant criteria. To our knowledge, there are almost no SCP studies built around echinoderms, crustaceans, mollusks (but see Kabbadj et al., 2018), or marine mammals although scientists, NGOs and government acknowledge that these are also priorities for management (Weeks and Adams 2018; Derville, 2018). For instance, sea cucumber fisheries are significant in many archipelagos, and while the status and management of this resource is frequently debated (Andréfouët et al., 2019b; Bosserelle et al., 2017; Purcell et al., 2013), no SCP studies have focused on this taxon, or used population data. Similarly, several critically endangered species, such as dugong in New Caledonia, are the focus of many conservation projects (e.g., Cleguer et al. 2015), yet, relevant information such as feeding and reproduction areas, or migration pathways, have not been used in SCP scenarios, except for turtle nesting beaches (e.g., Green et al., 2009). Lack of spatialised data readily available likely hinder the development of appropriate scenarios.

In terms of data, modelling and approximate proxies are often used to fill data gaps, but there are shortcomings due to their inherent limitations. These limitations are often poorly acknowledged in the literature. For many scenarios, the collection of relevant accurate 'hard' data with known limitations seems to be quite rare; they are therefore highly recommended. Enough resources should be allocated for initial data collection, especially for baseline data that are often taken for granted, such as habitat maps, biodiversity, or fishery data. For instance, a systematization of the spatialisation of the socio-economic surveys, especially those related to fisheries (such as in Léopold et al., 2014), should be a priority.

Molecular data are increasingly available for POTIs and have long served conservation (Von der Heyden et al., 2014), but methods to include genetics and genomics data in SCP have been emerging only recently (Beger et al., 2014) and, to our knowledge, no example is available for the POTIs, yet. Molecular data are one efficient way to understand connectivity at demographic and evolutionary time scales and validate connectivity models (Trembl et al., 2015, Reisser et al. 2020), which could improve SCP to a great extent, depending on the scale of the exercise. However, considering the cost of sampling and analysis especially for population genetics, investigations can only be performed for a limited number of species, and the choice of candidate species is not trivial if the conservation objective is general and not specific to those species. Multi-species modelling could be a solution, as discussed for South Africa (Nielsen et al., 2017). However, other limitations arise, such as differences in the density of samples per planning domain or planning unit, especially for multiple island exercises.

Finally, beyond the nature of data, we emphasize SCP methodological priorities, namely the need to document well the projects, conduct sensitivity analyses and, most importantly, use accurate data to, at least, validate the proxies or model outputs used for SCP.

## 5.2 Mariculture activity

In terms of gaps, we noticed that mariculture has never been used in any SCP scenario in the POTIs, either within a conservation or fisheries management approach. Outside the POTI region, Indonesia brings an example of mariculture integrated to SCP, with seaweed and pearl farming (Grantham et al., 2013). Mariculture in island lagoons or coastal areas is at various stages of development in many Pacific Ocean places and have often only occurred at small scale in the past decades (Adams et al., 2001). In the past 20 years, black pearl farming in French Polynesia, Cook Islands and Fiji, or shrimp farming in New Caledonia have developed over large areas and have become economically significant. For instance, black pearl farming in French Polynesia is the 2<sup>nd</sup> source of income for the country with activities having taken place in no less than 35 islands since farming began (Andréfouët and Adjeroud, 2019). A most likely path for development in the POTIs is the aquarium trade, for which areas for valuable specimen collection, spat collection, or rearing are increasing (e.g., Teitelbaum and Friedman, 2008, for giant clams).

Even if mariculture remains today marginal in many countries, the future needs for local stock enhancement, the proximity of the Asian seafood and jewellery market, the extent of shallow lagoons offering suitable locations, the possibility to grow high value products in small areas with simple technology, and an interest for local populations to work with marine resources, could increase the need to account for mariculture in future SCP scenarios. For instance, given the extent of black pearl farming activities in many French Polynesian lagoons, it is likely that specific SCP scenarios for optimal zoning according to this activity will emerge soon. These could also take advantage of hydrodynamic 3D models implemented to compute connectivity matrices for pearl oyster larval dispersal (Dumas et al., 2012; Thomas et al., 2016), as well as genetics study that can help mapping populations and larval dispersal source and sinks (Reisser et al., 2020). In the context of different uses and activities that require specific management, such as mariculture, fishing and conservation zones, multi-objective SCP tools can help.

### 5.3 Ciguatera risk

Third, ciguatera spatial risk has never been integrated into SCP. For islands where there are ciguatera-endemic areas, it can be stated that ciguateric areas are *de facto* protected as *no take* (or 'less take') areas, since they tend to be avoided by fishers. Hence, SCP scenarios could take advantage of the situation by maximizing the inclusion of areas known to be ciguateric into reserves, to decrease the fisher opportunity costs. Several other factors obviously need to be considered, including: i) the habitat quality and its suitability as a conservation objective, in case ciguatera was due to coastal degradation; and ii) the availability of spatially-explicit ciguatera toxicity data, which are difficult and costly to collect and spatialize. If this information could be collected from fishers, who should care about and know ciguatera spatial patterns, even approximately, it could benefit to SCP and might influence opportunities for conservation. We can generalize this point about ciguatera to any factors (environmental, cultural or historical) that transform areas into *de facto* no take areas for local populations.

### 5.4 Customary management

Fourth, the need to consider customary management has been emphasized in several SCP scenarios with, for instance, the use of locked-in SCP function to automatically include customary protected areas in the conservation solution (Adams et al., 2011; Green et al., 2009; Horigue et al., 2015). However, a large amount of work remains to be carried out, particularly about the scaling of conservation network. In Vanuatu for instance, traditional micro-managed areas are the norm, are plentiful (Dumas et al., 2010), and probably will not be abandoned for other schemes. Understanding how to maximize the benefits of existing initiatives is a priority. In Polynesia region, existing protected *tapu* (or *tabu*, *taboo*) or *rāhui* (temporal closures) areas, have also been ignored thus far by SCP studies, while some local initiatives have recently revitalized these traditional practices (e.g. in French Polynesia: Bambridge et al., 2019; e.g. in Oceania: Cohen and Foale, 2011; Gruby and Basurto, 2013; Johannes, 2002).

In the context of sessile or sedentary fishery management, the effectiveness of temporal, rotating or permanent closures compared to other measures such as catch size limits and quotas, is still debated (Carvalho et al., 2019; Plagányi et al., 2015; Purcell et al., 2015; Van Wynsberge et al., 2013), a theme echoed by discussions on OECM (Gurney et al., 2021). Cultural values are still strongly anchored in many island societies despite the fast evolution towards a westernized, globalized, modern way of life (Buijs, 2009; McFarlane et al., 2019). However, cultural values remain poorly considered in POTI's SCP scenarios (Hamel et al., 2018), likely because they could be difficult to integrate due to varied tenure and governance systems, and strong bottom-up approaches to management. Interestingly in Fiji, mixed co-management systems exist, including for connected land-sea managed areas (Jupiter et al., 2014a; Weeks, 2017). Anthropology studies have characterized how local communities can value their marine environment for reasons that are beyond just access to food, identifying locations of high symbolic value (Foale et al., 2011), but this information is often not spatialized although it would be valuable for SCP.

## 5.5 SCP for very large MPAs

Fifth, in some countries, conservation took the path of implementing Very Large Marine Protected Areas, a path that is not necessarily exclusive of smaller local initiatives, but has dominated the political, if not the technical, conservation agenda. SCP has never been used for the zonation of VLMPAs in the POTIs (listed in Table 3). Even globally, the only example is the rezoning plan of Great Barrier Reef Marine Park Authority in Australia (Fernandes et al., 2005). In the POTIs, none of the boundaries or zoning plans (if any) of the VLMPAs or sanctuaries were designed using SCP methodology. Political decisions were made without much of spatial planning scientific prioritization. Considering the sizes of these MPAs, and the limited amount of conflicting stakeholder activities (if no fishing license or seabed mining), a SCP driven selection was often not justified. However, most of them need to define a zoning plan and a SCP approach has been recommended for their definitions as well as for the identification of new VLMPAs (Davies et al., 2017; Devillers et al., 2015).

It is likely that SCP will play a role for this, although the biggest challenges remain collecting suitable biological data across wide expanses of ocean, to build relevant and robust scenarios. Biodiversity models have been used at the scale of VLMPAs (e.g., Davies et al., 2017), but, again, data quality remains an issue and it might be better to focus on the representation of bio-physical regions defined by mapped physical and geomorphological features (Devillers et al., 2015). It is likely that in the near future, the problems inherent to optimizing conservation *vs* costs, and inferring management plans for these VLMPAs, will be under the scrutiny of the SCP community. Recent studies have proposed new definitions for bioregions in the Pacific Ocean (Beger et al., 2020; Garcia et al., 2018), that could help refining VLMPAs planning, based on representativity, but the relevance of these bioregion definitions remain data quality-dependent.

## 5.6 Mitigating local changes from global origin

Sixth, and last, the POTIs are highly vulnerable to global threats and management answers to these threats have not been tackled with SCP.

Some examples of climate change-driven SCP scenarios emerge from this review (Hawaii, French Polynesia and Fiji, respectively with Chung et al., 2019; Kabbadj et al., 2018; Weeks et al., 2013). However, their number is not congruent with the threats that represent warming, extreme events and elevated sea level to habitability (Duvat et al., 2021) or the need to maintain small-scale fisheries facing global warming (Bell et al., 2018).

Further, despite their remoteness and high geographical dispersion, globalization does not spare the POTIs, with growing integration of their economies into the global economy through trade, tourism, aids, etc. Thus, global crisis such as the economic crisis of 2008 or the present Covid-pandemic, can seriously affect the populations and local economies, including outward-oriented economies, such as those based on tourism or mariculture production for export. Adaptive planning could help managing induced changes. Accordingly, redesigning spatial schemes to diversify or re-introduce traditional activities using SCP would help foresee diversification strategies to improve adaptation and resilience to future change.

Adaptive planning would also be a way to consider these global effects in SCP at various time scales. For instance, while the effects of sea level rise on low lying islands are still scientifically debated (Tuck et al., 2019; Masselink et al., 2020), this process could accentuate the effects of poor land use (Yamano et al., 2007) and of tectonic activities that are also a feature of several POTIs, such as Vanuatu (Ballu et al., 2011). Increased flooding occurrences could trigger population migrations, which raise important questions on potential destinations, availability of land and tenure (Connell, 2016; Donner, 2015), including a change on the use of resources and potential for conservation. SCP could be useful to plan these migrations that could occur in the future at different spatial scales (within and between islands).

## 6 General objective and thesis outline

### 6.1 Research questions

The SCP studies performed in the POTIs seem to remain too large focused and not always tightly relevant to local features. The general research question addressed in this thesis stems from several gaps pointed out above:

**Q-0:** How and to what extent can we integrate more specifically the Pacific Ocean tropical Islands' specifics in systematic planning for the conservation and management of marine areas?

According to the local context and needs, determining which specific criteria would be studied within this thesis was conducted in two phases. As we specifically work in French Polynesia (see Chapter 1 Study sites), we first retained the features that are highly relevant for these islands: ciguatera risk and mariculture activity, namely black pearl farming. Second, we scanned the study zone with this two-criteria lens to identify islands that meet one or both criteria. Additional drivers guided the section. Then, from the sites identified, we refined the management questions and priorities after discussions with stakeholders and empirical observations, which determined additional locally relevant criteria.

This multi-criteria approach allowed us to encompass, in the end, a number of original criteria for SCP in line with the gaps previously identified in the literature. These criteria also provided concrete sample management issues to address with SCP approaches. In that respect, our general research question was declined in four specific research topics:

**Q-1:** is it possible to (and how can we) account for ciguatera in SCP;

**Q-2:** how can SCP guide the management of mariculture, and particularly black pearl farming in its various steps;

**Q-3:** how can SCP articulate with traditional management;

**Q-4:** how can SCP serve diversification strategies to mitigate external impacts on local activities, in particular on black pearl farming.



The approach angle of this thesis was based on SCP as the core prioritization step, also called site selection step. Besides, where possible, we incorporated guidance from the expressed needs of the stakeholders, such as *Direction des Ressources Marines* (DRM) and *Délégation à la Recherche de Polynésie française* (DREC).

## 6.2 Thesis outline

**Chapter 1** presents the study zone, French Polynesia and three case study islands, namely Raivavae, Takaroa and Gambier, their characteristics and an overview of the fieldwork undertaken to collect original data on small-scale fisheries and ciguatera.

Through the following chapters, the research question of this thesis was examined regarding the five topics, sometimes interrelated. Each of the following chapters was the subject of a peer-reviewed article (published, in review or submitted).

**Chapter 2** answered Q1 by developing a methodology to (i) generate ciguatera risk quantitative and spatial information from map-based surveys, and integrate it to SCP by modulation of opportunity cost to fishers, and (ii) improve spatial precision of fishery grounds delineation. This framework was applied to Raivavae Island. Sensitivity of the results to conservation targets and relative weight between ciguatera risk and fishery opportunity were explored. Further sensitivity analyses were conducted specifically on basic parameters for SCP, such as compactness penalty and habitat map resolutions, which are rarely questioned and reported.

**Chapter 3** aimed at identifying suitable locations for the restocking of adult *Pinctada margaritifera* pearl oysters (Q2), exploring this time systematic planning towards solely a resource management perspective specific to French Polynesia lagoons. The exercise focused on Takaroa atoll lagoon, which was an important place for black pearl farming but collapsed due to a massive mortality of oysters in 2014. The systematic spatial planning accounted for oyster habitat suitability as a conservation criteria, while costs were modelled using within lagoon oyster larval dispersal and connectivity, fishing ground locations and pearl producers' concessions.

**Chapter 4** focused on a *rāhui*, which is one of the multiple forms of traditional management practiced in the Pacific. As such, it explores answers for Q3. It investigates how SCP could articulate with the *rāhui* and improve the efficiency of the traditional design. For this, SCP scenarios drew from the *rāhui* objectives as it is currently planned in Raivavae Island, to preserve and increase marine resource stock for sustainable fisheries, particularly giant clam stock. Raivavae *rāhui* has a specific split design accounting for spatial equity between villages and we explored different configurations. SCP thus accounted for giant clam distribution as resource conservation criteria. It also integrated fishery and ciguatera information to the opportunity cost to minimize, taking advantage of the methodology developed in Chapter 2.

**Chapter 5** focused on another management question in Gambier, where the Covid-pandemic ended up further weakening the main economic activity, pearl oyster farming. To foresee diversification strategies in the context of an island dominated by a single activity, black pearl farming (Q4), multi-zone SCP was used for designing and comparing scenarios of multi-use lagoon, including “business as usual” and “back to tradition” scenarios, and examining the

impacts of each zone on the others. The criteria used included remarkable coral communities, wild oyster stock, oyster restocking scheme following traditional management, mariculture information as well as opportunity cost to fishers including ciguatera risk, taking advantage of the results and methodologies developed in Chapters 2 and 3.

Finally, the **Discussion section** summarized the main findings and lessons learnt in this thesis. Then we open perspectives to the POTIs scale, and discuss how these specifics would be relevant to other situations. We finally widened the reflection to some additional aspects that could be integrated to future SCP use.



## Chapter I – Study sites



## Chapter I – Study sites

This thesis is based on a multi-criteria approach for the analysis of different sites in the Pacific. This vast oceanic region of nearly 43 million km<sup>2</sup> accounts for more than 25,000 islands. To select the study sites, we were primarily guided by our partners' anchorage in terms of sites, associated available information and potential multi-criteria dimension that are relevant to our five questions.

### 1 French Polynesia

#### 1.1 Geography

As a geopolitical territory, French Polynesia covers 4.8 million km<sup>2</sup> through a large economic exclusive zone that extends from -132°W to -158.1°W longitude and from -4.5°S to -31.2°S latitude. French Polynesia counts 118 islands (totaling 4,200 km<sup>2</sup> land) that are grouped under five archipelagos: Marquesas, Tuamotu, Society, Austral and Gambier Archipelagos.

The formation of the islands can be linked to different geological processes, including volcanic activity. Hot spots, located under the Pacific tectonic plate, produce basal magma and perforate the oceanic crust intermittently to form seamounts and islands. These form alignments as the oceanic plate moves across the surface, drawing the archipelagos (Graviou et al., 2013). In French Polynesia, the islands are designated under two main types: “high islands” with volcanic relief (e.g. Raivavae and Mangareva), or “low islands”, which are atolls (e.g. Takaroa). The exact genesis of all atoll and island lagoons as we see them today is still debated in many cases, and can be island specific (Droxler and Jorry, 2021, Montaggioni et al., 2015).

Among all French Polynesian Islands, 64 are inhabited and only one, Tahiti, concentrates 70 % of the total 280,000 inhab. (based on the 2019 census) (ISPF, 2019). Tahiti is the largest island and centralizes both political authorities and the major part of the economic activities. Before Covid, this isolated territory was connected by plane mainly to Paris (17,000 km), Los Angeles (6,600 km) and to a lesser extent Auckland (4,000 km), Sydney (5,700), Tokyo (9,500 km), Santiago Chile (7,900 km), Hawaii (4,200 km) and Cook Islands (1,200 km) (IEOM, 2015).

#### 1.2 History, politics, and institutions

Currently, French Polynesia political regime is unique among the French overseas territories. The institutions are the territorial government, the territorial assembly, who may enact “country laws”, and the Economic, Social and Cultural Council. Since the 2004 Organic law that strengthens the status of autonomy, the Territorial Government is competent in all matters, with the exception of those expressly assigned to the country of France which include civil rights, foreign policy, defense, scientific research and university education, etc.) (HCRFP, 2021). However, the environment and health are under the competence of French Polynesia, so are the research activities in these fields, which are carried out by public institutes or

services such as *Institut Louis Malardé* (ILM) and *Direction des Ressources Marines* (DRM). The *Délégation à la Recherche* service prepares, coordinates and implements research policy in French Polynesia (DREC, 2021).

### 1.3 Economic drivers and the black pearl sector

French Polynesia's economy boomed in the 60's due to the nuclear tests program, and has since struggled to reduce its dependence on public transfers from the France metropole (Dropsy and Montet, 2018; Poirine, 1999). It also has the characteristics of small island economies due to isolated territory, in addition to important distances between the islands. This, combined with structural factors, small domestic market and high cost of production are among its main characteristics

Currently, the tertiary sector is the main economic driver in Tahiti and Moorea and employs 80% of the active population in these islands (ISPF, 2018), while the economy of the archipelagos relies more on the primary sector. Tourism and public administration are the main sources of employments in "the islands" (as opposed to Tahiti and Moorea). Black pearl production is the first export sector in French Polynesia and, along with small-scale tourism, it represents one of the few possible sources of income for numbers of households in peripheral islands. Additional subsistence revenues are brought by fishery, handicraft and copra (from coconuts), the latter having been subsidized by the government to limit demographic loss from the peripheral islands.

Albeit black pearl farming sector remains the second income generating activity in French Polynesia after tourism, this sector has undergone a continuous crisis that shortly followed its golden age. Black pearls are produced since the 90's and after years of expansion until the record in 2000, revenues generated from pearl export have dramatically dropped, divided by four in 2019 (IEOM, 2020) (Figure 10). Largely dependent on international markets, notably Hong Kong and Japan for 90% of sales, the balance between supply and demand has been exposed to several economic crises or political instabilities (such as the 1997 Asian financial crisis, the 2008 global crisis, social unrest in Hong Kong in 2019 and the current pandemic) and to direct competition from Japan and Australian pearls. In addition, structural inner factors affected the sector, such as overproduction, adoption (2001) and then suspension (2007) of quality control measures and environmental vulnerability.

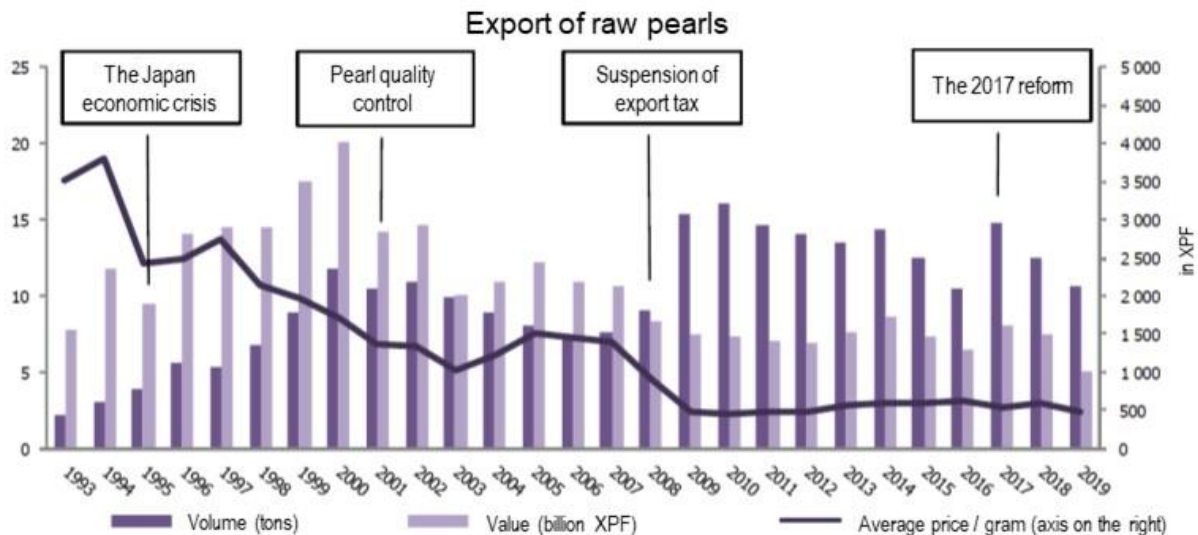


Figure 10. Annual volumes, values and average price of raw black pearl from French Polynesian production (adapted from IEOM, 2020).

To face these issues, the sector largely benefits from public support including research programs and trainings. Pearl oyster professionals and the Government have attempted sectoral reforms to improve the management of the activity, with a growing concern on the pressures on the lagoon ecosystems. The public technical service, *Direction des Ressources Marines* (DRM), has a division specifically dedicated to the management of the black pearl farming activity.

#### 1.4 The pearl oyster farming activity

Going back in history, this *Pinctada margaritifera* bivalve species was used for traditional mother-of-pearl adornments and to carve hooks for fishing. From the 1800's, oysters were collected mainly from a dozen productive islands for international trade and the button industry, which contributed significantly to the economic growth of French Polynesia, leading at the same time to a significant decline in stocks, observed from the early 20th century. Demand and collection dropped after World War II due to the plastic revolution, and new economic opportunities and developments occurred in French Polynesia following the establishment of nuclear test sites in the Tuamotu-Gambier archipelago (Le Penne, 2009).

Natural pearls were only occasionally found in oysters before the government promoted research and development programs in the 1960s to produce cultured black pearls, following practices already in use in Asia. In a nutshell, the production of quality pearls takes 3 to 4 years and is based on two distinct activities: (i) spat collection (juveniles) and (ii) oyster farming (adults). The harvesting of wild adult oysters is prohibited in French Polynesia, in order to protect wild stocks. Therefore, oyster farming first requires collecting spats through lines of collectors deployed in the water column on which the spat, produced by fertile wild adult stocks, can settle. Spat collection success is however erratic in time and space, and depends on reproductive wild oyster stock abundance in the lagoon, hydrodynamic circulation and suitable environmental conditions at all oyster life stages (Sangare et al., 2020). Then, oyster farming includes: i) managing spat growth until they reach sufficient size to be grafted; ii) grafting a bead nucleus; and then iii) monitoring the growth of grafted stocks until,

eventually, iv) harvesting the pearl (Figure 11). Farms are organized around central working buildings on stilts above the lagoon or along the shore, in which manipulations and grafting take place, after spats and oysters get transported back and forth from hectares of immersed lines of spats collectors and baskets of adult oysters. The lagoon space is thus a critical resource for this activity. DRM controls the farmed areas by delivering yearly marine concessions, which are subjected to a fee. Conversely, spat collecting lines can be deployed anywhere in lagoon areas, except in Gambier lagoon and Ahe Atoll (Tuamotu Archipelago) where it is authorized only within a single area.

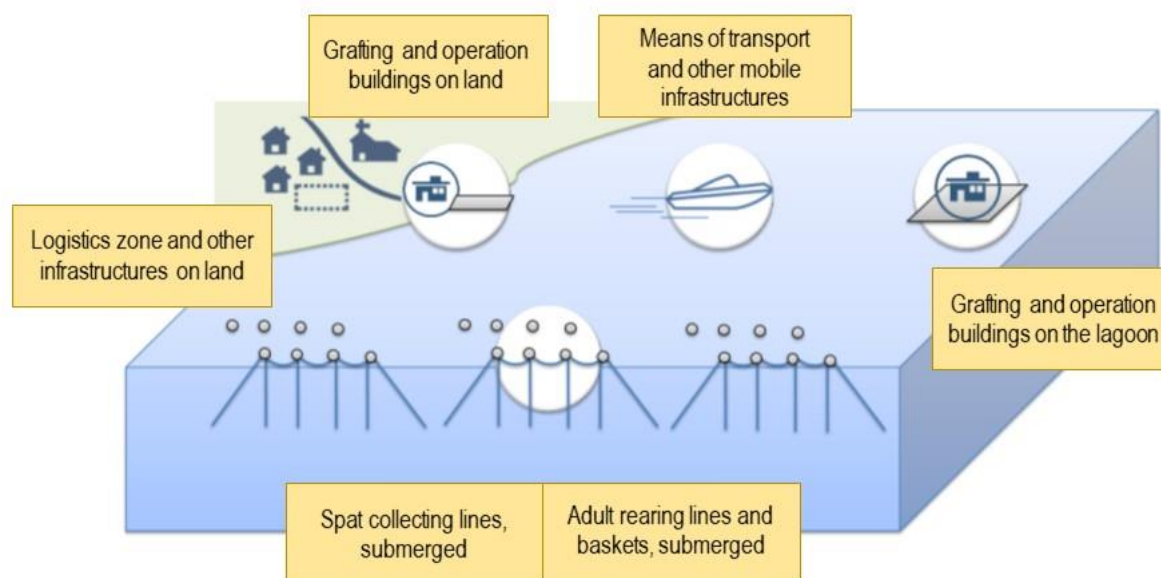


Figure 11. Schematic presentation of the pearl oyster farming infrastructures and their usual spatial organization (adapted from Gaertner-Mazouni and Rodriguez, 2017).

In front of the pearl market crisis and environmental risks such as mass mortality events (Andréfouët et al., 2015), DRM manages the activity to improve sustainability of both farmers' income and ecosystem quality. This strategy translates into reducing exploited surface areas, to eventually decrease production and pressure on the exploited lagoon ecosystems. An additional measure being currently considered by DRM is to restock the lagoon with adult oysters after pearl harvesting, to increase the wild broodstock instead of using them for food or for mother-of-pearl shells. Indeed, since *Pinctada margaritifera* oysters are protandrous hermaphrodite, restocking adult oysters after 3-4 years may increase female populations, which have been reported to be very low (Andréfouët et al., 2016). High density restocking within dedicated sanctuaries could therefore maximize reproduction and ultimately ensure sustainable spat production.

Another concern that emerged in the last decade is potential pollution from the waste induced by pearl oyster farming activity. Significant levels of micro-plastic contamination were found in several atolls (Gardon et al., 2021). The amount of buoys, lines, ropes etc. that have sunk to the bottom of the lagoon, has been estimated at some sites in order to guide depollution actions (source: DRM).



Throughout the islands in French Polynesia, small-scale fishery is largely practiced (Andrefouët and Adjeroud, 2019) and fishers are always aware of ciguatera risks. According to the gaps identified above in the SCP review, taking into account black pearl farming, small-scale fisheries and ciguatera seems a good starting point to answer Q-0 and adapt SCP to local criteria. In order to allow answering to Q-1, Q-2, Q-3 and Q-4, the following rationale explains the choices for the sites.

## 2 Rationale for site selection

The overarching postulate of this work is to develop specific SCP scenarios relevant for French Polynesia Islands; hence, we restrain our site selection among its five archipelagos and 118 islands. In addition, we also considered criteria deemed very important for French Polynesia islands but neglected in previous SCP case studies.

First, we were particularly interested in black pearl farming, as this is an outstanding activity for French Polynesia, currently taking place in 17 islands (DRM, 2019), with various degrees of dynamism and spatial extent, and as this activity has never been considered in SCP case studies.

The second trait that we prioritized was ciguatera. Indeed, this criterion too has not been studied with a SCP approach. In French Polynesia, Institut Louis Malardé (ILM) records ciguatera poisoning events occurrences and several islands were notably concerned, which guided our short listing of candidate islands.

Finally, the ‘Management of Atolls’ research project (MANA, 2017-2021) funded by the *Agence Nationale de la Recherche*, studied a series of French Polynesia atolls and generated a number of original data sets potentially useful to develop relevant and original SCP scenarios.

The goal was to focus on three islands at the most, among the potential study sites, where to conduct field missions and surveys among fishers to collect new data to create spatialized and quantitative information on lagoon uses, fisheries, and ciguatera.

The final choice of study sites was also driven by the availability of other types of information that are necessary to make a SCP analysis i.e. spatialized and quantified information at an adequate resolution, on which to rely in case of impediment to conduct on-site missions. The type of information sought included in particular habitat maps, which are used as proxies of biodiversity. These baseline data are available for every island through the Millennium Coral Reef Mapping Project (Andréfouët et al., 2006), but at coarse geomorphological thematic and spatial resolutions. Prior to considering mapping a new lagoon, we identified sites where adequate and accurate habitat maps were available. Availability of high resolution bathymetry map was also deemed useful, and an original criteria.

Among the nine short-listed islands (Table 4), we finally chose Takaroa, Raivavae and Gambier for their contrasting characteristics in terms of oyster farming, ciguatera risk, degree of inhabitants’ reliance on local fishery resource for their livelihood, and representativeness in terms of island and archipelago diversity (Figure 12A). In the end, logistical constraints linked to the organization of field missions (facility, access, cost) were also considered. For instance,

despite the great interest in Rapa, its traditional fishery organization and the record of a recent ciguatera outbreak, the island was too barely accessible to be selected.

Fieldwork was conducted in August (Takaroa) and November 2019 (Mangareva and Raivavae). Fortunately, travel restrictions due to the Covid-19 pandemic did not impact field data collection.

Table 4. Candidate islands, their status and available data, for this PhD potential study sites.

Abbreviations: Y = Yes; N = No; bathy = bathymetry; BL Oyster = Black lipped Oyster.

Archipelago	Island	Oyster farming	High incidence of ciguatera poisoning	Biodiversity inventory	Information on fisheries	Geomorphological habitat	Detailed habitat
Australes	Rapa	N	Y	Y (2002)	?	Y	N
<b>Australes</b>	<b>Raivavae</b>	N	Y	Y	Y <i>giant clams</i> (2010)	Y	Y
<b>Gambier</b>	<b>Gambier</b>	Y	Y	Y ( <i>coral, algae</i> )	N	Y	Y
Société	Raiatea	Y	N	Y	Y	Y	Y
Tuamotu	Ahe	Y	N	Y ( <i>fish, BL Oyster</i> )	N	Y	N (but bathy)
Tuamotu	Fakarava	Y	Y (2008)	Y	N	Y	Y
Tuamotu	Kaukura	N	Y (but in fish parks)	N	N	Y	N
<b>Tuamotu</b>	<b>Takaroa</b>	Y	N	Y ( <i>BL Oyster</i> ) (2013)	N	Y	N (but bathy)
Tuamotu	Tikehau	N	N	Y (2003)	Y (2003)	Y	N

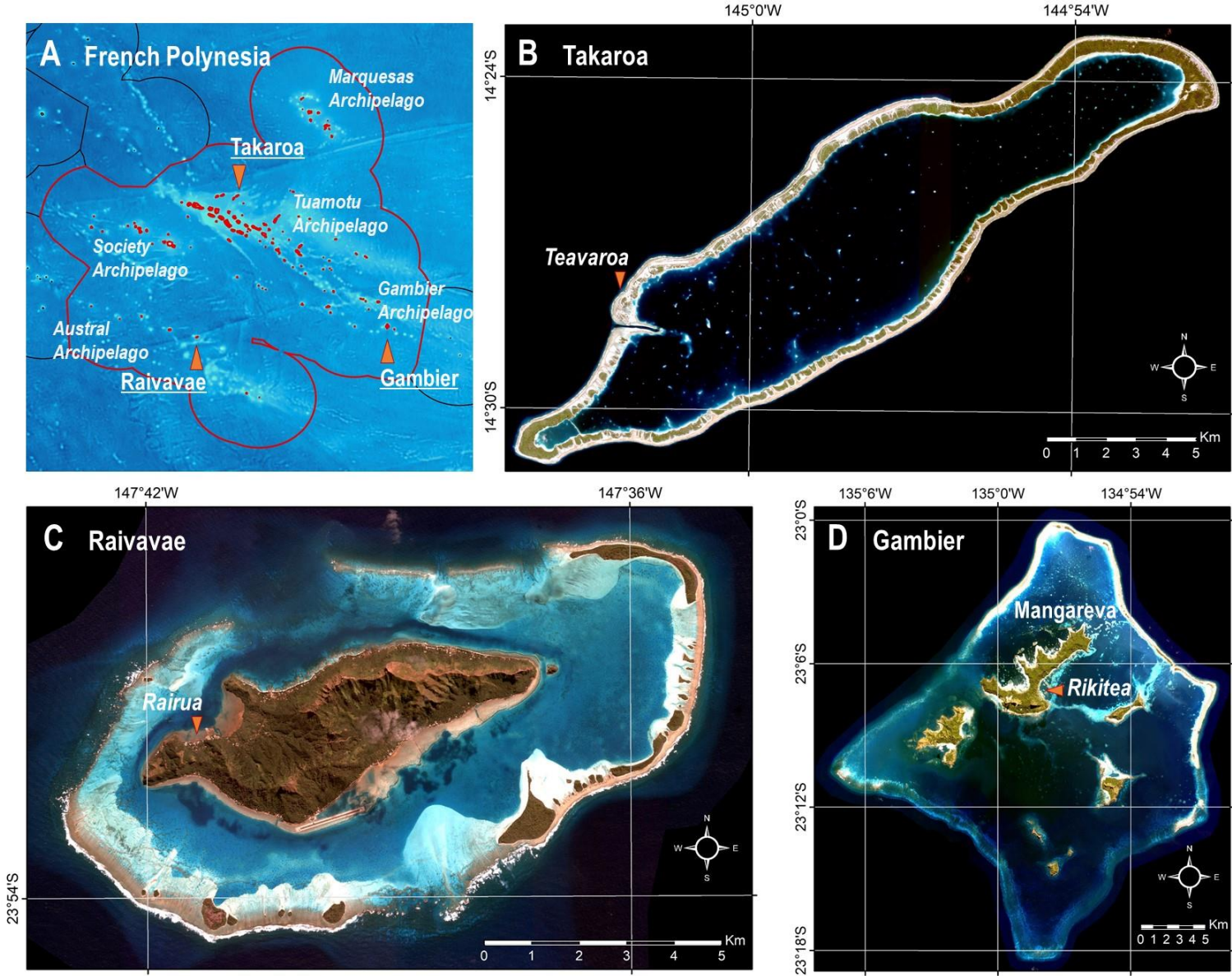


Figure 12. Maps of the study sites. (A) Map of the Economic Exclusive Zone of French Polynesia, location of its five archipelagoes and the three selected study sites. (B) Takarua. (C) Raivavae. (D) Gambier.

### 3 Three contrasted islands in French Polynesia

#### 3.1 Takaroa atoll, in the Tuamotu Archipelago

Takaroa is an atoll located in the Tuamotu Archipelago, at 145°W longitude and 14.27°S latitude (Figure 12B). The atoll rim has an elliptical shape, measuring 26 km long and 3 to 7 km width, enclosing an 85-km<sup>2</sup> lagoon with a mean depth at 25 m and a max depth at 47.5 m. It is located at 590 km from Tahiti and the 900 or so inhabitants, mainly based in Teavaroa village, are connected to the capital by sea freight and by air approximately once a week, with increased frequency during school holidays. In this remote island, pearl oyster farming was virtually the only economic activity, before it collapsed. It had started in the 1970s and Takaroa once was one of the most productive atolls (Andréfouët et al., 2016).

Pearl farming has declined due to successive mass mortality events that were recorded in December 2000, January 2001 (Andréfouët et al., 2015) and especially in 2014, when reared and wild stocks collapsed. The lagoon has been in ‘trophic crisis’ since then and oyster growth and reproduction rates in Takaroa were still very low five years after, despite normal temperatures and availability of abundant food (Monaco et al., 2021). Many farm facilities (buildings on stilts, buoys and lines) remain in stand-by in the lagoon, in the hope of a recovery and the possibility to re-start oyster culture. The few remaining farmers get the juveniles from Takapoto spat collection, the ‘sister island’, which is located 10 km southwestward.

Hypotheses to explain these events include micro-algal blooms and pathogenic infections in relation with meteorological conditions of great calm with high sea surface temperature and low swell (Rodier et al., 2019). This can particularly affect the atolls that are hydrodynamically semi-closed, such as Takaroa and many others in the Tuamotu Archipelago (Andréfouët et al., 2015). Indeed, Takaroa has only one pass and many but shallow *hoa*, which are zones where the atoll rim has a lower elevation and allows tidal and wave-induced flushing from the ocean to the lagoon. Acquiring biophysical data and building hydrodynamic models are necessary to improve our understanding and to help the management of pearl producing lagoons. Regarding these aspects, Takaroa stands among the relatively well studied sites in French Polynesia (Andréfouët and Adjeroud, 2019), and it has been instrumented since 2009 with instrumentation for physical measurements and bathymetric information by single beam echosounder (Le Gendre et al., 2010). As part of the MANA project (2018-2021) and in collaboration with DRM, further instrumentation and modeling has been undertaken.

Due to the drop of pearl oyster industry, fishery and copra (coconut exploitation) are currently the main subsistence activities on the island (ISPF, 2017), which also counts two family-run accommodations for small-scale tourism. The majority of inhabitants practice subsistence fishing and recreational activity (Figure 13).

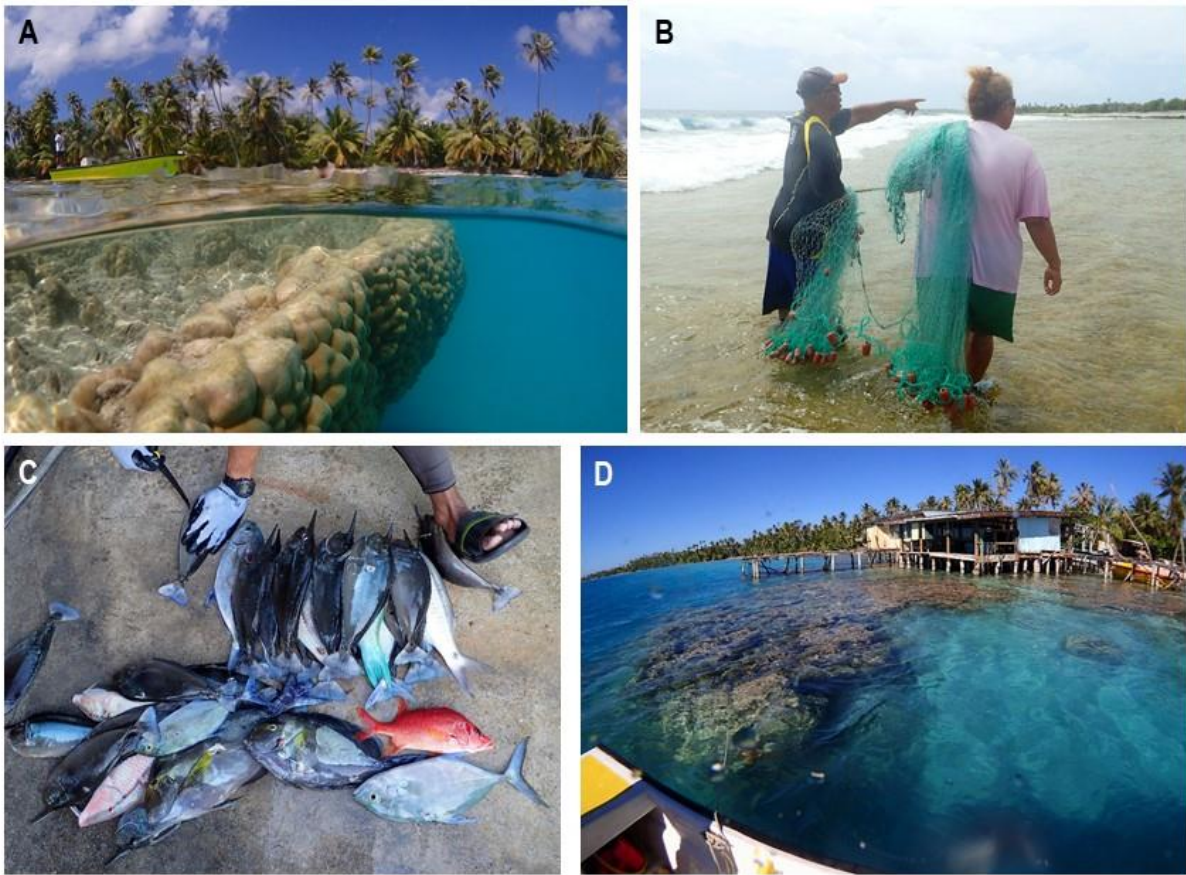


Figure 13. Illustrations of Takarao Atoll.

Different small-scale fishing types and catch (A, B, C) and one of the few active pearl oyster farms in Takarao island (Photos: LVA).

During a 14-day field trip conducted in August 2019 in Takarao, we surveyed 44 fishers by map-based interviews following the methodology described in Chapter 2 (survey model available in Appendix 3). We collected spatialized and quantified information on their fishing grounds, associated annual fishing frequency, gears, mean amount fished in kg and major species commonly caught in each fishing ground. We also compiled local knowledge on ciguatera risk (e.g. poisoning events occurrences, year, locations, fish species involved, etc.) as well as fishing grounds generally avoided by the population.

### 3.2 Raivavae High Island, in the Austral Archipelago

Raivavae is a high island in the Austral Archipelago, located at  $-147.67^{\circ}\text{W}$  longitude and  $-23.87^{\circ}\text{S}$  latitude (Figure 12C). Mount Hiro rises to 437 m. and the 16 km<sup>2</sup> Island is home to 940 inhabitants, and is surrounded by a 86-km<sup>2</sup> lagoon. Raivavae has four districts: Mahanatoa, Anatonu, Vaiuru and Rairua, where the town hall is located. It is situated at 630 km south east from Tahiti and connected to the capital by sea freight and by air approximately twice a week, with increased frequency during school holidays.

Raivavae rural economy includes fine weaving handicrafts and some accommodation structures to host small-scale tourism, and nearly no pearl farming activities. The main pattern is that Islanders rely strongly on local supplies for food, and have maintained a

significant local agriculture and artisanal fishery. Raivavae is one of the last island where traditional pirogues are used daily, with wooden pieces sewn together (Figure 14A). A notable feature of Raivavae fishery is that giant clams account for a substantial part of the fishery, either for local consumption or for export to Tahiti (Kronen et al., 2009) (Figure 14 C, D). Considering the importance of fishery, as a pillar of food security, the main fishers gathered in a fisher committee. In coordination with town and religious representatives, they were preparing a project of rāhui, a traditional rotating reserve, to manage and sustain their resources within the lagoon. However, the design of the rāhui was questioned among the fishers as it was very restrictive – a surface area equivalent to the half of the lagoon, distributed across the four districts. Thus emerged the interest of finding alternative options through a SCP analysis. For this, minimizing the opportunity costs for fishers was primarily needed, but we also wanted to include in the study the ciguatera criterion, an aspect very important to fishers in Raivavae.



Figure 14. Illustrations of Raivavae Island.

(A) Traditional pirogues used for fishing; (B) map-based survey conducted with a fisher on fishing practices and knowledge on ciguatera; (C and D) abundance of giant clam resource in the lagoon and their usual consumption, in Raivavae Island (Photos: LVA and SA (B)).

Indeed, a major ciguatera poisoning event was reported in 2007-2008, which implicated several fish species and also giant clams (Chinain et al., 2010). The situation has remained critical until today, and ciguatera is a serious problem for the islanders. Local knowledge on where and what species are at risk is an important factor in determining the fishing grounds,

based on personal perception and shared information of previous poisoning cases (Chinain et al., 2020). Today, the entire lagoon is theoretically open to fishing, but in practice, some areas are less fished or avoided altogether, and are therefore *de facto* ‘protected’ because of the risk of ciguatera.

To collect fishery and ciguatera information, a 9-day field mission in Raivavae allowed us to survey 59 fishers all around the island, following the same methodology as in Takaroa.

### 3.3 Mangareva Island, in the Gambier archipelago

The Gambier archipelago is composed of several high islands, located at 135°W longitude and 23.20°S latitude (Figure 12D). In this study, the term Gambier designates all the islands located within the same lagoon, thus excluding Maria Est and Marutea Sud atolls, which are also part of the Gambier municipality. Auorotini, or Mount Duff at 441 m. dominates the main village, Rikitea, on the main island, which is Mangareva. Mangareva is 15 km<sup>2</sup> and home to the majority of the 1,430 Gambier inhabitants. A fairly open barrier reef borders a 486-km<sup>2</sup> lagoon, which harbors remarkable habitat diversity and coral communities unique to French Polynesia (Figure 15C). Gambier is separated from Tahiti by 1,650 km and such a distance translates into high transportation and freight costs, either by air or sea.

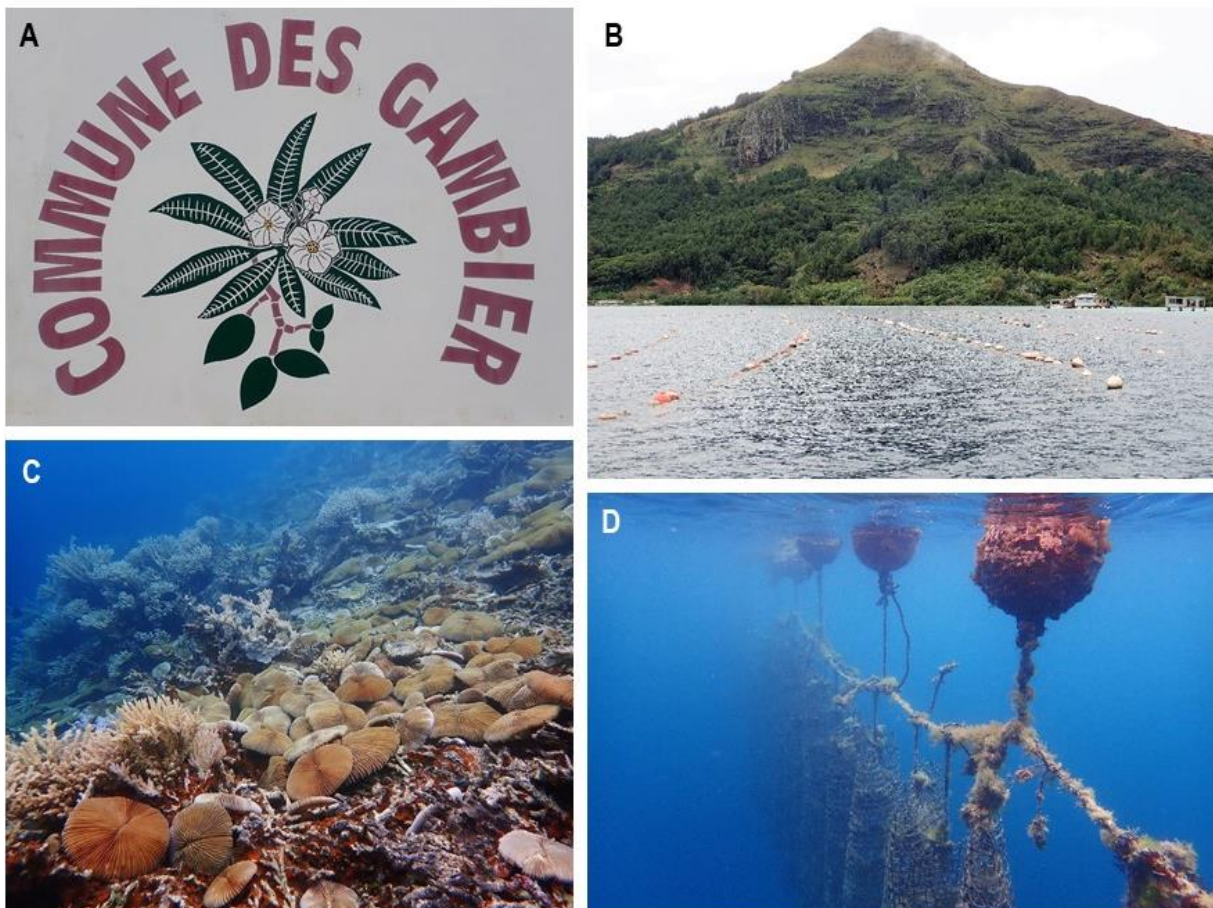


Figure 15. Illustrations of Gambier lagoon.

(A) The Gambier's logo; (B and D) farm concessions of pearl oyster lines with associated baskets of reared oysters, covering important spatial extents in the lagoon near Mangareva Island; (C) the remarkable coral communities, typical of Gambier lagoon (Photos: LVA).

After a period of demographic decrease, Gambier inversed the tendency and became attractive again from the late 1960s due to activities linked to nuclear weapon testing program on the neighboring Island Moruroa.

Pearl oyster farming took off in Gambier lagoon in the 1980s. This activity is now the main driver of the economic dynamism (Figure 15 B, D), and Gambier black pearls are renowned for their colour and luster. With 160 professionals, this sector covers all the farming stages within Gambier lagoon, from spat collection to adult farming, resulting in a production which is autonomous from the other islands (IEOM, 2020). Gambier has several groups of pearl farmers, aiming to coordinate their sales and take common decisions related to farming in the lagoon.

No mass mortality event was recorded in the Gambier lagoon, possibly due to the open nature of the lagoon and a more southern location, resulting in lower sea temperatures than in the Tuamotu region.

Fishing is practiced in Gambier in every households, as in many Pacific Ocean tropical islands as a cultural heritage, recreational activity and for food provision (Bell et al., 2011; André et al., 2021a). However, ciguatera poisoning represents a significant issue in Gambier as well (Chinain et al., 2020), where the causative agent, *Gambierdiscus*, was first discovered back in the early 1970s (Yasumoto et al., 1977). Consequently, local fishers are particularly aware of the risk of ciguatera.

To collect fishery and ciguatera information, the 9-day field trip conducted in Mangareva Island allowed to survey 42 fishers from all around the island. In coordination with DRM to assess the current priorities in terms of pearl farming management, the spatial extent of concessions appeared high. DRM wishes to reduce it and allow more space for other activities, including oyster restocking, fisheries and conservation of the remarkable coral communities.



To summarize, the choice of the three sites was justified regarding their characteristics, how our criteria were fulfilled, and considering their specific management needs that could be addressed using SCP approaches (Table 5).

Table 5. Synopsis of the study sites.

For each site, the corresponding examined criteria, management priorities, research questions and corresponding chapters are presented.

	<b>Raivavae</b>	<b>Takaroa</b>	<b>Gambier</b>
<b>Archipelago</b>	Austral	Tuamotu	Gambier
<b>Geomorphology</b>	High island, shallow lagoon	Atoll	High island, deep lagoon
<b>Economic main activity</b>	Rural	Pearl farming (collapsed)	Pearl farming
<b>Importance of fishery</b>	Very high	Moderate	Moderate
<b>Ciguatera</b>	Very high	Low	Very high
<b>Data availability (cf. Table 4)</b>	High	High	High
<b>Management priorities and questions</b>	Reserve design integrating ciguatera risk along with fishery pressure Rāhui design evaluation before its implementation, taking into account fishery and ciguatera	Identification of sites for oyster restocking, taking into account habitat suitability, larval dispersal, concessions, sunk waste and fishery	Reduction of pearl farming concessions and diversification of the activities
<b>Research questions</b>	Q0, Q1, Q3	Q0, Q2	Q0, Q2, Q3, Q4
<b>Chapters</b>	Chapters 2 and 4	Chapter 3	Chapter 5

## Chapter II – Ciguatera risk



## Chapter II – Ciguatera risk

### A framework for mapping local knowledge on ciguatera and artisanal fisheries to inform systematic conservation planning

Laure Vaitiare André <sup>1,2</sup>, Simon Van Wynsberge <sup>3</sup>, Mireille Chinain <sup>4</sup>, Clémence Mahana iti Gatti <sup>4</sup>, Alexandra Dempsey <sup>5</sup>, Serge Andréfouët <sup>1</sup>

1 IRD Institut de Recherche pour le Développement – France, UMR 9220 Entropie (Institut de Recherche pour le Développement – France, Université de la Réunion, Université de la Nouvelle-Calédonie, Ifremer, Centre National de la Recherche Scientifique), BP A5, 98848 Nouméa cedex, New Caledonia

2 SU Sorbonne Université, 21, rue de l'école de médecine, 75006 Paris, France

3 Ifremer Institut Français de Recherche pour l'Exploitation de la Mer, UMR 9220 Entropie (Institut de Recherche pour le Développement – France, Université de la Réunion, Université de la Nouvelle-Calédonie, Ifremer, Centre National de la Recherche Scientifique), BP A5, 98848 Nouméa cedex, New Caledonia

4 ILM Institut Louis Malardé, Laboratoire des Biotoxines Marines, UMR 241 EIO (Ifremer, Institut Louis Malardé, Institut de Recherche pour le Développement, Université de la Polynésie française), BP 30, 98713 Papeete, Tahiti, French Polynesia

5 KSLOF Khaled bin Sultan Living Oceans Foundation, 821 Chesapeake Avenue #3568, Annapolis, MD 21403, USA

#### Published in ICES Journal of Marine Science

André, L. V, Van Wynsberge, S., Chinain, M., Gatti, C. M. I., Dempsey, A., and Andréfouët, S. A. 2021. framework for mapping local knowledge on ciguatera and artisanal fisheries to inform systematic conservation planning. – ICES Journal of Marine Science, doi:10.1093/icesjms/fsab016

**Abstract**

Millions of people's livelihoods rely on artisanal fisheries. However, in many regions fishers are increasingly facing ciguatera poisoning, a seafood-borne illness. The toxin, produced by benthic dinoflagellates, can spread through marine food webs and to humans by direct consumption. Ciguatera risk can play a major role in fisher's activities but has never been considered in any marine spatial plans thus far. To fill this gap, we examined if integrating ciguatera in systematic conservation plans could affect these decisions. We developed through map-based interviews, a novel seven-step framework to collect and map local knowledge on ciguatera risk and fisheries activities with two innovations: (i) better mapping of fishing grounds by combining geomorphological habitat and fishing gear information, and (ii) integrating ciguatera risk directly into systematic spatial planning designs and scenarios conceived to maximize benthic habitat conservation while minimizing impacts to fishers. The approach is illustrated for Raivavae Island, in French Polynesia, Pacific Ocean. We found that integrating ciguatera zones significantly improved prioritization solutions with a 24–38% decrease of costs to fishers compared to scenarios based solely on fishery data. This framework was designed for scientists and managers to optimize the implementation of conservation plans and could be generalized to ciguatera-prone areas.

**Keywords**

Marine Biotoxins, Small-Scale Fisheries, Marine Protected Area, Raivavae Island, French Polynesia, Marxan.

## 1 Introduction

Ciguatera poisoning is the most prevalent, phycotoxin-related seafood poisoning worldwide. It affects an estimated 10,000 to 50,000 people annually (Friedman *et al.*, 2008) and thus represents a major threat to many fisheries and consumers. Originally limited to tropical and inter-tropical regions of the world such as the Pacific Ocean, Caribbean Sea and Indian Ocean, a geographic extension of ciguatera outbreaks to temperate areas has been observed since 2000, which could be explained by climate change (Friedman *et al.*, 2017), as well as the expansion of travel, tourism, and increased importation of fish from endemic regions. Ciguatera originates from marine biotoxins, namely ciguatoxins, produced by dinoflagellates microalgae in the genera *Gambierdiscus* and *Fukuyoa* (Chinain *et al.*, 2020). These microalgae develop on dead corals colonized by macro-algae, which are grazed upon by herbivorous fish or various marine invertebrates (Darius *et al.*, 2018). Ciguatoxins further accumulate in marine organisms' tissues all along the food web, thus rendering catches unsuitable for consumption, causing a combination of gastro-intestinal, cardiovascular and neurological symptoms (Gatti *et al.*, 2008). In ciguatera-endemic areas where inhabitants rely heavily on local marine resources for their subsistence, ciguatera outbreaks such as in Raivavae Island, (Chinain *et al.*, 2010), or Rapa (Iti) Island (Chinain *et al.*, 2020), French Polynesia, can significantly impact the small local economy by the cost of the illness (Morin *et al.* 2016; Rongo and van Woesik 2012), loss of a food sources, decrease of professional fishers revenues and slowdown in tourism and recreational activities. It also carries major health risk, compelling inhabitants to modify their dietary patterns, as shown by the progressive shift from high-nutritional value food resources towards less healthy products such as imported and/or canned products, with the risk of increasing sugar and fat intake (Lewis and Ruff, 1993).

Ciguatera risk is often limited to localized, specific areas and, when known, they are avoided as much as possible by fishers. In the tropical islands and coastal regions where it occurs, artisanal fishers have to deal with this constraint, relying on their knowledge and experience to develop ciguatera avoidance strategies (Chinain *et al.*, 2010; Friedman *et al.*, 2017). Local knowledge is increasingly recognized as a reliable source of information for scientific studies as well as for environmental management and conservation (Ban *et al.*, 2009; Green *et al.*, 2009). Owing to its impacts on artisanal fisheries and affected communities livelihoods, it can be useful to integrate ciguatera local knowledge into marine spatial planning decisions as ciguatera risk significantly reduces the spatial extent of safe fishing grounds for fishers. Hereafter, we develop this idea within the context of systematic conservation planning (SCP).

SCP has been initially developed to identify areas that meet predefined conservation objectives while minimizing the induced constraints for society (Margules and Pressey, 2000; Moilanen *et al.*, 2009; Pressey and Bottril, 2009). This domain has since extended beyond the only aspect of identifying protected areas while minimizing constraints (Kukkala and Moilanen, 2013), but this concept remains central to SCP. This approach relies on optimization algorithms to find the best solutions in the spatial domain at stake. Conservation objectives often focus on biodiversity representation and rely on proxies such as habitat maps or abundance of selected taxa. Constraints to minimize are often measured through opportunity costs (Naidoo *et al.*, 2006). In a marine realm, opportunity costs to fishers are often used. These costs translate the loss of access to fishing grounds selected for conservation and closed to extractive activities.

Many marine SCP examples have emerged in the past decade, using simple to complex scenarios in terms of scales, objectives and cost functions (Ban and Klein, 2009; Magris *et al.*, 2014; Álvarez-Romero *et al.*, 2018, André *et al.*, 2021).

In marine tropical regions, insular and coastal ecosystems often include coral reefs, which are remarkable reservoirs of biodiversity providing valuable ecosystem services for coastal or insular communities (in Oceania, see Payri and Vidal, 2019). Often, biodiversity conservation plans are in conflict with human activities, and SCP is increasingly used in these conflicting areas to help finding solutions. However, accessing accurate and reliable data represents a true challenge for SCP, particularly on opportunity costs to fishers (Ban *et al.*, 2009; Deas *et al.*, 2014, André *et al.*, 2021). Indeed, apart from some exceptions, there is a substantial lack of available and updated knowledge on artisanal fisheries worldwide (Jacquet and Pauly, 2008; FAO, 2018) despite they directly employ and support food security for millions of people (FAO, 2017). For example, in Oceania, the PROCFish program (<https://coastfish.spc.int/en/projects/procfish>) collected consequent data on coastal fisheries, but these are now 15 years old or more (Kronen *et al.*, 2009) and have not been updated since. Coral reef fishery data are also virtually never spatially-explicit (see for instance Cinner *et al.*, 2009), and few examples of fishery atlases can be pointed out, such as the non-professional lagoon fishery atlas for the North of New Caledonia (Guillemot and Léopold, 2010). Proxies can be used instead of fishery data (Mills *et al.*, 2010; Weeks *et al.*, 2010), but the use of an inadequate proxy can considerably bias planning scenario outcomes (Deas *et al.*, 2014).

Updated and reliable information can be acquired from fishers' interviews (Wendt *et al.*, 2016; Aylesworth *et al.*, 2017), providing values of catch and data to characterize fisheries (McCluskey and Lewison, 2008). To promote accurate spatial data acquisition on catches directly from fishers, a first step by step protocol to integrate local knowledge into a spatial reference using a Geographic Information System (GIS) was proposed by Close and Hall (2006). On this basis, Léopold *et al.* (2014) proposed a five-step framework to define a stratified random sampling of coastal regular fishers, conduct map-based interviews, integrate the collected information into GIS layers, make statistical extrapolation of fisher data to the fishery scale and map catch, effort and catch per unit effort. This information allows describing spatially catch, gear, effort and fishing grounds. However, that framework did not include the collection of other forms of related environmental knowledge, such as ciguatera, and it was not specifically thought to be an integral part of a SCP project. To fill these gaps, and include for the first time ciguatera, we built upon Léopold *et al.* (2014) and provide a new formalized framework including seven steps, which altogether also provide a method to foster systematic conservation planning projects in a more integrated fashion. Compared to Léopold *et al.* (2014), we aim to focus on three major improvements. First, along with fisheries information, we collected ciguatera local knowledge through map-based interviews with precision on the nature of the risk: suspected *vs* proven ciguatera risk. Second, we refined the mapping of the fishing activity by using habitat maps that indirectly inform on where the different fishing gears can be practically used (Okada *et al.*, 2005). Third, we built a function of cost that modulates opportunity cost to fishers according to ciguatera risk, for SCP applications. The benefit of using this cost function is demonstrated for a French Polynesian island affected by ciguatera and where artisanal fishing is extensive. Through the SCP scenarios, a sensitivity analysis was carried out for different values of conservation targets (representing habitat

diversity) and for different levels of importance allocated to the ciguatera risk in the fishing activity. Finally, we discussed the implications of our findings for planning approaches in the context of artisanal fisheries exposed to ciguatera.

## 2 Material and Methods

### 2.1 Study area

The study was performed in French Polynesia in the South Central Pacific Ocean. We focused on Raivavae Island ( $23^{\circ}50'S$ ,  $140^{\circ}40'W$ ) located in The Austral Archipelago, 710 km south of Tahiti (Figure 16a). This 15 km<sup>2</sup> high island of volcanic origin is home to 903 inhabitants, 255 households (census 2017) (ISPF, 2020), mainly settled along the shore. Raivavae has a 86 km<sup>2</sup> reef and lagoon system, with fringing reefs, a lagoon with shallow flats, and a barrier reef delimited by reef crests and the oceanic reef slope. The barrier reef is punctuated by a number of *motu* (reef islands) and by one main pass and two small passes (Figure 16b). Islanders' livelihood mainly relies on artisanal fisheries, traditional agriculture and handicraft (Kronen *et al.*, 2009).

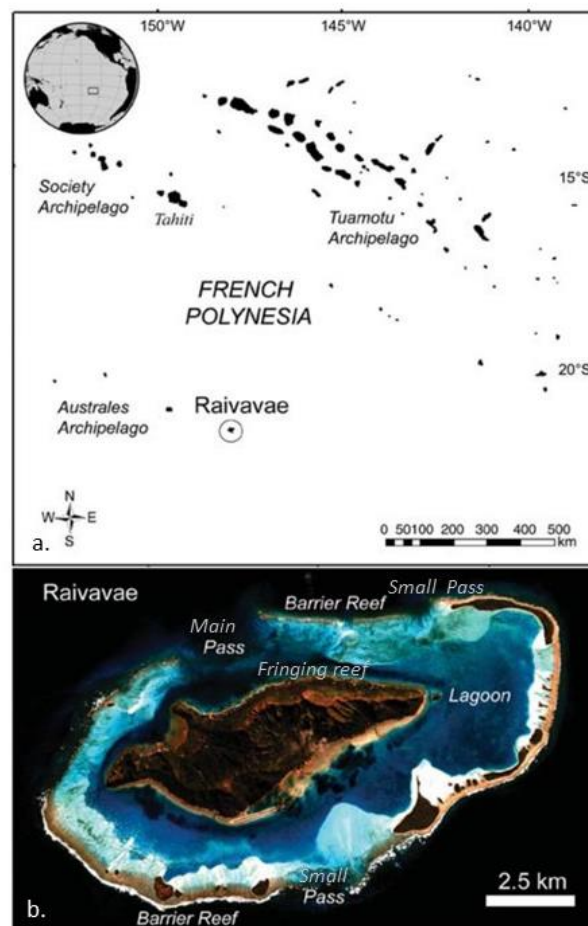


Figure 16. a. Location of Raivavae in French Polynesia; b. Satellite view of Raivavae Island with the main features (from Andréfouët *et al.*, 2009).

Raivavae marine resources were previously studied three times, due to the especially active reef-fisheries of this island. It was first surveyed by the reef fishery ProcFish program in 2004. The survey draws out high abundances of finfish and invertebrates, especially giant clams (Kronen *et al.*, 2009). Second, the giant clam stocks were also specifically surveyed and quantified twice, in 2005 and 2010 (Andréfouët *et al.*, 2009, Van Wynsberge *et al.*, 2013).

Raivavae was affected in 2007-2008 by a major ciguatera poisoning outbreak. The Raivavae lagoon was studied to characterize both the distribution and abundance of *Gambierdiscus* spp. populations and the toxic status of a variety of finfish species highly prized by the local community (Chinain *et al.*, 2010). Since then, ciguatera has been a major concern for the population, with numerous cases of poisoning, including also from giant clams (Laurent *et al.*, 2012).

## 2.2 The seven-step framework

We developed a seven-step framework for mapping artisanal fisheries and ciguatera risk based on fishers' knowledge and to inform SCP projects. The framework builds on Léopold *et al.* (2014) but includes several novelties which are highlighted throughout. For clarity sake, we describe hereafter, within the framework, some aspects that are specific to Raivavae Island (e.g., types of fishing gears) and could differ elsewhere.

### Interview ethics

Data collection, storage and process were conducted following the European Data Protection Regulation (GDPR) guidelines (European Union, 2016). Participants were previously informed of the aims of the study, their rights regarding data modification, possibility to further retract from the study, then, were invited to sign a consent form. To ensure they remained anonymous, a survey number was assigned to each participant at the beginning of the interview. All interviews were voluntary, without rewards.

### Step 1. Sampling design and data collection

#### Sampling unit

For the framework to be adapted to artisanal fisheries, we considered individual fishers as the relevant sampling unit instead of outboard powered vessels as in some studies (e.g., Léopold *et al.* 2014). Artisanal fishers in Raivavae, like in most Oceania islands, do not always have powered means of transportation, which can be multiple (e.g. use of *va'a*, which is the traditional outrigger, kayak, shore fishing, or snorkelling from the shore).

#### Sampling strategy

Priority when sampling was given to key informants identified as the most productive fishers, by reputation. To identify these fishers we relied on (i) the fishers themselves, who could point to individuals known to be productive fishers, (ii) the townhall staff, (iii) via randomly interviewing people met in public places such as the townhall, public square, churches, main or secondary roads and, when presents, wharfs and fish markets. We also paid attention to interview fishers representing the different villages all around the island, as a geographic representation criteria.



### Interviews duration

We followed practical recommendations of Close and Hall (2006). Questionnaires, in French, (Appendix 3) were kept as brief as possible, while still including a minimum of crossed questions to cross-check answers, and lasted between 30min and 1h30min, depending on the reactivity of fishers and the diversity of their fishing practices. Interviews were conducted in French, or in local Raivavae dialect with the help of an interpreter.

### Description of the fishery

Open-ended and structured questions were used (e.g., Aswani and Hamilton, 2004) to identify the diversity of fisheries conducted by the fisher and collect qualitative and quantitative data on each of them. For each fisher, the diversity of fishery activity was defined by (i) fishing purposes (i.e., self-consumption at the household level, or for sale or gift to local *vs* remote residents); (ii) fishing location; (iii) fishing gears; (iv) means of transportations; (v) fishing frequency; and (vi) species, size and volume usually harvested. Fishers declared the average perceived catch per unit fishing trip. About the species caught, vernacular names referring to monophyletic or polyphyletic taxonomic groups were collected and the species were identified during the interview, with reference to taxonomy (Bacchet *et al.*, 2010).

To facilitate comparison with other sites, we also characterized the Raivavae fishery using the FAO matrix scoring method. This method was developed as a Sustainable Development Goal 14 Indicator, to enhance policy and management, and to promote knowledge about small-scale fisheries. This matrix uses 13 characteristics related to fishing (vessel, gear, storage, crew, time commitment, etc.), each one having four description levels and a score from 0 to 3. Aggregate score characterizes the fishing unit from small-scale to industrial (aggregated score between 0 and 39) (FAO CWP Secretariat, 2019; Savoré, 2019).

### Fishery grounds

A base map was designed following Close and Hall (2006) recommendations, and adapted to highlight optimally the different types of reefs (fringing, patch, barrier reef, pass). A true-color view of a Quickbird satellite image of the whole island (see Figure 16b) was printed on A1 format (1:15.000<sup>e</sup> scale) (S1b), including relevant points of reference and localities name. Enlargements were also printed for some portions of the island such as the village surroundings, for specific reefs and for the pass. The prints were laminated to allow drawing on them with whiteboard markers and wiping off the information after each interview.

Fishers were asked to delineate the different places where they fished, one by one, on the map. For each place, fishers were asked to describe the corresponding fishing activity (gear, frequency, species targeted, *etc.*), for which a unique code was assigned. For a given fishing activity, a fisher would often visit multiple places, corresponding to multiple fishing activity polygons. These were grouped under the same code corresponding to a unique fishing zone. All fishing polygons drawn by one fisher correspond to this fisher's fishing ground. All fishing polygons drawn by all fishers correspond to the island fishing grounds (Figure 17). After each interview, the resulting map of the informant was photographed and archived.

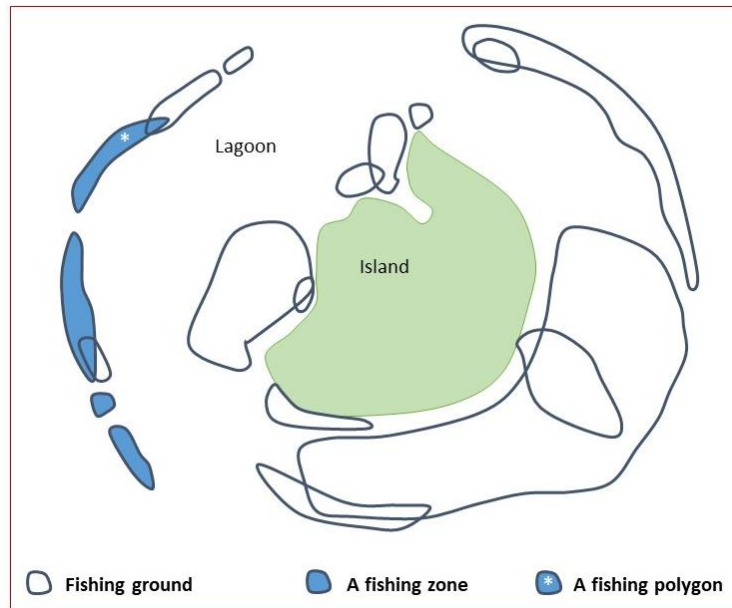


Figure 17. Illustrated definition of fishing polygon, fishing zone and fishing ground.

“Fishing ground” refers to all the places where a given fisher goes fishing. A “fishing zone” refers to the place(s) of a unique fishing activity, characterized by one gear, type of species caught, mean weight of catch, and frequency. If the fishing zone is composed of multiple places, each place corresponds to a “fishing polygon”.

### Fishery temporality

To gather information on fishing productivity on a yearly basis, we asked about frequency of each fishing activity. We partly followed the recall technique through short-term memory (Brennan *et al.*, 1996). The first questions concerned the most recent fishing trip and the usual frequency of each fishing activity. Then, we used the map as a base to identify additional fishing zones and detail each fishing activity, going back in time. Lastly, we used cross-checked questions about fishing habits and temporalities per week and/or per month, by season and all year round.

### Description of ciguatera

After assuring that each informant interviewed knew what ciguatera was, they were invited to provide the following information: (i) did anyone (himself or among close relatives) had already been affected by ciguatera poisoning? If yes, when did it happen? Where was the fishing area? Which species was involved and at what size? (ii) Nowadays, are there areas where he/she avoids to fish because of the ciguatera risk? These information were used to characterize sites with (i) “proven” and (ii) “suspected” ciguatera risk, respectively.

### Ciguatera spatial domains

On the map previously used to collect fishery information, fishers were asked to indicate with a red marker the “proven” or “suspected” ciguatera risk zones. Each ciguatera zone was assigned a specific code.

### Representativeness of the sampling effort

The representativeness of the sampling effort was checked by plotting the cumulated total areal cover of fishing grounds as a function of the number of interviews performed. The accumulation curve was expected to be asymptotic if the sampling was adequate, with new interviews providing only negligible extension of the fishing grounds. This exercise was performed for all fishing activities confounded.

### Step 2. Integration of fisher's knowledge into a geodatabase

After all questionnaires were completed for each fishing activity, the quantitative and qualitative information was homogenized to exhaustively render the modalities of each described fishing gear (similar gears collated under the same generic name), fishing effort frequency (homogenization to the same unit of time), weight of catch per fishing trip (homogenization to the same unit of weight), scientific and local species names (homogenization to a unique designation for each species or group of species). For group fishing sessions, we divided the total catch between the numbers of participants and considered these values as attributes of each fishing zone.

For each fisher, each fishing polygon as it was drawn on the map by the fisher, was digitized into GIS vector polygons, using as a background the same satellite image used as prints for the surveys (S1b).

Eventually, each digitized fishing zone was systematically associated with:

- a fishing gear;
- an annual fishing effort  $f_z$  (number of fishing trip per year per fisher per fishing zone);
- a CPUE (catch per unit effort, expressed in kg per fishing trip per fisher per fishing zone);
- a list of species caught (or group of species).

To estimate the annual catch per fishing zone per fisher ( $c_z$ ), we used the homogenized descriptors of annual fishing effort  $f_z$  and CPUE [Equation (1)].

$$c_z = f_z * CPUE \quad (1)$$

Note that  $c_z$  usually referred to a group of several species rather than to species-specific catches.

### Step 3. Refinement of fishing polygons using reef geomorphology information

This step is an addition to the Léopold *et al.* (2014) framework.

Each fishing gear is typically used in some specific types of environments. For instance, harpoons thrown by hand (or *pātia*) are used in shallow water when walking along the shallowest parts of the reefs. However, areas drawn by fishers on the printed map were generally coarsely delineated and inclusive of environments where the mentioned fishing gear would unlikely be used (such as deep areas for the aforementioned *pātia*). Therefore, to define a plausible environment for each fishing gear, the outline of each polygon was refined using a

geomorphological map (Figure 18). In Raivavae, such map was available (Andréfouët *et al.*, 2009). It describes shallow *vs* deep areas, and the main reef types (fringing, barrier, patch) and their different geomorphological units (reef flats, slopes, etc.). A correspondence between each fishing gear and the different geomorphological units was generated (Table 6) and used to refine each fishing polygon based on its intersection with each of the relevant geomorphological unit.

Table 6. Correspondence between fishing gears and geomorphological strata.

Pana is a spike used to extract giant clams. Pātia is a hand harpoon. Line: nylon in hand or downrigger. Hand harvest is mainly for lobsters. Auihopu is a specific tool to catch octopus. The geomorphological strata are located on the habitat map of Raivavae (Figure 18).

Gears	Geomorphological strata								
	Forereef	Crest	<i>Motu</i> reef flat	Backreef	Hard ground on sediment ary terrace	Lagoon	Patch reef	Deep patch reef	Fringin g reef
Spear gun	X			X	X	X	X	X	X
<i>Pana</i>	X	X	X	X	X	X	X	X	X
<i>Pātia</i>		X	X	X	X				X
Line	X			X	X	X	X	X	X
Gillnet	X	X	X	X	X	X	X	X	X
Hand harvest		X	X	X	X		X		X
<i>Auihopu</i>	X	X	X	X	X	X	X	X	X

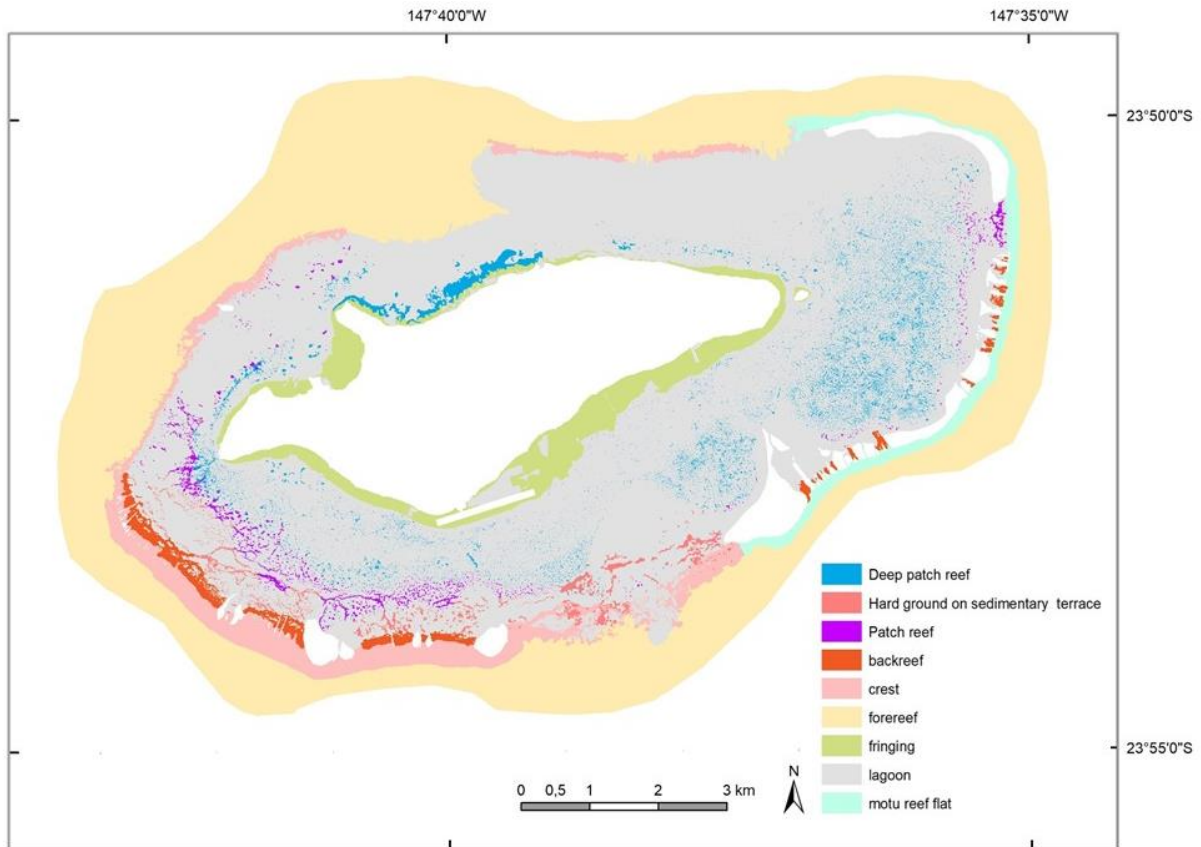


Figure 18. Location of the different geomorphological strata, on Raivavae Island (geomorphological habitat map consistent with the Coral Reef Millennium Mapping Project, Andréfouët et al., 2006), applied to refine fishing zones according to the fishing gear used (Table 6).

To practically refine fishing zones according to the geomorphological strata relevant to each fishing gear in a time-effective way, all the fishing polygons drawn by the fishers were merged by fishing gear, allowing to produce one map for each fishing gear. Then, these maps were intersected by the corresponding geomorphological maps with a GIS tool, resulting in new sets of polygons with more accurate contours ( $S_p$ ) (Figure 19).

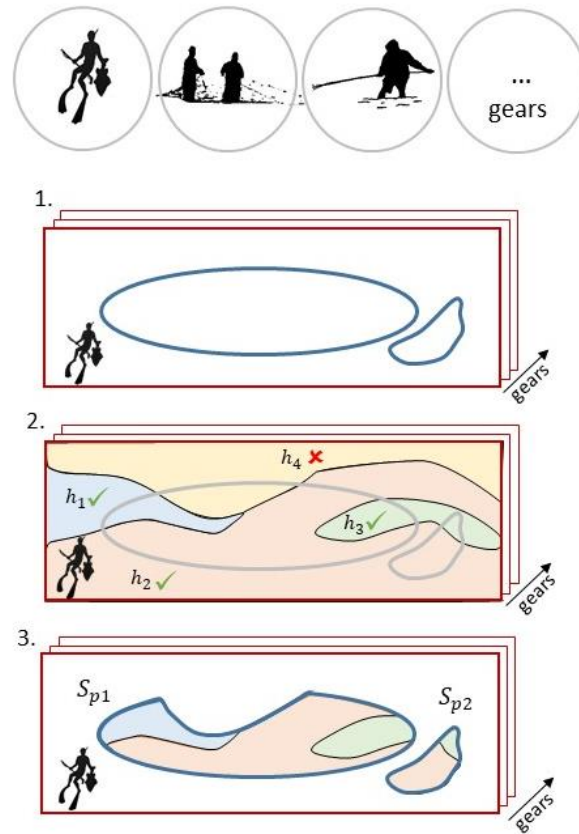


Figure 19. Procedure to refine fishing polygons according to geomorphological strata.

1. All fishing polygons were grouped by fishing gear (ex. spear gun), to produce a single map for each fishing gear. 2. For each fishing gear, the corresponding geomorphological strata were selected. 3. These were intersected with the fishing gear map to produce more accurate fishing grounds. In this example, strata  $h_1$  to  $h_3$  were relevant to spear gun while stratum  $h_4$  was not.

To estimate the annual catch per refined fishing polygon  $p$  ( $c_p$ ) from the annual catch per fishing zone ( $c_z$ ), the later was weighted by the proportion of the fishing zone's area ( $S_z$ ) corresponding to the refined polygon  $p$  ( $S_p$ ) [Equation (2)].

$$c_p = c_z * \frac{S_p}{S_z} \quad (2)$$

### Step 4: Integration of fisher's knowledge about ciguatera into a geodatabase

This step is an addition to the Léopold *et al.* (2014) framework.

For each fisher providing spatial information on ciguatera, each zone was digitized into GIS polygons  $S_c$ , similarly to the fishing zones. Each ciguatera polygon was systematically characterized by the type of risk, which was either:

- proven risk, described by the species responsible for a reported human poisoning event, and date of poisoning;
- suspected risk, a zone currently avoided due to habit or hearsay.

To produce a single ciguatera map, we integrated these information into a single layer, applying different coefficients, depending on the relative importance/potential impact on fishers' practices, and to take into account the potential temporal variability of ciguatera (Table 7). These coefficients yielded a quantitative risk  $r_p$  value for each polygon.

Table 7. Coefficients of risk ( $r_p$ ) attributed to ciguatera zones, depending on their types.

Type of ciguatera zone	$r_p$
Proven poisoning 0-5 years ago	10
Proven poisoning 6-10 years ago	5
Proven poisoning 11+ years ago	2
Suspected risk, currently avoided zone	1

### Step 5. Planning unit overlay procedure for fisheries

Numerous fishing activity polygons can overlap. To produce a comprehensive map of the summed fisheries, the refined fishing polygon layers were overlaid with a grid of hexagonal cells following the GIS procedure of Goñi *et al.* (2008), also followed by Léopold *et al.* (2014). Within a SCP project, these hexagonal cells are called planning units (PUs). The PU size should be chosen in light of the fishing polygons size, ideally to best represent the data spatial variation (Van Wynsberge *et al.* 2015). In Raivavae, an adequate PU was 1 km<sup>2</sup> size and of hexagonal shape. The reef and lagoon domain was covered by 111 PUs, some being clipped to follow the outer habitats and land limits. When these clipped PUs were smaller than 0.1 km<sup>2</sup>, they were merged to the neighbouring one sharing the longest boundary length.

For each fishing gear, the values of annual catch ( $c_p$  from Eq. (2)) for each refined fishing polygon ( $S_p$ ) were assigned to PUs ( $k$ ), proportionally to their surface area intersecting each PU ( $S_{p,k}$ ) [Equation (3)].

$$c_{p,k} = c_p * \frac{S_{p,k}}{S_p} \quad (3)$$

The within-PU estimates of annual catch were then summed among all the resulting fractions of polygons to obtain the value of total annual catch for each PU ( $c_k$ ) [Equation (4)].

$$c_k = \sum_p c_{p,k} \quad (4)$$

Adapting Léopold *et al.* (2014) methodology and following Walters (2003)'s recommendations, the spatial estimates of annual catch in each PU were expressed per unit surface area (km<sup>2</sup>) on the basis of the PU surface area, producing an index of catch per unit of surface area ( $c_k = \text{CaPUS index, in kg}\cdot\text{km}^{-2}\cdot\text{y}^{-1}$ ). This resulting index can then be used as a value to estimate the spatial opportunity cost to fishers.

### Step 6. Planning unit overlay procedure for ciguatera

Regarding ciguatera, we considered that the risk was not a function of the proportion of the polygon surface area intersecting the PUs defined at the previous steps. As a ciguatera polygon could either be very small, encircled by fishers with precise memory of the place where the toxic fish was captured, or quite large by others, we generalized the spatial information by spreading the risk to the whole PU. The risk  $r_p$  attributed to each polygon was then directly assigned to the intersecting PU(s)  $r_{p,k}$  [Equation (5)]. The within-PU estimate of ciguatera risk was then summed among each PU to obtain  $r_k$ , the ciguatera risk per unit of surface area ( $r_k = \text{CiPUS index of relative ciguatera risk}\cdot\text{km}^{-2}$ ) [Equation (6)].

$$r_{p,k} = r_p \quad (5) \quad r_k = \sum_p r_{p,k} \quad (6)$$

### Step 7. Conservation scenarios based on habitats, fisheries and ciguatera information

The final step of the framework consisted in establishing a conservation scenario using SCP principles with the collected information. Specifically, we assessed the interest of integrating fisher's knowledge and ciguatera risk spatial data, based on the hypothesis that ciguatera zones were known and avoided by fishers, and consequently were characterized by a lower cost of conservation than fished zones. To demonstrate the importance of taking into account ciguatera risk in SCP, we also compared the spatial distribution of the conservation solutions between scenarios with and without ciguatera. Systematic Conservation Planning scenarios were run with Marxan software, which is intended to deliver decision support for reserve system design (Possingham *et al.*, 2000). Marxan considers a series of planning units for the domain of interest, each one being assigned a value in terms of conservation objective (e.g., representation of biodiversity) and socio-economic cost (e.g., opportunity cost to fishers). In this study, we used the diversity of habitats as a conservation objective, considering habitats as proxies of the biodiversity they host. A quantitative objective (target) must be set, along with a number of parameters such as the compactness of the network. Marxan implements an algorithm with a given number of repetitions to solve the problem and find prioritization solutions, which are a series of planning units that altogether will meet the objective at the lowest possible cost. Marxan provides two types of outputs. First, the *best solution* is the network that provides best compromise between objective met and cost of conservation.



Second, a *selection frequency* of each planning unit, which describes how frequently a planning unit is included in the solution for the given number of repetitions. The most frequently selected planning units are generally prioritised in a conservation network if the best solution is not kept for some reasons.

The scenarios included:

- conservation objectives that should include 10%, 20% and 30% of the area of each mapped habitats, using this time a detailed habitat map from Purkis *et al.* (2019). This Raivavae habitat map included 21 habitats defined by their geomorphologic and benthic attributes. These levels of target were chosen as they are commonly used in SCP conservation scenario and can refer to international guidelines (e.g., see Gairin and Andréfouët, 2020).
- spatially explicit cost, integrating a combination of fishery and ciguatera knowledge, as described above.

To parameterize the costs while integrating the ciguatera risk, we stated that opportunity costs to fishers were modulated by the ciguatera risk. We built a cost function using the CaPUS and CiPUS factors calculated above [Eqs. (4) and (6)]. CiPUS values were log-transformed to lessen the effects of high values. The terms were also normalized, to bring the values to a common scale. To test the sensitivity of this new cost function to the ciguatera parameter, we used a coefficient  $a$  to represent the importance of ciguatera relative to the fishing activity factor. We tested three values for  $a$  (0, 0.5 and 1; [Eq. (7)]), respectively generating scenarios with three different cost factors: (i) only opportunity cost to fishers (no ciguatera), (ii) opportunity cost to fishers modulated by half weight ciguatera, and (iii) opportunity cost to fishers equally modulated by ciguatera. The bar above the terms in [Eq. (7)] refers to the normalisation of terms by their maximal value.

$$\text{cost factor} = \frac{\overline{\text{CaPUS}} + a \times (1 - \overline{\text{Log}(1 + \text{CiPUS})})}{\overline{\text{CaPUS}}} \quad \text{with} \quad a = \{0; 0.5; 1\} \quad (7)$$

As for Marxan settings, in order to avoid the introduction of other factors of variation, BLM (Boundary Length Modifier, the compactness parameter) was set at 0, and SPF (Species Penalty Factor, a penalizing parameter if the objective is not met) was set at fixed values for all scenarios, and calibrated for the most constraining scenario (Scenario 7, Table 8). Therefore, any variation would only be due to either the change of type of costs or the change of the value of the target. Calibration of SPF was done following the suggested procedure from Ardron *et al.* (2010). Number of repetitions was set to 1000 to avoid local minima while keeping a reasonable calculation time. Table 8 summarizes the different scenarios applied.

Table 8. List of scenarios implemented to test the effect of ciguatera in conservation plans, with different values of the ciguatera coefficient  $a$ , in the cost function.

Scenario	Target	$a$	
Sc 1	10%	0	(Fisheries only)
Sc 2	10%	0.5	(Fisheries and $\frac{1}{2}$ ciguatera)
Sc 3	10%	1	(Fisheries and ciguatera)
Sc 4	20%	0	(Fisheries only)
Sc 5	20%	0.5	(Fisheries and $\frac{1}{2}$ ciguatera)
Sc 6	20%	1	(Fisheries and ciguatera)
Sc 7	30%	0	(Fisheries only)
Sc 8	30%	0.5	(Fisheries and $\frac{1}{2}$ ciguatera)
Sc 9	30%	1	(Fisheries and ciguatera)

The importance of taking into account ciguatera risk in SCP was tested on the basis of two criteria. First, for each target (i.e., 10%; 20%; or 30%), a Chi-square test was computed to compare the spatial distribution of the selection frequencies of prioritized PUs between each of the different scenario ( $a = 0$ ;  $a = 0.5$ ;  $a = 1$  in [Eq. (7)]). Second, to assess the effectiveness of these cost factors, the same approach as Weeks *et al.* (2010) was followed. Considering the cost that takes ciguatera risk into account ( $a = 1$  in [Eq. (7)]) as the “true” cost of planning units, we assessed the differences of true costs between (i) the best solution networks from scenarios based only on fishery opportunity costs and (ii) scenarios based on fishery and ciguatera costs. This was done for the three levels of conservation targets (Table 9).

Table 9. Comparison of the costs for fishers

(cost based on fishery cost and ciguatera risk) of SCP best solution networks from scenarios that did not take ciguatera into account ( $a=0$ ), versus those that took ciguatera into account ( $a=1$ ). In bracket is the relative difference of cost between scenario with ciguatera and without ciguatera.

SCP Scenario	Cost for fishers
<b>Conservation target: 10%</b>	
Without ciguatera ( $a=0$ )	6.69
With ciguatera ( $a=1$ )	4.63 (-30%)
<b>Conservation target: 20%</b>	
Without ciguatera ( $a=0$ )	12.25
With ciguatera ( $a=1$ )	7.60 (-38%)
<b>Conservation target: 30%</b>	
Without ciguatera ( $a=0$ )	15.76
With ciguatera ( $a=1$ )	12.02 (-24%)

### 3 Results

#### 3.1 Fishery assets and fishing grounds

Overall, among the 903 inhabitants, 59 fishers were interviewed all around the island, representing the inhabited area completely. Considering there is typically one main fisher per household and an average of five persons per household, this sampling covers approximately one third of the fishers on the island. In contrast, ProcFish estimated that they surveyed 14% of the total population (30 out of 212 households, for a total of 1074 persons as in 2004) (Kronen *et al.*, 2009). No woman was interviewed, as none of them appeared to be main fisher or had regular fishing activity. Fishing was mainly for subsistence (83% of overall catches) and partly for gift / selling locally, notably for parish fairs (4% of overall catches), or, to a lesser extent, export to Tahiti (13% of overall catches). Fishers declared using a variety of fishing gears, three targeting finfish (i.e., Spear gun, *Pātia*, Line, Gillnet,) and three targeting invertebrates (*Pana*, *Auihopu*, and Hand harvest). According to the FAO matrix scores instantiated using the questionnaire results, the fishery in Raivavae was of an artisanal dimension, with most of aggregated scores at 0 (only twice, aggregated scores reached 7). This classification as a small-scale fishery resulted from the characteristics highlighted by the matrix, such as a generally short time commitment, mainly direct consumption (sometimes frozen storage), and mostly household consumption (sometimes sale to traders in Tahiti). Raivavae fishing ground as a whole (finfish and invertebrates including clams and lobsters) reached 120 tons yield annually (i.e., averaging  $1.4 \text{ t}\cdot\text{km}^{-2}\cdot\text{y}^{-1}$ ).

The 59 fishers interviewed described 359 fishing grounds. The survey was spatially representative of Raivavae fishery, as the cumulative curve of total fishing grounds area reached an asymptote at  $81 \text{ km}^2$  (from  $86 \text{ km}^2$  of the lagoon surface area), with most of the total fishing grounds area already captured by the 20<sup>th</sup> most informative interviews (Figure 20). Fishing activity took place all around the lagoon, and on the different reef geomorphological strata.

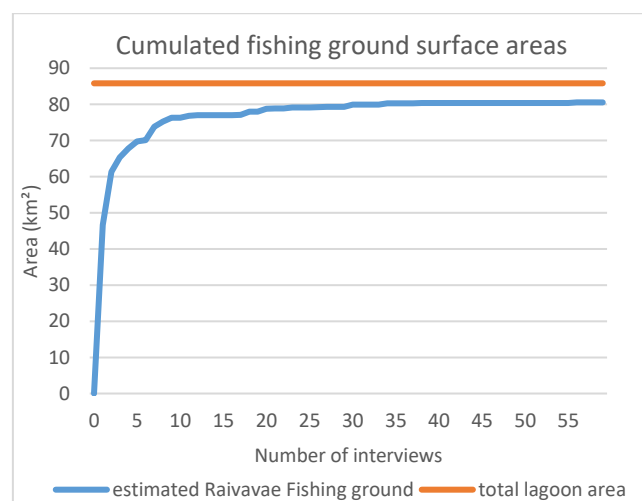


Figure 20. Cumulated fishing ground surface areas as a function of the number of interviews.

It reaches an asymptote at  $81 \text{ km}^2$ . The total lagoon surface area, reaching  $86 \text{ km}^2$ , is displayed for comparison purpose.

Step 2 and 3 of the framework provided spatially realistic maps of fishers' fishing grounds at various levels of integration (per fishing gear, per fisher, per village, for the whole island, etc.) (Figure 21). Step 3 particularly refined the fishing grounds for gears employed for resources found in specific geomorphologic habitats. It decreased the fishing grounds surface areas by 0 to 84% depending on fishers and fishing gears, with an overall average of 7% decrease. The fishing gears that were concerned the most by surface area decrease were *Pātia* and Hand Harvest (with maximum reduction of 83.8 and 83.6% respectively; 16 and 13% on average) and, to a lower extent, Spear gun (with 64% maximum reduction and 9% on average). The fishing gears that were concerned the least by surface area decrease were *Pana*, *Auihopu* and Line (1-2% on average).

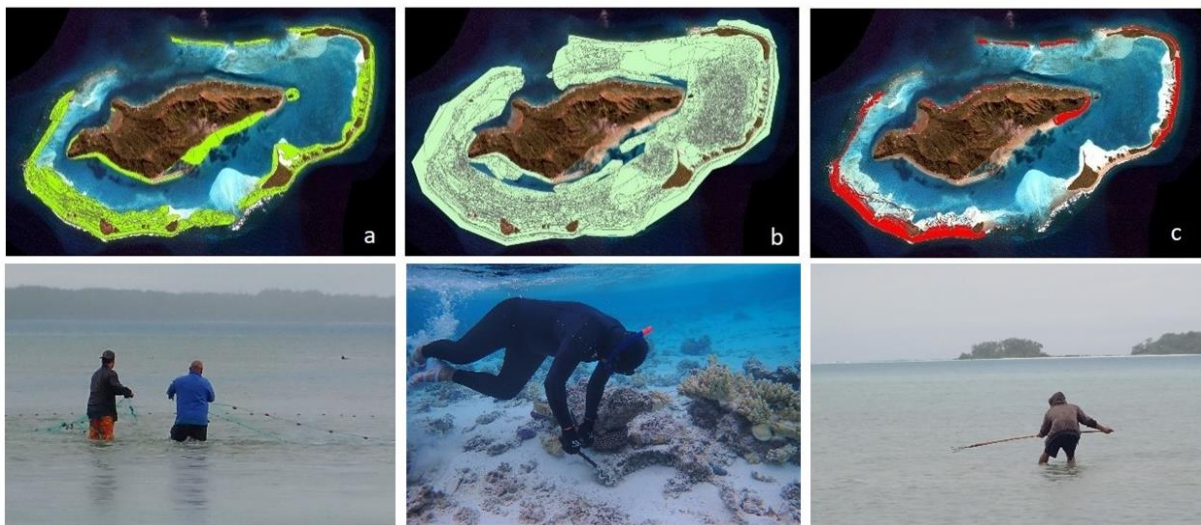


Figure 21. Examples of fishing grounds grouped by fishing gear and refined by geomorphological strata

a. fishing grounds with fishing net, in shallow areas; b. fishing grounds with pana to collect giant clams, in both shallow and deep areas; c. fishing grounds with pātia hand harpoon. Below each map, fishing activity with the relevant gear (Photos L. V. André, November 2019).

Among the 111 planning units generated by the overlay procedure (step 5), only one had no fishery catch at all, and was located at the forereef side of the main pass. Thus, the Raivavae lagoon and reef ecosystems were virtually fully used for fishing activities. The highest total catch per unit of surface area (CaPUS) reached  $9,009 \text{ kg}\cdot\text{km}^{-2}\cdot\text{y}^{-1}$ , and was located in the Western part of the lagoon, in a planning unit including lagoon, reef crest and forereef. High values of CaPUS were also found in the South and South-western parts of the lagoon (Figure 22a).

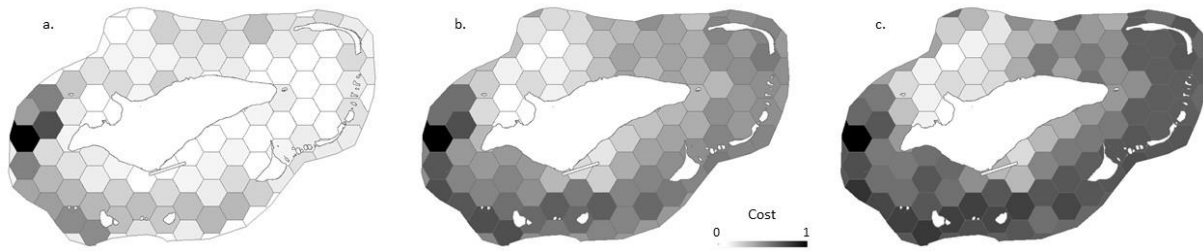


Figure 22. Maps of opportunity costs to fishers

(unitless, from 0 to 1), calculated as fisheries modulated by ciguatera (see [Eq. (6)]) with different relative weights of ciguatera: a. relative ciguatera weight  $a = 0$  (only fisheries as a cost); b.  $a = 0.5$ ; c.  $a = 1$ . In each case, values are normalised by the maximal value.

### 3.2 Mapping ciguatera risk

The 59 fishers interviewed identified 148 ciguatera zones, including 80 and 68 zones of proven risk and suspected risk respectively. Among the proven ciguatera zones, poisoning occurred in 39, 11 and 30 zones 0-5 years, 6-10 years, and 11+ years before, respectively. Ciguatera was still regarded in 2019 as a prominent issue in terms of fishing activity with a distinct spatial signature for most fishers. Areas with the highest risks were the main pass and the Northwest quarter of the lagoon, then, at a secondary level of risk the airport zone and the Northern small pass, and, to a lower level, the zone of the South-western reef (Figure 23). In particular, the main Northern pass, previously identified as a high risk zone since 2007 (Chinain *et al.*, 2010), has still been largely designated by fishers during the 2019 survey as an area to avoid. Interestingly, the high ciguatera risk (coefficient) that appears in the main Northern pass (covering seven planning units, Figure 23) resulted at 96 % from zones of suspected risk, *vs* only 4% from proven risk. Conversely, in the Northern small pass, the relatively high ciguatera coefficient was explained at 99% from proven risk. If we consider only proven risk, this latter zone becomes the highest risk zone, followed by the North-western reef, and then the North-western fringing reef. Ciguatera zones were widely distributed and many overlapped the fishing grounds. After the PU overlay procedure (step 6), ciguatera-free zones occupied only 34 planning units. Thus, 75% of the reef and lagoon ecosystems area was considered at risk by fishers ( $r_k > 0$ ), through their aggregated knowledge (Figure 23).

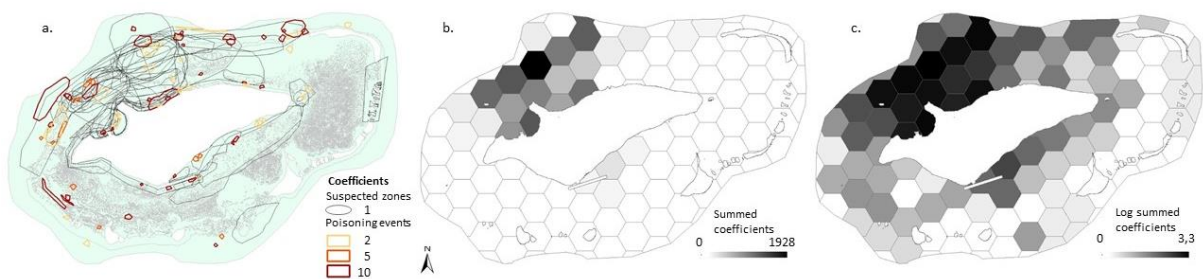


Figure 23. Maps of ciguatera:

a. as described by fishers, with coefficients from 1 to 10 depending on the nature of the risk (see Table 7); b. with planning unit overlay, the values in grey-scale are the coefficients summed among each planning unit; c. with planning unit overlay and values log transformed.

### 3.3 Effect of ciguatera on Systematic Conservation Planning solutions

Taking into account ciguatera in the calculation of costs [Eq. (7)] modified the spatial distribution of the solutions (Figures 22b and c). In particular, the Northern part of the lagoon around the main reef pass, identified with high ciguatera risk alleviated the fishery costs, except for the planning units affected by the highest fishing effort, which were located in the Western part of the lagoon. This area was also characterized by a low risk of ciguatera. These results were observed for both weight factors assigned to ciguatera risk ( $a = 0.5$  and  $a = 1$ ).

Selection frequencies and best solutions from SCP scenarios (see Table 8) appear in Figure 24. The distribution of planning units selection frequencies were significantly different between scenarios that took ciguatera risk into account and scenarios that did not (Chi<sup>2</sup> test,  $p < 0.001$ ). Regarding best solutions, the SCP scenarios that do not account for ciguatera risk suggested prioritizing planning units located in the North-western part and the Eastern part of the lagoon (Figures 24a; d; g). By contrast, the SCP scenarios that accounted for ciguatera risk suggested prioritizing, in addition, the Northern part and the South-western part of the lagoon (Figures 24c; f; i). These results were consistent for all conservation targets (10%, 20%, and 30%).

When considering ciguatera risk, the costs of best solutions for fishers dropped by 30, 38, and 24% compared to the cost of best solutions provided by scenarios that did not considered ciguatera risk, at conservation targets of 10, 20 and 30% respectively (Table 9).

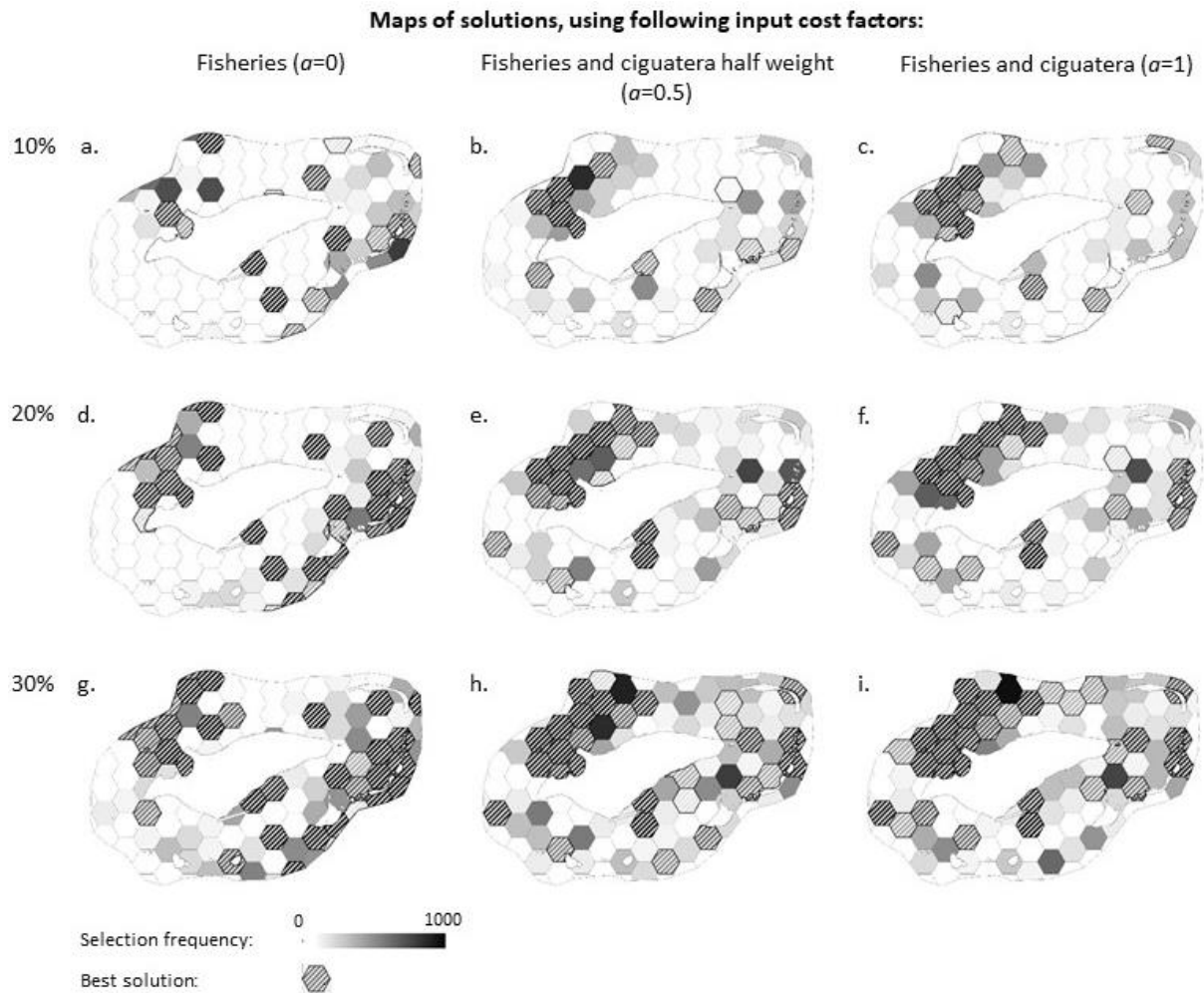


Figure 24. The solutions from the nine scenarios comparing three targets (10, 20, and 30%) and three maps of costs used as inputs.

Darker planning units have a higher selection frequency, among the 1000 repetitions. Best network is symbolized by hatched planning units, for each scenario. Upper panels (a-c) refer to the 10%-conservation-target-scenarios. Middle panels (d-f) refer to the 20% -conservation-target-scenarios. Lower panels (g-i) refer to the 30% -conservation-target-scenarios. Left panels (a; d; g) are solutions to SCP scenarios that consider the fisheries cost factor as input cost, while the other panels are solutions to SCP scenarios that consider ciguatera in the definition of cost, with lower importance than fishery cost ( $\alpha = 0.5$ ; panels b; e; h), and with as much importance as fishery cost ( $\alpha = 1$ ; panels c; f; i).

## 4 Discussion

The seven-step framework performed in this study enriched the framework proposed by Léopold *et al.* (2014) for mapping artisanal fisheries using local knowledge. The framework was improved by taking into account habitat delineation, thus providing more accurate maps of fishing effort. The framework was also extended by taking into account for the first time the ciguatera risk. We discuss these points hereafter, as well as the implications for systematic conservation planning in areas affected by ciguatera.

### 4.1 Mapping fisheries using local knowledge

Raivavae Island was known for its active artisanal fishery and this still proved to be the case in 2019. The cumulative curve of total fishing grounds area reached an asymptote at 81 km<sup>2</sup>, which was close to the total lagoon surface area (86 km<sup>2</sup>; Figure 20). This suggests that very few areas are exempt of fishing pressure. Our quantitative estimates (1.4 t·km<sup>-2</sup>·y<sup>-1</sup>) are consistent with the ProcFish study (Kronen *et al.*, 2009) which found, with a different method of investigation, that total fishing yield (for subsistence and exportations) on the total reef system surface area was 1.5 t·km<sup>-2</sup>·y<sup>-1</sup>. These estimates are also in the same range as that of Newton *et al.* (2007) who concluded to a fishing pressure less than 1 t·km<sup>-2</sup>·y<sup>-1</sup> on average for French Polynesia. While Raivavae population heavily relies on lagoon and reef resources, the level of exploitation appears sustainable since it is below 5 t·km<sup>-2</sup>·y<sup>-1</sup>, the estimated maximum sustainable yield for island coral reef fisheries (Newton *et al.*, 2007).

In this study, an original step was added to Léopold *et al.* (2014)'s framework, which increased the accuracy of mapping fishing grounds with geomorphological strata. The process was significant for some fishing gears, such as *Pātia*, Hand harvest and Spear gun (16, 13 and 9% of surface reduction on average, respectively), which are deployed and used on specific geomorphological strata such as reef crests, flats, and patch reefs. This step could be of particular interest if the planning unit shapes are based on data outlines and distribution, as advocated by Van Wynsberge *et al.* (2015). More broadly, whatever the planning unit shapes, the interest of this step may depend on the scale and the precision required to solve the problem, on the precision with which fishers represent their fishing grounds, and the quality and scale of the printed map.

Léopold *et al.*'s (2014) step of statistical generalisation from the surveyed sample to the scale of the entire island could not be followed here because it requires quantitative integrated data on the whole fishery (e.g., available from official catch records), which were lacking for Raivavae. However, this lack of inference does not undermine our conclusions. Indeed, first, the accumulation curve (Figure 20) shows that the sample size allowed to reach a good representative level of the fishing efforts on the island, at least spatially; second, we interviewed 6.5% of the total population, representing 23% of the households, from all villages, which is a satisfactory level of population sampling. Hence, it is likely that the trends emerging from the present survey would match data from a more intensive population survey. Finally, the ultimate goal of the fishery and ciguatera survey was a SCP application, which primarily requires hierarchizing the spatial distribution of fishing effort, but not necessarily the total quantities of catches. When total quantities become a critical management information (e.g.,



to establish quotas), the statistical generalisation step could be required and could be performed following Léopold *et al.* (2014) when enough information is available, or by extrapolating estimates at population scale from catch accumulation curves.

## 4.2 Mapping ciguatera risk using local knowledge

Despite the threat that ciguatera poses to artisanal fisheries and consumers and despite its inherent spatial component, ciguatera had never been integrated into a SCP before. This can be explained by the fact that acquiring ciguatera-related field data is a time consuming, costly task. Toxicological analysis of macroalgal host samples and fish tissue, as in Chinain *et al.* (2010) cannot be replicated widely. Mapping ciguatera risk at fine spatial resolution to produce relevant spatial information, for an island like Raivavae or for an entire archipelago, is not possible with available resources. Conversely, the present work demonstrates that collecting spatial information on ciguatera from local knowledge is an alternative of interest to comply with cost and time constraints. However, it does not provide exact and verified information on ciguatera and, hence, should be used with caution and within appropriate limits, e.g., it cannot be used for public health or food safety management programs.

The results highlight that ciguateric areas overlap fishing grounds in Raivavae. This aggregated fishers' knowledge shows that the two types of zones are not mutually exclusive and that their spatial co-distribution is complex, different fishers having different and complementary knowledge. Furthermore, some fishers could have disparate levels of knowledge on ciguatera risk (precise or vague on time and space, consistent or not between suspected risk with proven risk).

This local knowledge approach proved useful since it led to the identification of ciguatera risk areas that are consistent with the ciguatera risk map provided by Chinain *et al.* (2010). Indeed, both point out to the main pass, the North-western quarter of the lagoon and the airport zone as areas being most prone to ciguatera poisoning. Conversely, two zones previously identified as at low risk of ciguatera by Chinain *et al.* (2010), i.e. the Northern small pass and the South-western reef, were reportedly the sites of recent cases of ciguatera poisoning. These apparent discrepancies between the ciguatera status of Raivavae in 2007-2008 *vs* 2019 are consistent with previous observations that ciguatera risk can be spatially and temporally dynamic (Bienfang *et al.*, 2008).

We could not yet report to the population our findings, but it would be useful to get feedback on both the map of ciguatera risk and the fishing maps. Validation from the fishers first, and possibly from the authorities and the general population, would be useful as a first step towards the development of management plans with their approval. This step could not be realised yet after the present study but is meant to be conducted in the near future with French Polynesia authorities in charge of the management of lagoon resources.

## 5 Conclusion

### 5.1 Consequences for SCP applications

In SCP, costs always influence greatly the solutions (Cheok *et al.*, 2016; Deas *et al.*, 2014; Gurney *et al.*, 2015). While proxies are usually used to model the distribution of fishing efforts, a poor choice of proxy could disadvantage fishers even more than a scenario constrained without any proxy (Deas *et al.*, 2014; Weeks *et al.*, 2010). The framework provided in this study allows for collecting empirical spatialized information to build cost layers for SCP. As ciguatera zones were mapped via local knowledge, they are a proxy for true occurrence of ciguatera. However, despite this limitation, this proxy from local knowledge remains interesting to minimize the socio-economic cost of conservation for fishers.

Interestingly, as fishers not all have the same spatial perception of ciguatera risk in the lagoon, some of them may not recognise their own vision of ciguatera in the aggregated map of costs, which can decrease some fishers compliance to the conservation solutions. But this is the natural consequences when merging multiple perceptions and searching solutions that represent the overall population.

Our results highlight the fact that, for similar conservation objectives, integrating ciguatera local knowledge in the cost function resulted in a 24–38% decrease of costs to fishers compared to scenarios based solely on fishery data. This confirms that the challenge of balancing the distribution of areas to protect with fishers interests can be locally optimized by taking into account the distribution of areas with either proven or suspected ciguatera risk. In other words, there is direct value in promoting conservation for areas neglected by fishers due to the presence of ciguatera. However, this conclusion should be taken with adequate precautions. Indeed, in some instances, ciguatera outbreaks occur in degraded environmental conditions, after major disturbances of either natural or anthropogenic origin (Friedman *et al.*, 2017, for review and references therein). In that case, strategy questions arise of whether protecting a degraded zone for recovery, or prioritizing healthy ecosystems as refuge areas (Sacre *et al.*, 2019).

The present study relies on empirical costs that were measured through information specifically collected on the study site. It allowed producing a fishery atlas, with spatially-explicit information on the island fishing ground and fishing activity (gears, CPUE, annual frequency, mean of transportation, species caught, etc.). Fishery atlases exist for small-scale fisheries (Guillemot and Léopold, 2010), but they are a rare, valued baseline that are subject to changes over the years. The temporal variability of fishing activity is intertwined with the temporal variation of ciguatera risk, among other factors. Both types of information require regular updates. Adaptive planning, which is increasingly recommended in SCP (Mills *et al.*, 2015) to adjust planning to recipient expectations and changing environmental conditions, is definitely another framework layer to add in this context.

## 5.2 Possible extension of the framework to other sites

Several points must be considered to apply the framework proposed here to other sites and contexts. Here, fishing and ciguatera were factors well adapted for the Raivavae case study. Elsewhere, other factors may be also relevant, including different economic activities (tourism, mariculture, ports, etc.). Another emergent recommendation is that it can be necessary to integrate, in the design, how people value and are attached to their environment (Buijs, 2009; Charles and Wilson, 2009). Indeed, a case study of marine planning in Fiji (Gurney *et al.*, 2015) showed that integrating how fishers value their fishing grounds, led to a considerable change in protected area locations, and potentially more equity. Their results show that CPUE under a single cost scenario was 12–64% less than under a multiple costs scenario. Likewise, in Papua New-Guinea, Hamel *et al.*, (2018) showed that scenarios with commonly used fishery cost proxies (such as distance to landing sites) generated larger incidental costs than when considering the perceived value of fishing areas by households.

Second, in this study several choices in the methodology were made specifically for Raivavae Island. This includes how we defined the cost function using ciguatera and the weight of ciguatera *vs* fishery, or the type of habitats used to refine fishing grounds for each fishing gear. Sensitivity analyses (not shown) were performed to evaluate the extent by which these parameters may change the conclusions. These choices, however, may require some adaptations when applying the framework to other sites.

Third, application to other sites should consider the reliability of local knowledge, which may be site- and context-dependant. A study conducted in Solomon Islands assessed indigenous knowledge on long-term ecological change occurring to seagrass meadows, compared to historical aerial photographs and showed that fishers would generally track ecological change successfully, but levels of local knowledge could vary, even in small and culturally homogenous communities (Lauer and Aswani, 2010). The nature of the information collected from local knowledge is inherently driven by human perception dimension and historical or personal experience background. For example, in the present study, the Northern pass zone reached the highest ciguatera risk coefficient because it was very frequently pointed out as a zone with suspected risk, though few poisoning cases have been actually reported. Indeed, in the past, ciguatera outbreaks had previously occurred near the Northern pass (Chinain *et al.*, 2010), but current risk of ciguatera in this zone seems to have decreased due to the low proven cases in our survey. As historical perceptions may no longer be relevant, we tried to down play the perception of risk by attributing a relatively small weight to areas with suspected ciguatera risk *vs* those with proven ciguatera risk. This allowed standing out some proven risk zones, as mentioned above, but it reached its limit for the main pass zone. Another interpretation could be that ciguatera could still be present in this zone but thanks to the avoidance behaviour of fishers, few poisoning events actually occurred recently. In any case, if the pass is still considered ciguatoxic by fishers, it is important to integrate that information in the SCP framework.

Finally, the FAO Matrix, which provides a clear cut-off for differentiating large-scale from small-scale fisheries, definitely identified Raivavae fishery as a small-scale fishery. It is a new, useful tool to characterize the small-scale or artisanal character of a fishery and it can serve as a quantitative reference for comparison with other contexts, or to identify fishery sites with

similar characteristics. To investigate where the present framework could be applied, it is worth searching which sites would be characterised as small-scale fisheries with very low FAO Matrix scores, and simultaneously affected by ciguatera.

### 5.3 Further recommendations

Based on the discussion above, several aspects should be emphasized for this framework to be implemented with maximum benefits.

First, increasing the accuracy when mapping fishing grounds (step 3 of the framework) is particularly useful and easy to implement, even with fairly simple map based on reef unit geomorphology that are relevant to fishing gears. It is also possible to minimize the requirement for this step 3 if the fishers draw carefully their activities on the printed satellite image used for background. Therefore, this step should not be seen as an obstacle to apply the framework.

Second, local knowledge on ciguatera must be gathered from fishers representing the entire study domain, each fisher holding a partial knowledge related to his reference zone.

Third, fisheries and ciguatera status should be reassessed periodically as they can vary quickly over time and space. Fishing grounds and catch intensity depend on legal regulations, socio-economic drivers (e.g. population pressure, development of fishing methods, access to distribution markets, economic crisis), and environmental changes; among other factors. Similarly, ciguatera distribution and intensity vary over time, and should be regularly reassessed. In French Polynesia, inhabitants and medical staff are encouraged to report poisoning cases to health authorities through an online declaration form ([www.ciguatera.pf](http://www.ciguatera.pf)). Although data collected in the frame of this community-based participatory program are not exhaustive, they give a complementary indicator and can contribute to raise a red flag in case of mass poisoning outbreaks to implement further *in situ* investigations, like recently in the Marquesas archipelago (Darius *et al.*, 2018). Surveys should be developed and implemented in other ciguateric regions. For sound planning, we thus recommend re-evaluating the fishery and ciguatera situation every 5-10 years, or each time a major change (social or environmental) is reported in the island that may impact the status of fishing grounds and ciguatera.

### Acknowledgements

The present work, conducted in the frame of the PANGEA research program, was supported by funds from the Délégation à la Recherche de la Polynésie française (Conv. N° 06575/MED of September 28th, 2018), and the ANR-16-CE32-0004 MANA (Management of Atolls) project. The Raivavae geomorphologic map and Quickbird satellite image was funded by Direction des Ressources Marines. The Raivavae habitat map is a product from the Global Reef Expedition on board the M/Y Golden Shadow and was funded by the Khaled bin Sultan Living Ocean Foundation. We thank Raivavae inhabitants for their participation, especially Clarisse Teura Mahara Paulin, as well as the townhall staff for their logistical support. Finally, two anonymous reviewers helped improved the manuscript. Data available on request



## Chapter III – Mariculture management



## **Chapter III – Mariculture management**

### **Identification of suitable pearl oyster restocking zones in Takaroa Atoll following a mass-mortality event, using environmental and socio-economic data in a systematic prioritization approach.**

André Laure V.<sup>1, 2</sup>, Chinain Mireille<sup>3</sup>, Gatti Clémence M.i. <sup>3</sup>, Liao Vetea<sup>4</sup>, Van Wynsberge Simon<sup>5</sup>, Tedesco Pauline<sup>6</sup>, Serge Andréfouët<sup>1</sup>.

1 IRD Institut de Recherche pour le Développement – France, UMR 9220 Entropie (Institut de Recherche pour le Développement – France, Université de la Réunion, Université de la Nouvelle-Calédonie, Ifremer, Centre National de la Recherche Scientifique), BP A5, 98848 Nouméa cedex, New Caledonia

2 SU Sorbonne Université, 21, rue de l'école de médecine, 75006 Paris, France

3 ILM Institut Louis Malardé, Laboratoire des Biotoxines Marines, UMR 241 EIO (Ifremer, Institut Louis Malardé, Institut de Recherche pour le Développement, Université de la Polynésie française), BP 30, 98713 Papeete, Tahiti, French Polynesia

4 DRM Direction des Ressources Marines, Fare Ute, BP 20, 98713 Papeete, Tahiti, French Polynesia

5 Ifremer Institut Français de Recherche pour l'Exploitation de la Mer, UMR 9220 Entropie (Institut de Recherche pour le Développement – France, Université de la Réunion, Université de la Nouvelle-Calédonie, Ifremer, Centre National de la Recherche Scientifique), BP A5, 98848 Nouméa cedex, New Caledonia

6 Ifremer Institut Français de Recherche pour l'Exploitation de la Mer, DYNECO/PHYSED, BP 70, 29280 Plouzané, France

#### **Submitted to Marine Pollution Bulletin Journal**

André, L. V, Chinain, M., Gatti, C. M. I., Liao, V., Van Wynsberge, S., Tedesco, P., and Andréfouët, S. A. Identification of suitable pearl oyster restocking zones in Takaroa Atoll following a mass-mortality event, using environmental and socio-economic data in a systematic prioritization approach.

**Abstract**

Oyster farming for black pearl production is central in French Polynesia. It is the second source of national income and provides substantial job opportunities, notably in outlying islands. However, this sector has been undermined by successive crises, such as mass-mortalities of wild and reared oyster stocks due to environmental disturbances. Assuming improved conditions, an option to revive the activity consists in reintroducing oysters in lagoon strategic locations, so as to maximize reproduction and dispersal of larvae throughout the lagoon, hence promoting spat collection for farming and recolonization. For Takaroa, a Western Tuamotu atoll recently impacted by oyster mortalities, a systematic prioritization strategy identified suitable sites for oyster restocking, taking account of environmental and socio-economic criteria such as: location of suitable habitats for oyster settlement, lagoon connectivity estimated with hydrodynamic circulation model, farming waste accumulation, and opportunity cost to fishers and farmers. Identified sites provide managers with solutions for restocking measures.

**Keywords**

Spatial Planning; Marine Management; Connectivity; Aquaculture; *Pinctada margaritifera*; French Polynesia.



## 1 Introduction

In French Polynesia, the farming of the *Pinctada margaritifera* black-lipped oyster for black pearl production is an important component of the economy, particularly for remote islands (Le Pennec et al., 2009), where this sector is the main source of employment and income in households. In Tuamotu-Gambier archipelagos, one in two people live from the pearl industry, fishery or coconut exploitation (ISPF, 2018). Nevertheless, it has been weakened by successive economic and production crises (IEOM, 2020). This sector is also exposed to a number of environmental forcing factors and mass-mortality events, likely of multi factor origin, reported in several lagoons (Andréfouët et al., 2015).

Takaroa Atoll (Tuamotu Archipelago) (Figure 25) has been one of the most productive lagoons in the beginning of the black pearl industry in French Polynesia in terms of both pearl and spat production. As many as 81 million spats or oysters were exported to other lagoons between 1985 and 2015 (DRM, unpublished data). Mass-mortality events were recorded in 2000-2001 among farmed oysters in shallow water (Andréfouët et al., 2015), and particularly in 2014 among both farmed and wild oysters. This led to a quick decline of farming activities and a -24% decline in the oyster population between 2012 and 2017 census (ISPF, 2017). Five years later, the farming remains moribund, with *in situ* monitoring of farmed oysters suggesting slow growth ( $\sim 0.04$  mm/day, less than half the expected growth) and relatively low reproductive effort (Monaco et al., 2021). Spat collecting, an important process that allows the provision of natural *Pinctada margaritifera* oysters, remains uncertain. However, as of today, it is expected that the situation will continue to improve, with oysters able to eventually grow and reproduce normally again.

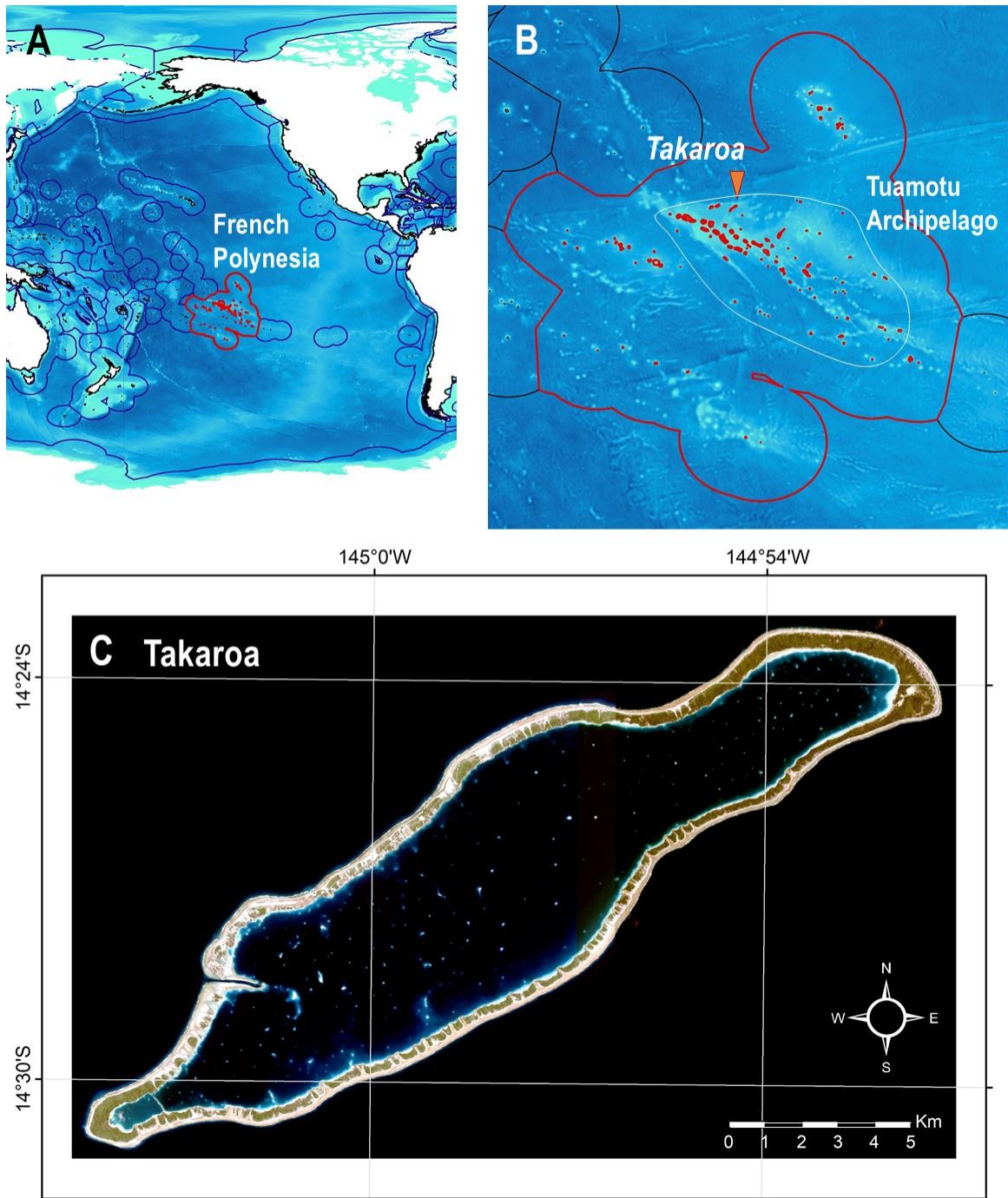


Figure 25. Maps of the study site.

(A) French Polynesia economic exclusive zone in the Pacific Ocean; (B) Location of Takaroa Atoll in the Tuamotu Archipelago; (C) Takaroa Atoll. Source of Ocean bathymetry: ETOPO1 (2011), source of Quickbird satellite image: DigitalGlobe (now Maxar) 2008.

In order to revitalize the wild stock and eventually, strengthen the potential for spat collecting, it has been suggested to restock the lagoon by either using imported adult oysters from healthier and productive atolls, in particular the neighbouring Takapoto atoll, and/or

releasing adult farmed oysters that cannot be used anymore for pearl production. This proposed initiative raises the question about the best restocking site locations, in order to i) maximize chances of survival and settlement of restocked oysters, ii) and minimize the impact on other activities, in particular fishing, that could negatively impact the site with physical damage, such as anchoring.

Besides these constraints, a noticeable issue in pearl farming atolls is the generated waste and its management. Indeed, spat collection and adult oyster rearing require a significant amount of immersed equipment such as lines, ropes, buoys, baskets, *etc.*, that eventually sink and are lost if not regularly maintained. As in many pearl farming lagoons, such as the Ahe Atoll (Andréfouët et al. 2014), Takaroa lagoon has accumulated significant amounts of waste that have sunk at the bottom of the lagoon, as evidenced in a survey coordinated by the technical service in charge of pearl farming management, *Direction des ressources marines* (DRM) (Source: DRM).

To achieve the goal of identifying the best restocking areas in Takaroa lagoon based on existing knowledge, we used a systematic prioritization tool and accounted for environmental parameters and socio economic uses of the lagoon, based on information already published or collected during a survey carried out in Takaroa in 2019.

## 2 Materiel and method

### 2.1 Study site

Takaroa is one of the most northern atolls in the Tuamotu Archipelago, located at 14.27°S latitude and 145°W longitude (Figure 25). The lagoon has a 86 km<sup>2</sup> surface area, with maximum and average depths of 47.5 m and 25 m, respectively (Andréfouët al. 2020). It is a semi-closed atoll as its only connections to the ocean are a single narrow 170 m-long and 20 m deep straight pass, and multiple ‘*hoa*’ (local name for shallow water passages between the ocean and the lagoon, across the atoll rim). The only village is located near the pass and accounts for the majority of the 674 inhabitants (based on the 2017 census; ISPF, 2017). Among them, 480 persons are in the 10-60 age group, which corresponds to the potential fishing-age population.

In this study, the environmental parameters considered were: (i) the depth and habitat range favorable for oysters according to a pre-mortality survey; (ii) the location of waste accumulations which represent a mobile substrate potentially unfavorable for relocation of oysters, and (iii) the lagoon areas that represent the best spawning sources able to disperse larvae throughout the entire lagoon. For this, a 3D hydrodynamic model was used to model larval dispersal and estimate connectivity between the lagoon sectors. As for socio-economic parameters, we based our analysis on (iv) the artisanal fishing activity inside the lagoon and (v) the most recent map of oyster farm concessions. To guide the site-selection, the first parameter, describing suitable habitats for oyster restocking, is an objective to maximize, whereas the next four parameters are considered as costs to minimize.

## 2.2 Available data on the study site

### *Bathymetry*

Lagoon bathymetry was previously surveyed using a mono-beam sounder, and a gridded product at 60 m resolution was interpolated, refined with the positioning of the very shallow top of pinnacles (locally called '*karena*') that could not be directly surveyed and were identified on very high resolution satellite imagery at 2.4 m resolution (Figure 25C). The bathymetric product is described in Andréfouët et al. (2020).

### *Wild oyster stock distribution and suitable habitats*

In Takaroa, dive surveys undertaken in 2013 estimated the wild oyster stock to be one million individuals (Andréfouët et al., 2016). Using the bathymetry data presented above, densities measured *in situ* at 22 stations were then generalised to the entire lagoon according to a depth-density relationship. The highest abundance of wild stocks was found at depths between 5 m and 25 m, and this depth range was then used as the suitable habitat for oysters in this study, including lagoon slopes as well as isolated coral pinnacles in the deep lagoon.

### *Distribution of artisanal fishing grounds*

Map-based fishery surveys were conducted among 44 fishers within population of potential fishing age at Takaroa, in August 2019, in order to spatialize and quantify fishing catch, following the methodology described in André et al. (2021b). In short, fishers individually answered a targeted questionnaire to locate their fishing grounds, the type and amount of catches, the types of fishing gear, and frequency of fishing activity. Details were kept per individual fishing ground for each fisher and answers were compiled, mapped and analysed using Geographical Information Systems (GIS) tools.

### *Hydrodynamics and connectivity matrices*

A previous study has focused on modelling the hydrodynamic circulation within Takaroa lagoon, according to tide and wind regimes (Tedesco, 2015). The model architecture, and specifications were similar to those described for Ahe Atoll by Dumas et al. (2012) and Thomas et al. (2014). Using ERA-Interim data from January 1979 until December 2011, Thomas et al. (2014) described the main wind regimes occurring during a 30-day period for the north-western Tuamotu. A total of 12 regimes represented the overall variability appropriately. These regimes mostly have an eastern direction, although average speed and frequency of occurrences vary (Thomas et al., 2014). During these regimes, hydrodynamic simulations show that the lagoon is structured in two main gyres separated by the jet from the pass during incoming tides (Figure 26A) (Tedesco, 2015). For our objectives, we considered only the main characteristics (average speed and direction) of four of these dominant wind regimes, and considered a subset of regimes covering the wider range of mean wind direction (Figure 26C), but acknowledge that the hydrodynamic pattern may change during short-term conditions (Tedesco, 2015). Wind regimes 3, 8, 9 and 12 were selected from Thomas et al. (2014).

Based on the hydrodynamic model, connectivity matrices were computed, following the methods described by Thomas et al. (2012, 2014) for Ahe Atoll. Here, we considered only the connectivity computed for the wild oyster stock (Thomas et al., 2014), which results in larval release close to the bottom of the lagoon. More specifically, Takaroa lagoon surface area was split into ten sub-zones with equal surface areas (Figure 26B) and connectivity matrices between these sub-zones allowed characterization of the dispersal potential for oyster spat under the four selected wind regimes. Among the simulations by Tedesco (2015), which explored the sensitivity to pelagic larval duration (Thomas et al., 2014), we considered that a pelagic oyster larval duration of 15 days was appropriate given the temperature and phytoplanktonic food conditions typical of Takaroa under normal conditions (Sangare et al., 2020) (Figure 26CD). We computed potential connectivity matrices, *sensu* Thomas et al. (2014). The measure of connectivity between two sub-zones  $i$  and  $j$  is the ratio between the number of larvae in the destination location  $j$  after 15 days of dispersal originating from the spawning site  $i$ , and the total number of larvae emitted in the spawning site  $i$ . The same number of larvae were deemed to be emitted for each sub-zone. We used these matrices as indicators of connectivity potential between each sub-zone, and specifically to identify the sub-zones that have the highest capacity to disperse larvae in all sub-zones, including themselves.

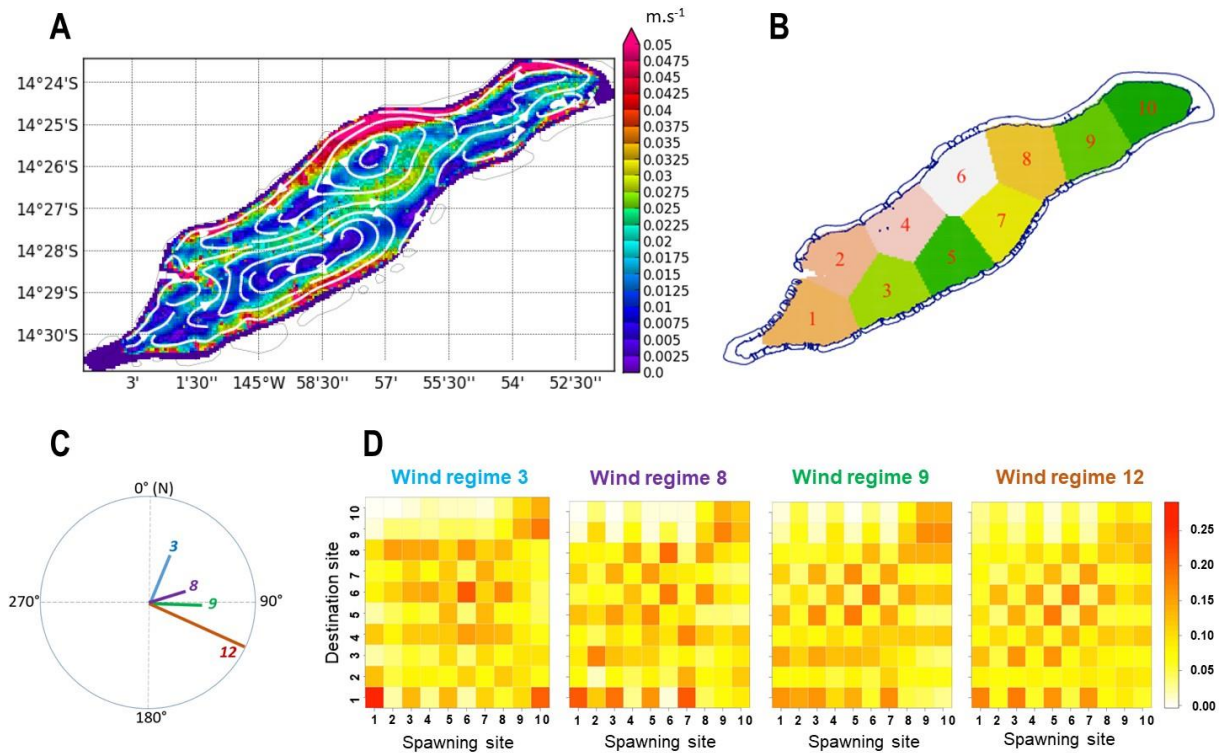


Figure 26. Hydrodynamic circulation modelling and connectivity matrices in Takaroa.

(A) Representation of depth-averaged current speed (color bar, m.s<sup>-1</sup>) and direction (white line) considering a trade wind regime direction 107 degrees, speed 6 m.s<sup>-1</sup> blowing for 30 days. Two circulation cells dominate the circulation, anticlockwise in the north and clockwise in the south. Note that the highest speed is along the edge of the atoll rim. (B) Ten sub-zones are defined in the lagoon to compute connectivity. (C) Simplified wind rose representing the mean direction and speed of the four representative wind regimes (3, 8, 9 and 12 as described in Thomas et al. (2014)). Circle radius = 7.6 m.s<sup>-1</sup> or the mean wind speed of regime 12. (D) Potential connectivity matrices between the ten different sub-zones, as a function of spawning  $i$  (x-axis) and destination  $j$  (y-axis) sub-zones, under the four wind regimes and for pelagic larval duration = 15 days.

### Macro-waste distribution

The amount of waste was assessed in a portion of the lagoon, by means of scuba-diving searches and photography (Figure 27B). The survey produced a semi-quantitative map of the accumulation of waste in the lagoon central zone (DRM, unpublished data). We interpreted this waste map with a suitability index for oyster restocking, assuming that substrates with a large amount of waste were not favourable for restocking because they are potentially mobile.

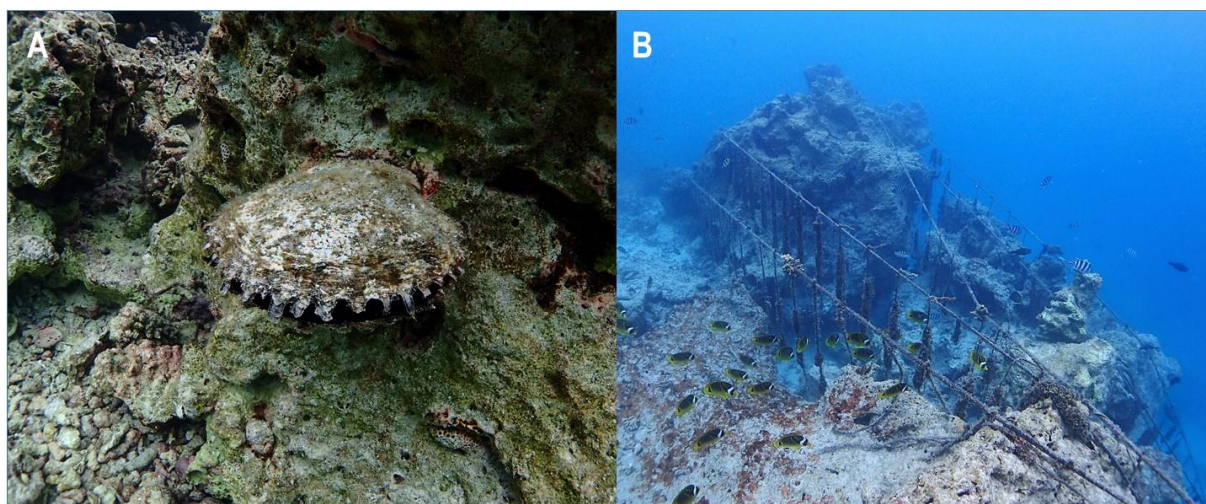


Figure 27. (A) Wild black-lipped oyster *Pinctada margaritifera* on a 'karena' in Takaraoa lagoon. (B) Example of moderate amount of pearl farming waste accumulated in the Takaraoa lagoon (sunk spat collecting lines and devices). (Photos L. V. André, August 2019).

### Pearl farming concessions

Active concessions are inventoried every year by DRM, including with field controls. We used the latest 2021 map of active concessions in Takaraoa as provided by DRM.

### 2.3 Spatial data aggregation

Prior to a systematic spatial prioritization analysis, it is necessary to define planning units (PU). These PUs were defined by a regular grid of hexagonal cells, to ensure the best perimeter – surface area ratio (Ardron et al., 2010). PU sizes were set at 25 ha to best suit spatial patterns of oyster concessions, fishing grounds and 5-25 m isobaths contours (Van Wynsberge et al., 2015). PU contours were trimmed when necessary, to match the external shape of the suitable oyster habitat layer. As a result, a total of 406 PU were defined in the lagoon surface area > 5 m depth, representing an 8490 ha study site. The following layers were then aggregated by planning unit (PU):

- **Layer of suitable habitat for oyster**, which translates into the 5-25 m depth range. Each PU was assigned the value of the surface area at this depth range within the PU;
- **Layer of connectivity sub-zones**, with coefficients ranging from 0, for sub-zones of high dispersal potential, to 1 for sub-zones with low dispersal potential, to be used as a cost layer in the subsequent planning analysis;
- **Layer of pearl farming wastes**, with coefficients ranging from 0 for areas with no waste detected (or no observation) to 1 corresponding to areas with high rates of waste accumulation;
- **Layer of active concessions** as of 2021. PUs were assigned the surface area occupied by concessions within each PU;

Layer of total fishery catch, which was obtained by calculating the catch density (in kg.km<sup>-2</sup>) of each fishing ground, then adjusting it to the surface area of the fishing ground within the PU, and finally by summing across all the fishing grounds within each PU, following the methodology described in André et al., 2021b). Resulting values were Log-transformed to reduce skewness.

## 2.4 Systematic site-selection scenarios

A systematic prioritization analysis was conducted using the Marxan © toolbox (Ball et al., 2009). Based on a minimum objective function, the goal of this exercise was to identify a certain proportion of the surface area favourable for oyster restocking that least impacts socio-economic activities, which are represented as costs, as well as the environmental parameters.

Simulations were conducted for three scenarios reflecting a gradient of quantitative targets  $t$  to reach: 10%; 20%; 30% of the surface area of suitable habitat for oyster restocking. The cumulative cost ( $C$ ) to minimize corresponded to the addition of the cost ( $c$ ) per PU ( $k$ ) across the four layers ( $l$ ), namely fishery catch, connectivity, waste and concessions [equation (1)]. To allow comparable values between cost layers, they were each normalised by their maximum value, hence individual cost for each PU ( $\bar{c}_k$ ) in each layer ranged from 0 to 1.

$$C_k = \sum_l \bar{c}_k \quad (1)$$

Additional Marxan parameter settings were tuned. The Boundary length modifier (BLM) was set at 0 because no compactness was deemed necessary for the PU selection for restocking. The Species penalty factor (Spf), in which increasing value compels the solution to meet the exact objective instead of just approaching it, but often at the expense of a higher cost, was tested following the methodology from Ardron et al. (2010).

Number of runs per scenario was set at 100. Each run provides a solution of selected PU network. For each scenario, Marxan outputs most commonly used are the ‘best solution’, which is the least costly solution run, and the ‘selection frequency’ of PUs among the 100 runs. The latter indicates how many times in 100 runs a given PU is part of the solution. In this study we used selection frequency outputs. Finally, for each scenario target ( $t$ ), total cost of the solution ( $S$ ) was calculated as the sum across PU ( $k$ ) of cumulative cost layer  $C_k$  multiplied by the selection frequency ( $f_k$ ) divided by the number of runs ( $n$ ) [equation (2)]. Here,  $n=100$ .

$$S_t = \sum_k (C_k * \frac{f_k}{n}) \quad (2)$$



### 3 Results

Data aggregation by PU revealed a complex Takaroa lagoon despite its small surface area (Figure 28).

The 5-25 m depth map shows that the main favourable areas for oyster restocking were located on flats and slopes around the shores of the lagoon, with some suitable habitat also available in the center of the lagoon due to '*karena*', totalling 3870 ha (Figure 28A). Once overlaid by PU, values provide how much surface area of this habitat is included in each PU (Figure 28B).

Connectivity of the sub-zones shows high dispersal potential for sub-zones 5, 6 and 7 (cost set at 0). These sub-zones displayed the highest dispersal rates towards most of the other zones. Medium rates of dispersal potential were found for sub-zones 3, 4 and 8, and the lowest rates were found for sub-zones 1, 2, 9 and 10 (cost = 0.5 and 0.8, respectively) (Figure 28C).

Waste from oyster farming in the center of the lagoon ranked from very high abundance (cost = 1) to medium nearby (cost = 0.75 or 0.50) (Figure 28C), whereas the rest of the lagoon was set to 0, however, this is likely an optimistic estimation because waste was also likely present around older concessions and beyond.

As of 2021, it was estimated that pearl farming concessions occupied 326 ha of the lagoon surface area, a very low value compared to historical data available for the atoll before the mass-mortality events. Most of the current concessions were mainly located along the south-east coast, some additional ones were near the pass and some small ones along the north-west coast (Figure 28C).

The fishery survey indicated that the 44 fishers used the entire lagoon space, albeit with considerable variation in catch rates among fishers. The zone of the pass, which is also near the village, yielded the highest catch, with 5251 kg.y<sup>-1</sup> in a PU. Medium levels of catch values were found in the north of the lagoon, along the north-west coast and in the center of the lagoon, where many fishers use spear-gun on '*karena*' as well as line and troll fishing from the boat. The total catch for the lagoon was estimated at 22 t per year (Figure 28D).

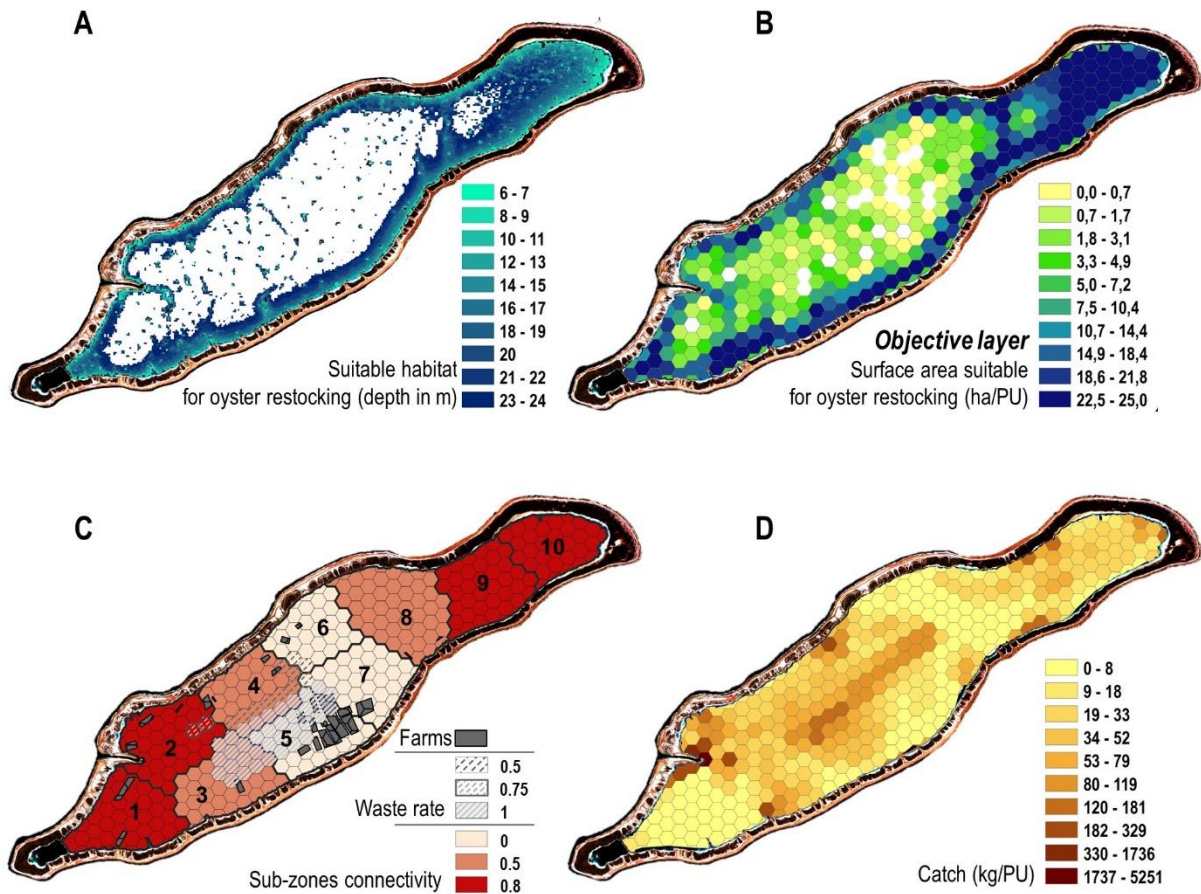


Figure 28. Spatial layers used for the systematic prioritization analysis.

(A) The 5-25 depth range representing the maximum extent of the potential restocking areas. (B) Surface area of potential restocking habitat, present in each planning units (PU). This layer is used as the objective layer for the systematic prioritization analysis. (C) Three cost layers: farm concessions, waste abundance rate and the ten sub-zones connectivity potential. (D) Fishery catch aggregated by PU (the fourth cost layer).

Combining the four normalised cost layers provided a resulting cost layer showing high cost levels in the center of the lagoon, mainly due to waste and fishing activity, but also near the pass, mainly due to the fishery, and finally in the north, due to low connectivity rates (Figure 29A).

Different targets were set (i.e., 10%, 20% and 30% of the 5-25 m depth range surface area) and opposed to the combined cost layer, and optimal solutions were always found. PU selection frequency is displayed in Figure 29BCD for the three scenarios.

All the different scenarios identified candidate sites (PU) for oyster restocking, with an incremental number of PU expectedly matching the increasing targets. Selection frequency was > 80-90 (pink colours) for many PU located in the north and south sides of the middle section of the lagoon (Figure 29BCD). The pattern of solutions confirms that the south-central border is particularly suitable for restocking. Other possibilities were also identified at lower

frequency (purplish colours), offering flexibility to managers for deciding different schemes of implementation.

Following some calibration tests, setting Spf at 5 resulted in a satisfying compromise between achieving or almost achieving the target for the three scenarios (see Table 10: shortfall  $\leq 1.1$  ha), providing satisfying levels of representation of the objective layer in the solution, while ensuring minimized costs.

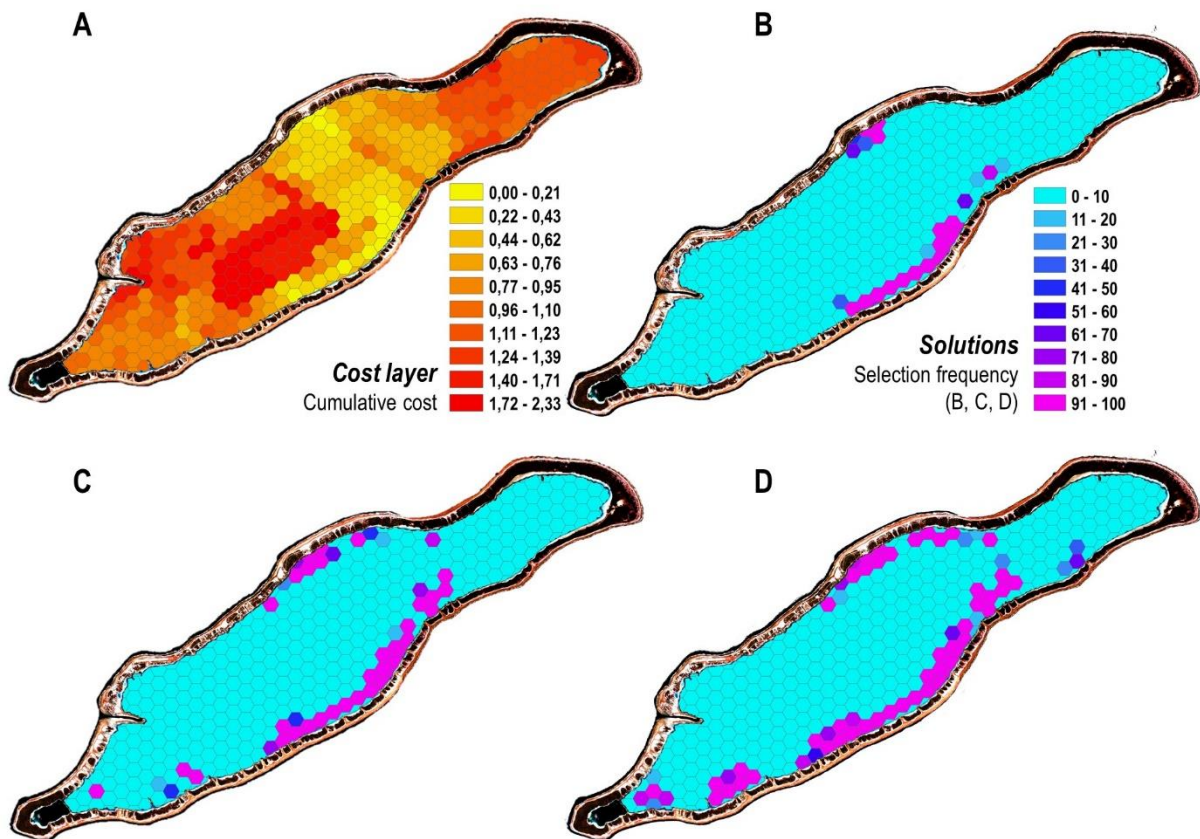


Figure 29. SCP solutions

(A) Cumulative cost, resulting from the aggregation (sum by PU) of the four types of cost. This layer is used as the cost layer for the systematic prioritization analysis. The three following vignettes are solutions to Scenario 1 with a target of 10% of the 5-25 m depth range set as restocking area (B), Scenario 2 with a 20% target (C) and Scenario 3 with a 30% target (D).

Table 10. Description of the three scenarios

with increasing targets, associated specie penalty factor (Spf), resulting shortfall (area missing from the PU selected as a solution to totally fulfil the target) and solution cost (no unit).

Scenarios	Target values		Spf	Shortfall to reach the target	Solution cost
	relative	absolute			
1	10 %	387 ha	5	0 - 0.9 ha	3.91
2	20 %	774 ha	5	0 - 1.1 ha	14.82
3	30 %	1,161 ha	5	0 - 0.6 ha	29.66

## 4 Discussion

In response to concerns raised by the pearl producers on ‘what can be done to restore the initial production levels?’ and at the request of DRM, this study helps identify practical management solutions, by combining pearl farming criteria, while also integrating other concerns. The highlighted solutions (Figure 29) provide a baseline for further discussions on restocking options in Takarua lagoon for stakeholders. To our knowledge, the use of a systematic spatial prioritisation toolbox for such a purpose has never been reported, and this study constitutes an original contribution to the panel of management or conservation questions addressed by the general field of systematic conservation planning in tropical island environments (André et al., 2021a), because it integrates the various issues related to pearl farming for the first time.

With more diverse criteria than most conservation plans for wild species, our study is consistent with the recommendations by André et al. (2021a) for the Pacific Islands, which identified a lack of planning studies taking into consideration local specific activities, such as black pearl farming, and invertebrate resources and their populations. Specifically for the Tuamotu Archipelago, a previous systematic conservation planning study addressed the question on how to conserve giant clam stocks and limit fishing while maintaining equitable conservation costs on different atolls (Kabbadj et al., 2018). This first application was in line with typical spatial planning exercises and goals that often balance biodiversity conservation with fishery opportunity costs. In the case of Takarua, the planning question was motivated by the reboot of an aquaculture activity impacted by oyster population mortalities; an application more rarely put forward in a systematic planning context.

Specifically for the management of pearl oyster farming, our analysis is as a first step towards the identification of favourable restocking zones. The restocking question is acute for Takarua, but also in several places where a decline in spat collecting has been observed, like in Ahe Atoll. Besides potential environmental changes, the decline in several atolls could be explained by the combined aging of the wild populations and the skewed sex-ratio due to the protandric nature of the species (Andréfouët et al., 2016), and by the growing suspicion that spat could be dominated by gametes released by the natural stock, and not by the farmed stock (Andréfouët et al., 2021; Reisser et al., 2020). All together the principles of the methodology put forward here are likely to be useful for a variety of lagoons in the future, and could be part of the management portfolio of DRM in French Polynesia, and possibly other countries where pearl farming based on spat collecting also takes place, such as Cook Islands and Fiji (Lal et al., 2020).

To apply these tools effectively, however, data are needed. Takarua is already well studied compared to most other pearl-growing areas, nevertheless, several aspects could be improved. Here, we used a limited data set to parameterize the best areas susceptible to maximize larval dispersal throughout the lagoon. This is reasonable because we used climatologic information and dispersal forced by typical trade wind regimes, which represented fairly typical present-day situations. However, other configurations exist, in wind patterns (including fast reversals not captured in the wind regime statistical analysis), but also in pelagic larval duration, larval food supply in the lagoon, temperature, and so forth (Thomas et al., 2014; 2016). The actual variations observed in the lagoon at different time scales are fully taken into account in the

present study. Future similar exercises to identify restocking areas will give more weight to connectivity than the other parameters. Refined analyses will take into account additional environmental condition scenarios prior to making final recommendations for the selection of restocking sites. Since new wind regime data also became available recently (Dutheil et al., 2020), the future simulations will be forced by these conditions. Nevertheless, we do not expect significant changes compared to the present results because these updated regimes remain dominated by easterly wind directions. Additionally, the wild stock estimation which was used for the connectivity simulations, which dates back to 2013, needs to be updated given that major changes have occurred in the meantime, most notably the 2014 mass-mortality event. The 2013 stock data were used to estimate the location of suitable habitat for restocking, but there may have also been some changes in substrate to invalidate our assumption. Therefore, new empirical observations on wild oyster stock abundance could be relevant to update our parameterization. Finally, extended lagoon waste assessment and some bottom cleaning are on the DRM's agenda and as work progresses, suitability of the areas may also change.

Artisanal fishing is an activity that occurs in all Pacific Islands, and related opportunity costs are included in most conservation spatial plans described in the literature (André et al. 2021a). Recently, we investigated how ciguatera could be an important criterion to take into account to lower the cost of conservation for fishers (André et al., 2021b). Indeed, in many Pacific Islands, ciguatera poisoning events are frequently reported. They result from the ingestion of poisonous marine products due to harmful microalgal blooms producing toxins that further bioaccumulate in the food web. Integrating the ciguatera risk aspect in spatial planning applications of tropical islands was an additional recommendation from André et al. (2021a). However, unlike what is observed in areas where ciguatera risk represents a major driver for fisher's use of the lagoon (André et al., 2021b; Chinain et al., 2010 and 2020), in the case of Takaroa, very few cases were actually reported by the island's dispensary. This observation was consistent with the results obtained following the map-based fishery surveys, at least concerning the area within the lagoon. Therefore, although the ciguatera criteria was not considered in the present study, it remains highly relevant elsewhere, especially in ciguatera-prone areas and, hence, should be integrated in future similar exercises.

In conclusion, this study provides a fresh canvas that paves the way for better integration of different types of spatial data and to develop new approaches for sustainable management of South Pacific lagoons, marine resources and related socio-economic activities.

### **Acknowledgements**

The study was funded by a doctoral fellowship from Sorbonne Université to LVA, the PANGEA PhD project (grant from Délégation à la Recherche de Polynésie française to Institut Louis Malardé, Conv. N° 06575/MED of September 28th, 2018), and by the MANA (Management of Atolls) project (grant from Agence Nationale de la Recherche ANR-16-CE32-0004). We acknowledge all the people of Takaroa including fishers and the city council representatives for their contribution to the questionnaire surveys. We thank Yoann Thomas, Franck Dumas and Romain Le Gendre who supervised the computations of the connectivity matrices and implemented the initial 3D model

## Chapter IV – Traditional management



## Chapter IV – Traditional management

### **Benefits of collaboration between indigenous fishery management and data-driven spatial planning approaches: the case of a Polynesian traditional design (*rāhui*)**

Laure Vaitiare André <sup>1,2</sup>, Simon Van Wynsberge <sup>3</sup>, Mireille Chinain <sup>4</sup>, Serge Andréfouët <sup>1</sup>

1 IRD Institut de Recherche pour le Développement – France, UMR 9220 Entropie (Institut de Recherche pour le Développement – France, Université de la Réunion, Université de la Nouvelle-Calédonie, Ifremer, Centre National de la Recherche Scientifique), BP A5, 98848 Nouméa cedex, New Caledonia

2 SU Sorbonne Université, 21, rue de l'école de médecine, 75006 Paris, France

3 Ifremer Institut Français de Recherche pour l'Exploitation de la Mer, UMR 9220 Entropie (Institut de Recherche pour le Développement – France, Université de la Réunion, Université de la Nouvelle-Calédonie, Ifremer, Centre National de la Recherche Scientifique), BP A5, 98848 Nouméa cedex, New Caledonia

4 ILM Institut Louis Malardé, Laboratoire des Biotoxines Marines, UMR 241 EIO (Ifremer, Institut Louis Malardé, Institut de Recherche pour le Développement, Université de la Polynésie française), BP 30, 98713 Papeete, Tahiti, French Polynesia

#### **Submitted to ICES Journal of Marine Science**

André, L. V, .Van Wynsberge, S., Chinain, M. and Andréfouët, S. A. Benefits of collaboration between indigenous fishery management and data-driven spatial planning approaches: the case of a Polynesian traditional design (*rāhui*).

## **Abstract**

Traditional indigenous fishery management schemes have gained increasing recognition worldwide. This fact acknowledges in particular a better compliance to ancient cultural practices, many still rooted in present communities despite globalization and modern livelihoods. This revival is widespread and welcome by policy makers, scientists, and the communities themselves. However, current environmental and socio-economic contexts are often not conform to ancient-time situations. Baselines are different. Effective adjustments of traditional practices may be advocated. Re-establishment of traditional schemes 'as is' warrants further investigations, and modern management approaches with quantitative assessment can help. A demonstration is provided here for a rural Polynesian island that faces declining marine resources. Recently, fishers discussed the implementation of a traditional system (called *rāhu*) to preserve lagoon resources, based on rotational closures of an arbitrary 50% of each lagoon subdivision. Upon the fishers' request, we used systematic conservation planning (SCP) tools to explore potential optimization pathways. All quantitative conservation objectives being equal, SCP suggested reserve sizes and costs on average 7 and 5 times lower than the traditional design. Traditional management is encouraged as it federates communities, and fishers are now aware of effective alternatives to enhance the initial design. Similar findings can be expected in many other regions.

## **Keywords**

Polynesia; Raivavae; Systematic Conservation Planning; Marxan; Marine Spatial Planning; Artisanal fisheries; Ciguatera; Locally Managed Marine Area; Community-Based Fishery Management, Indigenous Traditional Management



## 1 Introduction

Marine fishery resources need to be better managed worldwide to primarily counteract overfishing and on-going negative environmental changes (Jackson et al., 2001; Link & Watson, 2019). Despite some success stories of effective management and documented stock rebounds through for instance marine protected areas (e.g., Anderson et al., 2014), a general trend is a worldwide decrease in the quality and quantity of catches. Better management is called upon at all geographical scales, from offshore industrial fisheries in the high latitude seas (McBride et al., 2014) to small scale artisanal fisheries in remote tropical tenures, for both finfish and invertebrates (Alati et al., 2020; Warren & Steenbergen, 2021). Sustainable fishing and stock management can be promoted using a variety of political, socio-economic and environmental top-down measures, several directly targeting the fishing activity itself such as quotas, minimum/maximum catch sizes, and others focusing on spatial and temporal closure of fishing grounds. In order to take informed decisions, a vast array of data may be needed and modern management is, or should be, adaptive and driven by data (Pauly & Zeller, 2016). Ideally, critical socio-economic, biological and ecosystem data, from observations and models, should be channelled to decision-support tools used by managers and fishers (Lehodey et al., 2018).

Small-scale fishery systems that may correspond to a spatial unit defined by a narrow coherent set of characteristic resources, human, geographical and environmental features (Savoré et al., 2019), can also be managed by approaches that are very specific to this spatial unit (Cinner et al. 2012). Indeed, in freshwater and marine coastal areas, local management measures of small tenures are common (e.g., in Oceania, Karcher et al., 2020). They emerge from local decisions, through participatory and community-driven discussions, that themselves often follow traditional protocols and practices. In the past decades, these approaches have been increasingly recognised worldwide as efficient ways to manage fishery resources, on the ground that level of compliances to restrictions are higher, local relevant knowledge is used, and information is shared across the different social and governance layers of the community (Sangha et al., 2019; Fache & Pauwels, 2020; Smallhorn-West et al.; 2020a). Indeed, in many countries with low enforcement capacities, top-down decisions may even be unheard of by local remote communities. The benefits of traditional indigenous management, both inland and coastal, and how it can serve biodiversity conservation in its broad sense (including fishery resources) is reviewed in Gurney et al. (2021) in the context of Other Effective Area-Based Conservation Measures (OECM).

Objectively, it must be recognised that the strength of traditional indigenous approaches can also be their weaknesses, a reality that is also acknowledged in the literature (Léopold et al. 2013) and may call for adaptive comanagement with refined objectives (Weeks and Jupiter 2013, Jupiter et al; 2014). Indeed, the local dimension has inherent limits, which may lead to inefficient protection, for instance for marine species that are mobile across tenures that can be managed differently, or not managed at all. For instance, in Vanuatu, the micro-local management of numerous very small customary tenures precludes the effectiveness of these individually-managed areas in sustaining resources at a larger scale (Dumas et al., 2010; Léopold et al., 2013). Maintaining traditional rules can also be irrelevant considering all the

pressures that are new to previously isolated or much simpler socio-ecosystems. New spatially conflicting activities may have developed, ancient ones have disappeared, and global changes such as global warming may have already altered local ecosystems. Finally, customary decisions can be taken without critical adequate information, especially on biological aspects. Typically, new updated baselines should be considered, such as level of stocks, reproduction potential, or new factors of mortalities that can be easily missed by the locals (Lauer & Aswani, 2010). For instance, in French Polynesia, Andréfouët et al. (2013) reported that a 90% giant clam mass mortality was totally missed by local fishers even if they depended on this important resource. Taking into account relevant facts rather than beliefs is especially critical when the traditional management process is re-established after decades of interruption.

In light of these limitations, there are surprisingly still very few studies that have explicitly or implicitly sought to combine for fishery management or mapping purpose, a data driven approach with the traditional practices, in order to strengthen the effectiveness of the latter (e.g. Aswani & Hamilton, 2004; Weeks & Jupiter 2013; Horigue et al., 2015; Wendth et al. 2016, Smallhorn-West et al., 2019; Davies et al., 2020). This general issue was identified as a priority for Oceania in Weeks & Adams (2017, Question 34). Recently, Gurney et al. (2021) rightly advocate to co-build multiple indicators of effectiveness for existing OECM, but the case of the re-establishment of locally managed areas is not discussed in existing literature. In a revival context, we suggest that it is necessary to search for an optimal start that will launch the implementation process in the right direction for the sake of effectiveness. To that end, we consider that the collaboration between traditional practices and data driven approach should be promoted for the benefits of all parties. We aim to emphasise this added value hereafter.

With the aim of preserving biodiversity and resources, a structured data-driven approach for identifying conservation areas is systematic conservation planning (SCP). This analytic approach using spatial information provides transparent and data-driven solutions. Briefly, after defining the questions, objectives (i.e. quantified features of biodiversity to protect), spatial domain and group of stakeholders involved (Pressey & Bottril, 2009), the selection of priority areas for conservation through a SCP framework first requires dividing the study area into small units called planning units (PU), each one characterized by attributes related to conservation targets and constraints. Then, prioritisation algorithms are applied to identify the best set of minimum PU solutions that meet the objectives, while minimising the cost of the reserve, in terms of lost opportunity for human activities for example (Margules and Pressey, 2000; Kukkala and Moilanen, 2013). Finding these best trade-offs is done through numerical optimisation. Often, habitat maps are used to define objectives of biodiversity conservation, targeting a given percent of surface area of each habitat. The cost generated by the reserves on human activities is meant to be minimised. This is often estimated from socio economic costs to fishers, i.e. loss of opportunities in terms of fish catches (reviewed for the Pacific Island in André et al., 2021a). Importantly, SCP was initially developed to enhance locating and designing reserves for the conservation of biodiversity (Margules and Pressey, 2000), but it was less used to specifically set an objective on fishery resources, to ensure sustainability of the fishery in the long run while minimising immediate costs for fishers (but see for instance Kabbadj et al., 2018).

Here, using a French Polynesian case study, we present how a committee of indigenous fishers, curious about testing their traditional practices before re-implementing them, can

collaborate with spatial planning scientists having access to adequate data, to identify optimised solutions, hence potentially strengthening the traditional fishers approach to fisheries management.

## 2 Material and Methods

### Raivavae study site and the traditional *rāhui* fishery management

In the Pacific Ocean, many islands have maintained or re-introduced some forms of traditional spatial management of marine areas as part of cultural revival movements that have emerged since the late 1990's (Johannes, 2002). These include *tapu* areas (taboos), *bul* in Palau (Gruby et al., 2013; Friedlander et al., 2017) and *rāhui* in Polynesia (McCormack, 2011; Bambridge, 2016). All these instruments have been designated in international nomenclature as indigenous and community conserved areas (ICCAs) or locally managed marine areas (LMMAs) (Govan, 2009). In this study, we are particularly interested in *rāhui*, which involves a restriction of access to some area(s) during a certain period of time. It was originally linked to spiritual dimension and political control on resources rather than motivated by ecological considerations (Bambridge et al., 2016; Cohen and Foale, 2013). Through the form of temporary ban, rotating closures or periodically harvested closures, it can have different objectives such as to impose a ban after a drowning nearby, or to ban all marine resources or species specific extraction for stock replenishment, in anticipation of a celebration expected to require substantial food, for example (Conte, 2016; Ghasarian, 2016; McCormack, 2011).

*Rāhui* is an ancient concept that has evolved with the modern society rationales and constraints. In the current international context which promotes conservation initiatives, sustainable fisheries management and recognizes the merit of community-based management, *rāhui* have been re-established in the Polynesian region to manage marine resource stocks with a traditional grounding (Bambridge, 2016). The notion of traditional dimension is highlighted and promoted, and these local initiatives generally benefit from good support from local communities (Govan, 2009). In French Polynesia, *rāhui* is legally recognised by the French Polynesian technical service in charge of marine resources management, *Direction des Ressources Marines* (DRM, 2021) and gazetted in official texts. In the past decades, different *rāhui* initiatives were implemented, supported by inhabitants, local management committees or municipal staffs. An emblematic example is the traditional *rāhui* that was re-implemented in Rapa iti Island (Austral Archipelago) in the 1980s, from the population initiative, to protect and sustain marine resources they rely strongly on, and avoid potential overexploitation due to the introduction of modern fishing techniques and frozen storage equipment (Gasarian, 2016; Salvat et al., 2015). In the main French Polynesia Island, Tahiti (Society Archipelago), a *rāhui* was implemented in Teahupoo locality in 2013. It has been successful thus far in terms of marine resources replenishment and now constitutes a model that other municipalities wish to follow (DRM pers. com., Nov. 2019). A *rāhui* aimed for biodiversity conservation purpose has been implemented recently in Tautira district, Tahiti (Bambridge et al., 2019), whereas a *rāhui* is currently serving educational purpose in Anaa Atoll, Tuamotu Archipelago (Filous et al., 2021).

Raivavae Island ( $-147,67^{\circ}\text{W}$  longitude and  $-23,87^{\circ}\text{S}$  latitude) is located in the Austral Archipelago (French Polynesia), 700 km south of the main island of Tahiti (Figure 30a). This 18 km<sup>2</sup> volcanic island is home to 903 inhabitants (2019) and offers a 59-km<sup>2</sup> lagoon and reef system, which is connected to the ocean through one main pass in the north-west and two small passes in the north and south. Raivavae is administratively divided into four districts, namely Rairua, Mahanatoa, Anatonu and Vaiuru (Figure 30b).

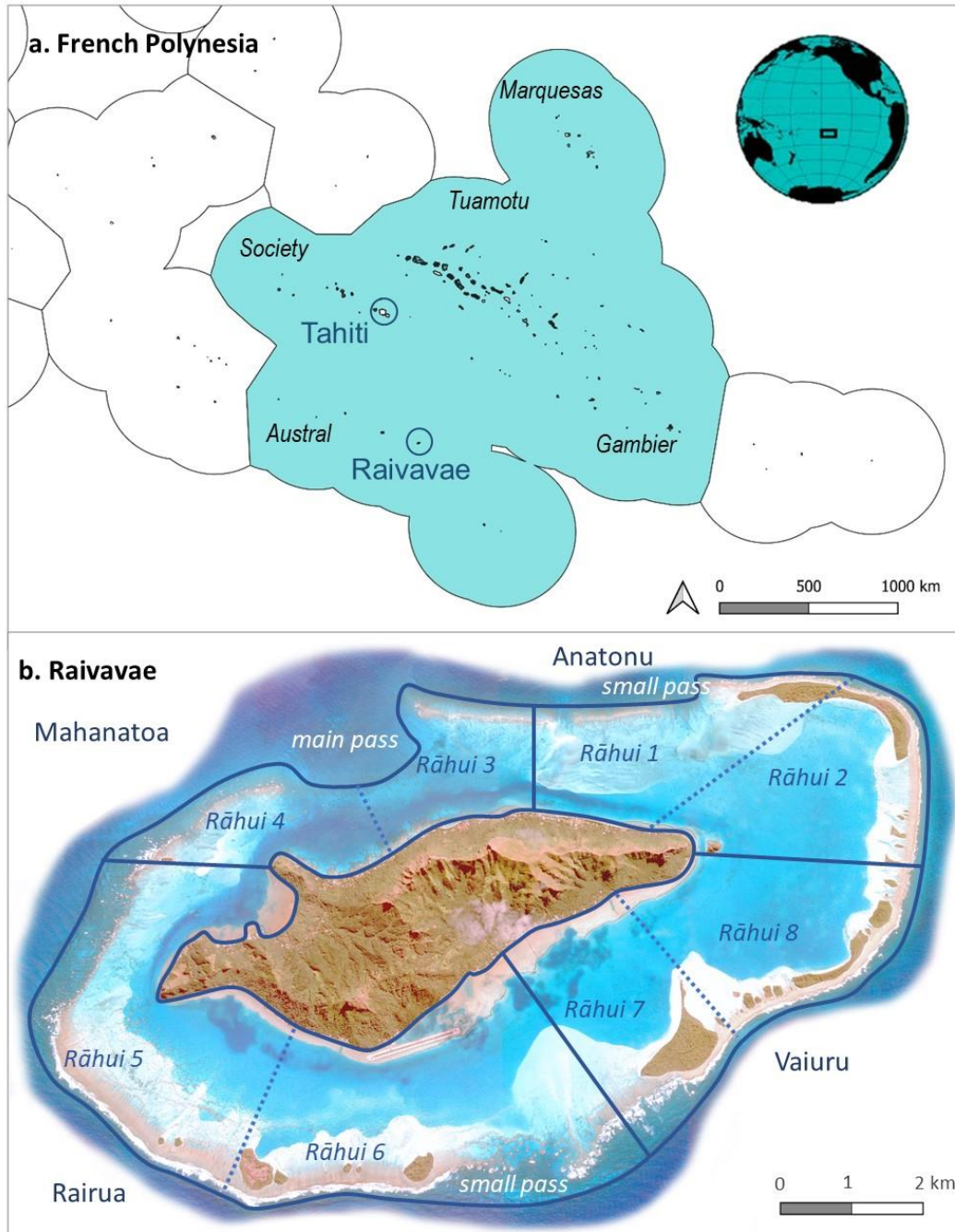


Figure 30. Map of the study site.

(a) Location of Raivavae Island in the Austral Archipelago, French Polynesia; (b) Raivavae's four administrative districts Rairua, Mahanatoa, Anatonu and Vaiuru, and the eight rāhui zones.

People in Raivavae rely strongly on local resources, most notably agriculture and artisanal fisheries (Kronen et al., 2009), with an estimated  $1.4 \text{ t}\cdot\text{km}^{-2}\cdot\text{y}^{-1}$  marine resources annual yield on average (André et al., 2021b). The main fishing grounds are located in the south-western barrier reef and back reef zone, with the highest yields reaching  $9 \text{ t}\cdot\text{km}^{-2}\cdot\text{y}^{-1}$ . A specific feature of this local fishery is its strong reliance on giant clams (*Tridacna maxima*), besides finfish (Kronen et al., 2009; Van Wynsberge et al., 2013). The giant clam fishery takes place throughout the entire lagoon (André et al., 2021b) and accounts for more than 15% of the annual catch biomass (considering the meat, without the shells) (unpublished data). An important part of this catch is exported to Tahiti as gifts for families or for sale. In periods of high exports, the sustainability of this resource exploitation raises concerns among the population.

Raivavae is also characterised by the presence of ciguatera poisoning, as illustrated by a major poisoning outbreak in 2007 (Chinain et al., 2010). Ciguatera poisoning results from the consumption of finfish or invertebrates contaminated with neurotoxins (known as ciguatoxins) that are produced by benthic dinoflagellates in the genera *Gambierdiscus* and *Fukuyoa*. Since 2007, numerous cases have been repeatedly reported on the island, and fishers have developed their own strategy to avoid ciguatera-prone areas and species (André et al., 2021b). In terms of restriction of access to marine resources, ciguatera is an important constraint in Raivavae and in many islands of the Pacific region as well. In French Polynesia, where several islands are severely impacted by recurrent outbreaks (Chinain et al., 2020), ciguatera is a major threat to food security. Recently, André et al. (2021b) showed how ciguatera can be used to inform SCP scenarios and benefit (or impact less) the fishers in a planning process, based on the hypothesis that the reserve-induced opportunity cost to fishers is lower where the risk of ciguatera is high. Specifically, the choice of conservation areas, closed to fishing, is directed towards low cost areas, i.e. presenting lower fishery catch and/or a high ciguatera risk. In Raivavae, areas with high ciguatera risk are found in the main pass, north small pass and airport strip zones (André et al., 2021b).

During the map-based interviews conducted in Raivavae in November 2019 (André et al., 2021b), the fishers expressed their concerns on their planned actions to sustainably manage the marine resources on which they depend. Indeed, through an environmental association, local fishers are advocating the implementation of a traditional reserve design, called *rāhui*, to protect their lagoon resources. This plan has gained momentum and is strongly supported by the population, town hall authorities and church representatives. The proposed *rāhui* design is simple as it closes all fisheries in half the surface area of each lagoon district subdivision. More specifically, it is intended to be implemented simultaneously in a portion of each district, so that the design is equitable for the entire population around the island. To this end, the management committee, composed of municipal staff, fishers and church representatives, proposes to split the lagoon in front of each district in two compact zones of equal surface area that extend from the shore to the barrier reef (Figure 30b). The committee proposes to implement the fishery closure in two phases. In phase 1, *rāhui* would be simultaneously implemented on one half of each district lagoon area (four areas under *rāhui* closure, either *rāhui* zones 2, 3, 5 and 7 in configuration 1, or the others in configuration 2, cf. Figure 30b), while allowing fishing in the other half of each district lagoon areas (Figure 30b). After three

years, phase 2 would start and closed vs open areas would switch within each district. Hence, the rāhui has both a spatial and a temporal dimension.

Nevertheless, this design is questioned among fishers because of its arbitrary specifications and the closure of a significant 50% of the total area. In this context, the fishers association and the management committee requested advices regarding their plans before it gets implemented.

To respond to the fishers' concerns, we used SCP tool to build scenarios that simulate the rāhui design in terms of objectives (protection of giant clam stock), compactness, and equitable distribution in each subdivision. However, the SCP scenarios should investigate if the same amount of giant clam that would be under protection with the rāhui can be protected using less surface areas, and less induced opportunity cost to fishers, subject of disapproval.

Hereafter, in agreement with local habits, we use the word rāhui as a management approach, and also to designate each single spatial area under protection.

## 2.1 Spatial data aggregation

Spatial information is required concerning each aspect of the scenarios and various spatial data already available and published for Raivavae Island were used here, namely:

- **(i) A map of geomorphological habitats**, available for Raivavae. This map was used to evaluate which habitats, and how much of it, was included in the rāhui and in the SCP-derived reserves;
- **(ii) A map of giant clam stocks** ( $\text{ind.m}^{-2}$ ), produced from previous *in situ* fine scale fieldwork conducted in 2005 (Andréfouët et al., 2009) and generalised to the lagoon using the aforementioned geomorphological habitat map. It was updated following field investigations in 2010 (Van Wynsberge et al., 2013). As giant clams are one of the main marine resources that inhabitants rely on (Kronen et al., 2009, André et al., 2021b), we used this map as a proxy for total marine resources;
- **(iii) A refined map of fishing grounds** and associated catch (kg), produced from map-based surveys conducted among the 59 fishers in 2019, following the methodology detailed in André et al. (2021b). In short, for each fishing ground, annual catch was estimated with the questionnaires. The fishing ground shapes drawn rapidly by the fishers during the interviews were spatially refined using GIS tool, to follow the outlines of the geomorphological habitats where each fishing gear can normally be used.
- **(iv) A map of ciguatera risk**, produced from local knowledge collected during the same 2019 map-based surveys. This data takes the form of a map with multiple zones and their associated coefficients of risk, depending on the nature of the risk (proven or suspected) and its date, following methodology detailed in André et al. (2021b). This layer was then used either in conjunction with the fishery ground map to build the opportunity cost map (see below), either as a standalone map to evaluate levels of ciguatera risk (see section 4 in methods below);

This set of spatial data were then aggregated into a grid of polygons of hexagonal shape, generated using ESRI ArcGIS tessellation tool. Hexagon shape is efficient in creating networks with low edge to area ratio (Ardrón et al., 2010). The size of hexagons was set at 100.000 m<sup>2</sup> to capture the patterns of the various input maps, and to be suitable for the district sizes ( $\approx$  a minimum of 40 PU per district was targeted). PU were defined across the entire lagoon, hence for 59 km<sup>2</sup>.

For each layer, values were aggregated by each PU, to get map of giant clam stocks in number of ind.PU<sup>-1</sup>, fishery catch in kg.PU<sup>-1</sup>, ciguatera risk in risk index per PU or habitat surface areas in m<sup>2</sup>.PU<sup>-1</sup>. Then, opportunity cost was calculated for each PU, by combining fishery catch and ciguatera risk, giving equal weight to each, following André et al. (2021b) framework.

## 2.2 SCP scenarios

We conducted SCP scenarios with ©Marxan software (Ball et al., 2009). First, a set of scenarios were executed at the district subdivision scale. For each rāhui zones and its 50% of the district area, we calculated the amount of giant clam stock using the map of giant clam stocks, and designed a SCP scenario with this exact same amount of giant clam stock as a conservation target. The PU authorised for potential solutions were limited to the whole district area. This way, eight SCP scenarios were computed (two rāhui targets per district) (Scenarios 1-8).

Further, a second set of scenarios was performed, this time at the lagoon scale. For the two possibilities of rāhui configuration at phase 1, which either closes zones 1, 4, 6, and 8 (configuration 1), or zones 2, 3, 5, and 7 (configuration 2) to fishing activities, we calculated the total amount of giant clam stocks inside all four closed areas. Two SCP scenarios (9 and 10) were designed by setting these exact same amounts of giant clam stock as conservation targets. For these two scenarios, PU could be selected in the entire lagoon area.

For all scenarios, the cost function to minimise was the opportunity cost from fishing and ciguatera combined information. Among ©Marxan settings, Species (or conservation feature) Penalty Factor (SPF) is used to determine how much emphasis should be placed on ensuring the target is met, and Boundary Length Modifier (BLM) aims at decreasing the summed length of overall boundaries of selected PU, increasing aggregation (Game and Grantham, 2008). Calibration of both was optimised for each scenario, following Ardrón et al. (2010) methodology, to meet the target and to reach a compactness similar to a rāhui, or approaching it (i.e., low fragmentation of the PU network, with one to three clusters allowed, maximum).

## 2.3 Comparison of SCP solutions with rāhui

The outcomes of SCP best solutions and rāhui designs were analysed and compared on the basis of four criteria: 1) the surface area closed to fishing activities; 2) the opportunity cost to fishers; 3) the level of incidental ciguatera risk reached by each design in open area. The level of risk associated with each PU was computed according to Table 11, after ranking the coefficients of risk into four classes. 4) The habitat representation, i.e. the number of habitats included in each design.

Note that the first two criteria were parameters included in the SCP optimisation function, while the two others were not.

Table 11. Levels of ciguatera risk considered, and PU distribution associated to each class of risk. The four risk classes were delimited according to the bottom decile, median and upper decile of ciguatera coefficients.

Level of risk	risk class	coefficient	number of PU	surface area (km <sup>2</sup> )
Very high risk	4	50-764	73	5.91
High risk	3	2-49	220	17.72
Moderate risk	2	1	104	8.43
Low risk	1	0	332	26.84

### 3 Results

#### 3.1 Data aggregation outputs

Fishing pressure varied between PU throughout the lagoon. Rairua reefs and back reefs displayed the highest levels of fishing per PU, including the southern small pass. PUs located in the remaining lagoon showed lower rates, except for some PUs that encompassed spots on the main pass, Mahanatoa fringing reef, a portion of Anatonu eastern reef and Vaiuru small pass (Figure 31a).

Ciguatera risk had the highest values in Mahanatoa district near main pass and the adjacent reefs, along with neighbouring fringing reefs. Other fringing reefs all around the island displayed medium to high values of ciguatera risk (Figure 31b).

Overall, the total opportunity cost, resulting from fishing pressure and ciguatera risk, provided the highest cost for PUs located on Rairua reefs, including some back reef sections, the small pass and the main pass areas. The narrow margin of Vaiuru and Anatonu eastern barrier reef also displayed high costs (Figure 31c).

The highest giant clam stocks were located on the eastern and south-western reefs and back reefs (up to 202,560 ind. for a 100,000 m<sup>2</sup> PU), and the northern hard bottom terrace (Figure 31f).



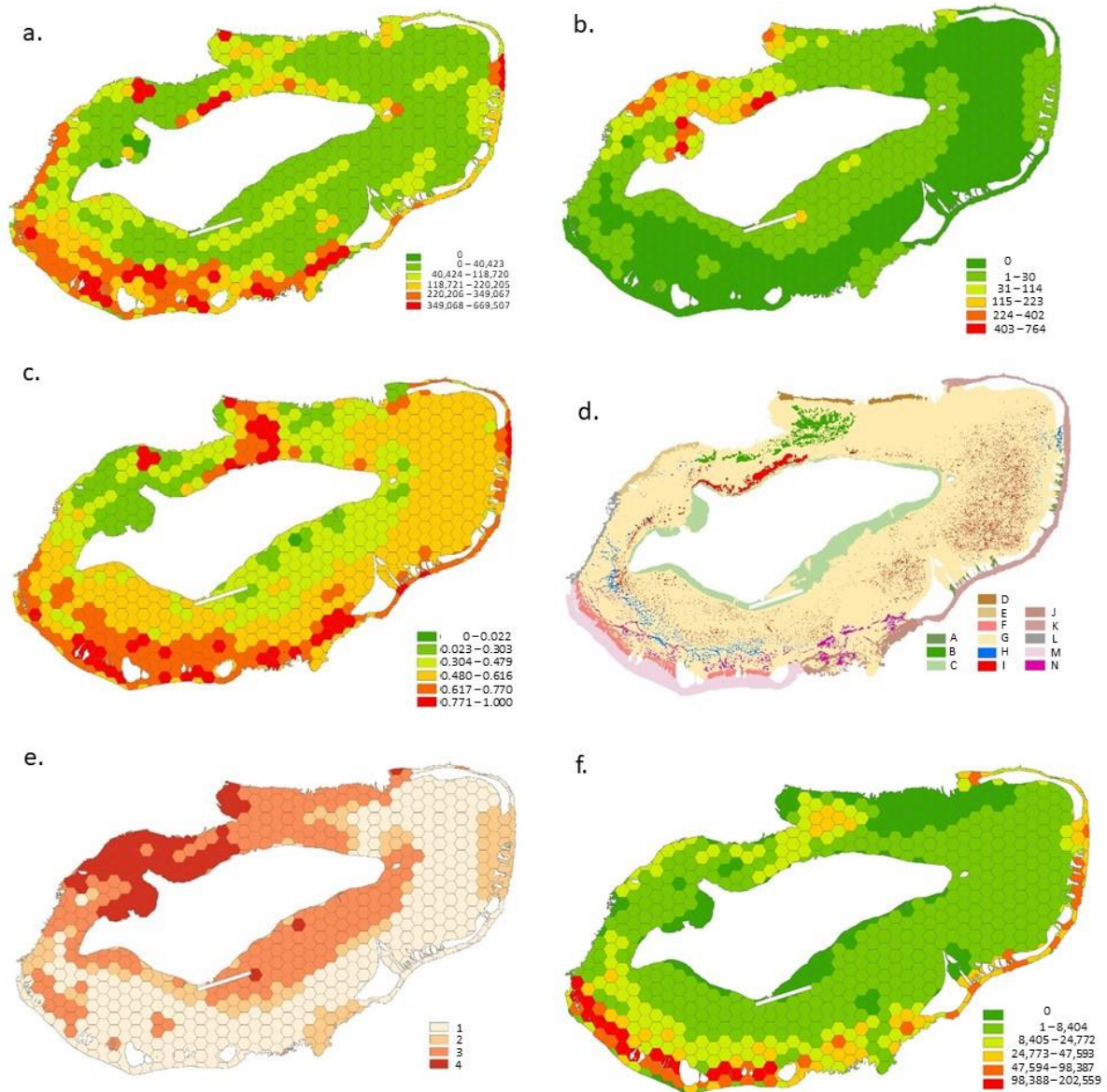


Figure 31. Ecological and socioeconomic features in Raivavae lagoon aggregated per PU.

a. Fishing pressure; b. Ciguatera risk distribution; c. Total opportunity cost distribution, resulting from combination of a and b; d. Geomorphological habitat map (A: east barrier, spillway; B: north hard ground on sedimentary terrace; C: fringing reef; D: north barrier, crest; E: north-west barrier, reef flat; F: south-west backreef, reef flat, rock; G: lagoon; H: shallow lagoonal patch reef; I: deep lagoonal patch reef; J: south barrier, crest; K: east barrier, reef flat; L: west barrier, crest; M: south-west barrier, terrace, hardground; N: south-west hardground on sedimentary terrace); e. Ciguatera risk levels from 1 to 4; f. Distribution of giant clam stocks. Maps c. and f. were used as inputs for SCP optimizations; maps d. and e. were used to analyse the incidental effects of rāhui and SCP designs.

### 3.2 Comparing SCP solutions with rāhui design

The analysis of rāhui and SCP designs were summarised in Table 12. For each rāhui, the corresponding SCP scenario could reach the same target of giant clam stock protection by closing areas 1.66 to 13.82 times smaller than the rāhui design (6.83 on average). Cost to fishers were 2.25 to 12.60 times lower for the SCP solutions than in the rāhui design (4.75 on average). This optimisation is illustrated for Rairua district (Figure 32). By contrast, and as expected according to the designs, the analysis of incidental effects showed higher habitat representation in rāhui than in SCP solutions, with a 1.20 to 3 factor (up to 9 *vs* 3 habitats for rāhui 7 *vs* Scenario 7, in Vaiuru).

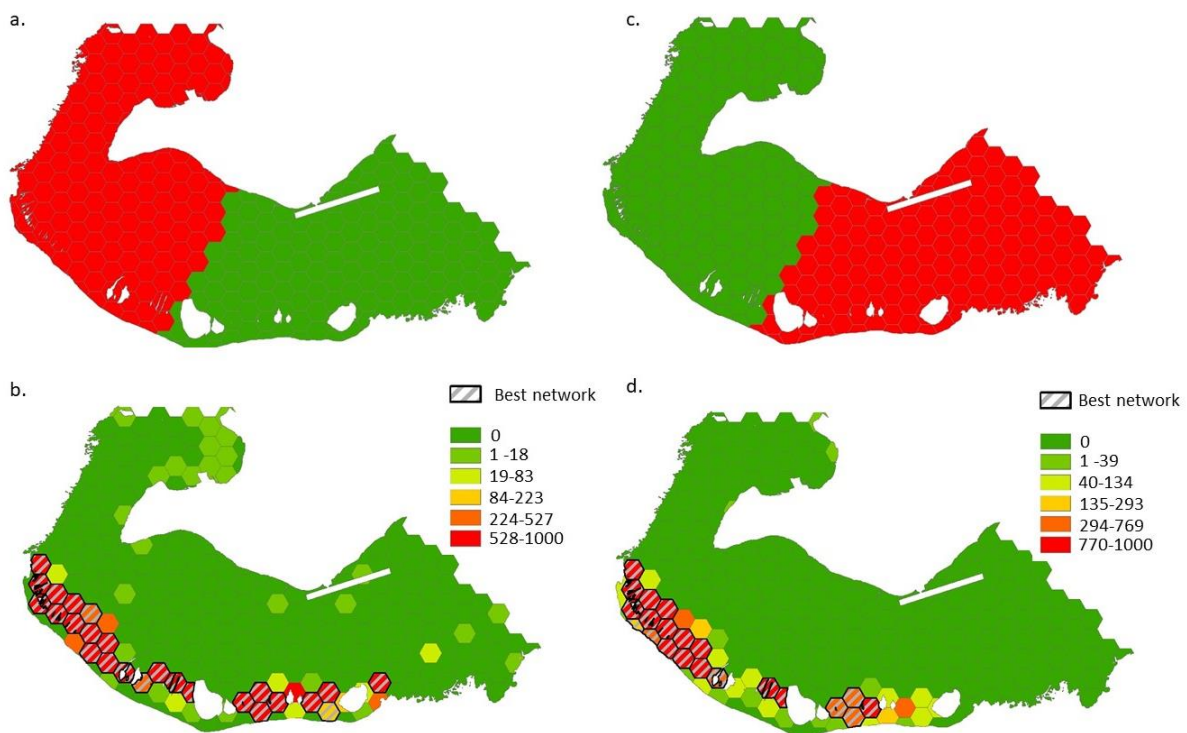


Figure 32. Map of the Rairua south-west district, under different options of management.

Top (panels a, c) rāhui design with areas closed to fisheries (red) or open (green). Bottom (panels b, d): shade colours reflect the PU selection frequency for the optimized solutions, hatched PU are selected for the best network. Panel a: rāhui 5; b: SCP optimisation with similar conservation target as in rāhui 5; c: rāhui 6; d: SCP optimisation with similar conservation target as in rāhui 6.

Scenarios 9 and 10 also showed the benefits brought by the SCP solutions, for a whole lagoon design, even more than for the summed district-based scenarios (i.e.; the 2 bottom lines of whole lagoon comparison, Table 12). Optimised solutions extended on surface areas 6.01 and 8.29 times smaller than rāhui configurations 1 and 2 respectively, and costs were 4.40 and 6.70 times lower for fishers. The level of habitat representation was 1.44 times lower for both scenarios (Table 12).

Table 12. Gauge of rāhui and optimisation scenarios, and ratios of efficiency, when performed at the scale of each district *vs* the whole lagoon.

Districts	Rāhui or Optimisation Scenarios (sc)	SPF (Marxan setting)	BLM (Marxan setting)	Giant clams (ind/m <sup>2</sup> ):	Surface area (km <sup>2</sup> )	Total Opportunity Cost	Number of Habitats included
				Stock included (rāhui) then set as a Target (scenario)			
Anatonu	Rāhui 1			312,804	6.41	37	6
	Sc 1	5	0.0001	312,801	0.46	3	3
	Ratio rāhui/sc			<b>1.00</b>	<b>13.82</b>	<b>12.60</b>	<b>2.00</b>
	Rāhui 2			744,048	7.23	49	6
	Sc 2	10	0.01	752,522	1.09	14	4
	Ratio rāhui/sc			<b>1.01</b>	<b>6.64</b>	<b>3.60</b>	<b>1.50</b>
Mahanatoa	Rāhui 3			405,908	3.50	28	5
	Sc 3	5	0.001	406,762	2.11	12	4
	Ratio rāhui/sc			<b>1.00</b>	<b>1.66</b>	<b>2.25</b>	<b>1.25</b>
	Rāhui 4			237,470	3.21	15	6
	Sc 4	5	0.001	244,338	1.04	6	4
	Ratio rāhui/sc			<b>1.03</b>	<b>3.09</b>	<b>2.37</b>	<b>1.50</b>
Rairua	Rāhui 5			3,112,274	12.18	75	9
	Sc 5	5	0.0001	3,114,631	2.35	18	6
	Ratio rāhui/sc			<b>1.00</b>	<b>5.17</b>	<b>4.16</b>	<b>1.50</b>
	Rāhui 6			2,532,236	12.18	85	8
	Sc 6	10	0.001	2,538,068	1.86	15	5
	Ratio rāhui/sc			<b>1.00</b>	<b>6.57</b>	<b>5.67</b>	<b>1.60</b>
Vaiuru	Rāhui 7			577,164	6.85	41	9
	Sc 7	10	0.001	585,708	0.61	9	3
	Ratio rāhui/sc			<b>1.01</b>	<b>11.30</b>	<b>4.77</b>	<b>3.00</b>
	Rāhui 8			1,001,423	7.32	49	6
	Sc 8	5	0.0001	1,014,838	1.15	19	5
	Ratio rāhui/sc			<b>1.01</b>	<b>6.36</b>	<b>2.61</b>	<b>1.20</b>
Whole lagoon	Rāhui 2,3,5,7			4,839,394	29.77	193	13
	Sc 2,3,5,7			4,859,623	6.17	53	11
	Ratio rāhui/sc			<b>1.00</b>	<b>4.83</b>	<b>3.66</b>	<b>1.18</b>
config. 1	Sc 9	5	0.001	4,839,135	4.96	44	9
	Ratio rāhui/sc			<b>1.00</b>	<b>6.01</b>	<b>4.40</b>	<b>1.44</b>
Whole lagoon	Rāhui 1,4,6,8			4,083,933	29.12	186	13
	Sc 1,4,6,8			4,110,045	4.51	43	11
	Ratio rāhui/sc			<b>0.99</b>	<b>6.46</b>	<b>4.32</b>	<b>1.18</b>
config. 2	Sc 10	5	0.0001	4,081,460	3.51	28	9
	Ratio rāhui/sc			<b>1.00</b>	<b>8.29</b>	<b>6.70</b>	<b>1.44</b>

At the scale of the lagoon, the four simultaneous rāhui under configuration 1 (i.e. rāhui 2, 3, 5 and 7) (Figure 33a), and the corresponding optimisations performed either at each district scale (Figure 33b), or at lagoon scale (Figure 33c) showed very different patterns of network reserve (Figure 33).

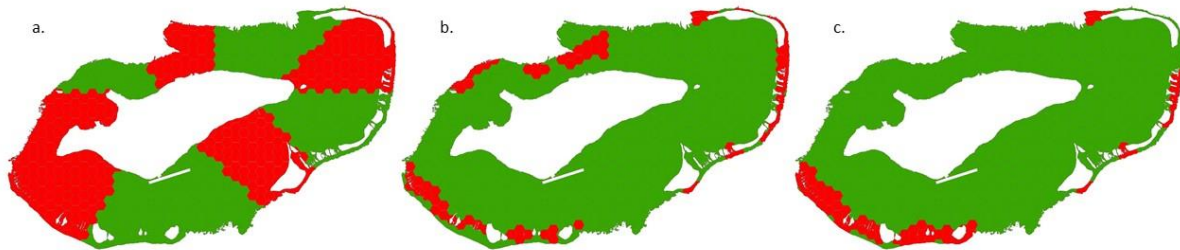


Figure 33. Example of management options, all protecting the same stock of giant clam resource (red for closed areas, green for open).

a: rāhui 2, 3, 5 and 7 (configuration 1); b: optimisation scenarios 2, 3, 5 and 7 performed at the scale of each district; c: global optimisation (scenario 9) performed at the scale of the whole lagoon.

Finally, incidental levels of ciguatera risk in areas left open for each rāhui configuration were contrasted, some having important proportions of surface areas with high to very high level of risk (Figure 34a, see rāhui 3 and 4), compared to others (rāhui 2 and 8) (see Supplementary material S1 for table of values). When comparing the areas that were left open for fishing, important differences appeared between rāhui designs and SCP optimisations (Figure 34b). Particularly, SCP allowed for larger areas open to fisheries, and higher surface areas of low ciguatera risk, except for scenario 4, due to the high risk of ciguatera across this whole Mahanatoa district.

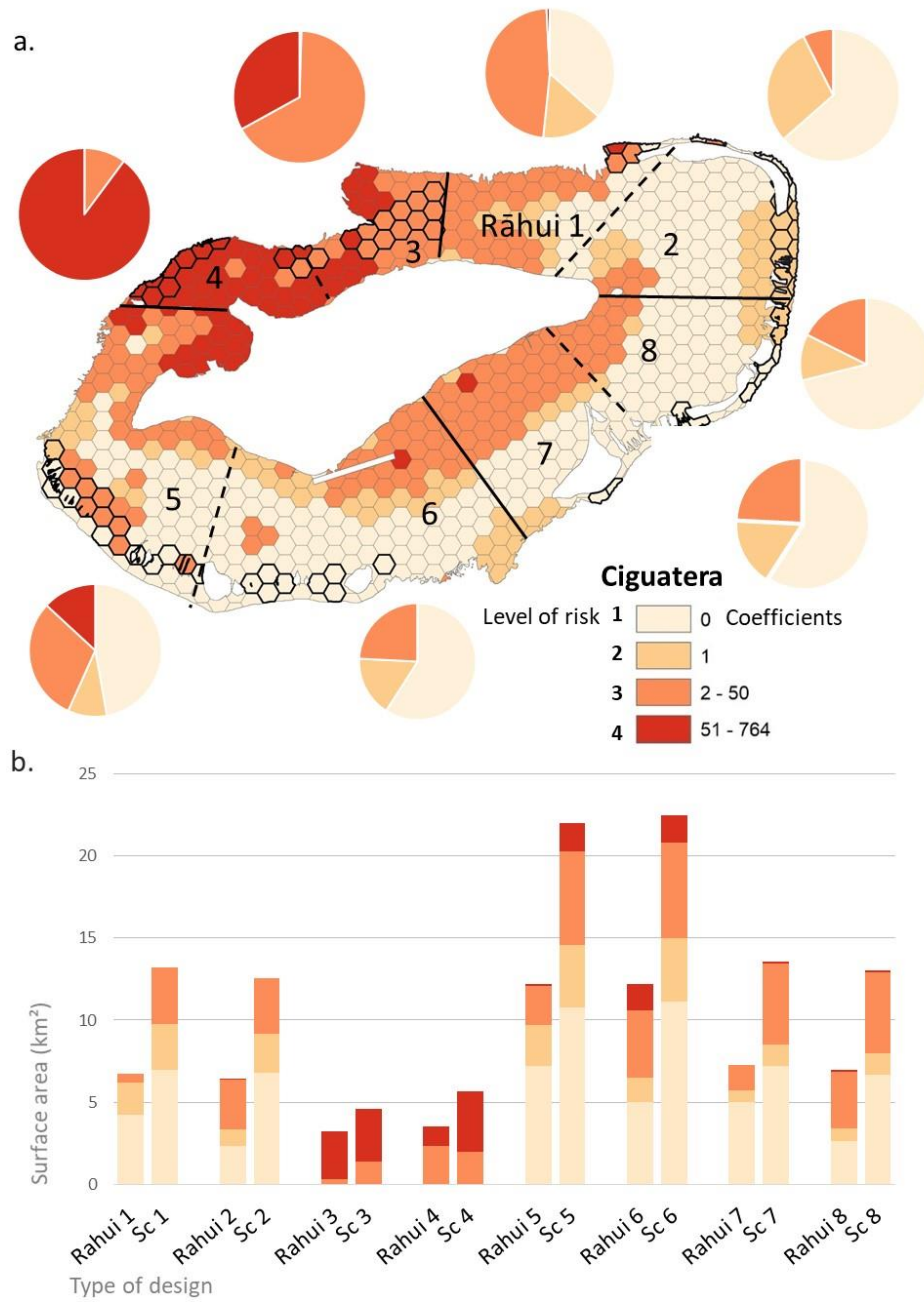


Figure 34. Incidental levels of ciguatera risk in the reserve designs.

a: map of the four levels of ciguatera risk, and pie charts for each rāhui showing the proportion of areas within each level of risk. Bold PU shows solutions for (scenarios 2, 3, 5, 7). b: levels of ciguatera risk and their respective surface area in the district zone left open for fishing activities, under each type of design (note that, for instance, when rāhui 1 is implemented, the domain open for fishing corresponds to rāhui 2).

## 4 Discussion

In this study, the general objective was to seek pathways to optimise the re-establishment of a traditional indigenous fishery management through a collaboration with quantitative planning methods. We explored how the efficiency of a French Polynesian traditional rāhui design could be enhanced using spatial prioritisation tools and spatial information on (i) marine resource abundance (giant clam stock), (ii) socio-economic costs that integrate fishing pressure and ciguatera risk, (iii) incidental habitat diversity (at geomorphological level) and (vi) incidental level of ciguatera risk.

The SCP design either mimicked the same district spatial limits of rāhui, or extended across the whole lagoon. Several SCP designs identified solutions that were less restrictive for fishers owing to reduction of protected surface areas and socio-economic costs induced, while achieving the same rāhui's resource targets. Comparisons were conducted among the different SCP designs and rāhui design in terms of quantitative outcomes. Incidental level of ciguatera risk and number of habitats included in each design were analysed as well.

Several findings that could serve to evaluate other case studies in other traditional management contexts can be highlighted. They include 1) the improvements that can be brought to traditional designs, 2) a critical view on the quantitative methods used to optimise the indigenous design set in a very local and specific context, and 3) the final practical recommendations.

### 4.1 Improvements brought by SCP designs to rāhui

The analysis performed here brings key information that should raise the interest of stakeholders and particularly the local fishers, who were questioning the initial rāhui design. Results showed that SCP solutions brought substantial enhancements from the perspective of surface areas, socio-economic costs and levels of ciguatera risk. The different SCP solutions identified reserve designs 6.83 times smaller and 4.75 times less costly, on average (Table 12).

The giant clam stocks included in rāhui varied substantially between the different districts, e.g. by up to a factor of 13 in the case of rāhui 4 in Mahanatoa, *vs* rāhui 5 in Rairua (Table 12). This is explained by an uneven spatial distribution of giant clam stocks throughout the lagoon (Figure 31f). Accordingly, the SCP scenarios 9 and 10 for the whole lagoon displayed solutions that were mainly positioned on one district only, Rairua (Figure 33), which is consistent with the stock abundance.

Working at both district and lagoon scales raises the problem on deciding which scaling option would be best, as both could generate benefits and limitations regarding ecology or social dimensions (Mills et al., 2010; Pressey and Bottril, 2009; Kabbadj et al. 2018). In this study, optimisations at lagoon scale (scenarios 9 and 10) provided the most efficient networks, both smallest and least costly (Table 12), but they were not equitable among the different districts since mostly Rairua was selected. Conversely, rāhui design and scenarios 1–8 were more balanced, by design. This result, opposing districts *vs* whole island scenarios, was consistent with findings from previous SCP studies. A study carried out on an island in the Philippines by Weeks et al. (2010) found that while overall efficiency was twice as high and

40% larger at the island scale than considering local tenure boundaries, the latter would likely be more socio-economically viable and equitable. Another SCP study in the Tuamotu Archipelago, in French Polynesia (Kabbadj et al., 2018), reached similar conclusions, this time comparing each individual-island solutions to a solution computed for the whole archipelago. Solutions for each island were less efficient overall (0.71 *vs* 0.99 level of equity expressed in relative cost for the island scale and the archipelago scale, respectively), but avoided putting all the conservation costs to one or two islands only. Here, the concept of spreading the cost induced by a reserve among the districts was naturally accounted for in the *rāhui* conception.

## 4.2 SCP approach: original contributions, nuances and limitations

Before systematically recommending the use of SCP approaches to optimise *rāhui* or alternative forms of community-based management, it is worth taking some precautions.

First, the temporal dimension is critical to the *rāhui* concept (Gnanalingam et al. 2021), and the study conducted here could not integrate this dimension. Comparisons of the design performances are valid for phase 1 only, for the first implementation. To go further, any data driven simulation (not only SCP) would ideally require to model several cycles of opening/closing to fishery, to assess the full impact and value of such a rotating closure, as for sea cucumbers in Australia (Plagányi et al., 2015), or abalones in New Zealand (Gnanalingam et al., 2021). In the case of *Raivavae*, this component would require knowledge on the giant clam population dynamics (Van Wynsberge et al., 2017), but few data is currently available specifically for *Raivavae*. We lack robust knowledge on too many local population dynamic factors (growth, natural mortality, fertility, reproduction and recruitment success, etc.) to run a realistic model (as attempted by Van Wynsberge et al., 2013), since they are bound to evolve following the initial ban.

Modelling temporal aspects in SCP is challenging as these tools implicitly tackle static conservation planning problems (Possingham et al., 2009). Nevertheless, a few SCP studies considered temporal dynamics using multiple sets of the same input data, such as sea surface temperature time series (Makino et al., 2014) or monthly fishery bycatch data (Grantham et al., 2008). In that perspective, a temporal *rāhui* study would ideally require additional consecutive data sets collected post-implementation. Moreover, additional important factors would be necessary, such as dynamic of fishing effort, its spatial reallocation, catch levels and consequences on the stocks. For instance, Halpern et al. (2004) demonstrated that protecting 50% of the surface area of a site, which is similar to this *rāhui* design, leads to a theoretical fishing pressure doubled in the open area, but it would allow for a three-fold compensation factor in resource production and export production. These considerations are not taken into account in SCP optimisation, which aims to minimise the size of the reserves to decrease costs to users. We acknowledge that the temporal dimension is missing from our assessment, nevertheless, the initial phase is critical and brings useful information, allowing to recommend careful planning to optimise the lagoon exploitation and conservation.

Second, SCP classically sets objectives of biodiversity, most often using some proxies or surrogates, like for instance subsets of species, habitats distribution maps, or environmental variables. Previous SCP studies in Fiji had focused on adaptive co-management of SCP with the communities (Weeks and Jupiter, 2013), or on the integration of socio-economic factors

to SCP design considering multiple stakeholders (Gurney et al., 2015), which converges at some point, with this study. However, these plans were always oriented towards biodiversity conservation, both targeting the representation of geomorphological habitats. Here, to obey rāhui's objectives to preserve marine resources, the SCP scenarios were set to reach objectives of resource representation, namely giant clam, which was considered as a proxy for all resources protected by the rāhui. This way, some recommendations emerging from the review on SCP in Pacific Islands (André et al. 2021a) were applied to better adapt SCP tool to the local context and needs, which can be different from strict biodiversity conservation *per se* (Gurney et al. 2021). For the present study, a distribution map of Raivavae finfish abundance and diversity would have been valuable, but was not available. For instance, the ProcFish fishery study (Kronen et al., 2009) was the last comprehensive study that censused fishes *in situ* in the lagoon, yet it did not provide enough data (insufficient station replicates per habitat) to be able to infer a reliable finfish resources map. If a new census is to be undertaken, adequate sampling efforts are advocated to allow for generalisation using habitats (Van Wynsberge et al., 2012; Knudby et al., 2011).

Third, while only the giant clam stock could be integrated as a resource, the socio-economic costs were inferred from recent (2019) interviews of the most active fishers in the island (André et al., 2021b), who commonly target both invertebrates and finfish. It was decided for SCP scenarios to account for all fishers and fishing activities when mapping costs, hence, majoring the importance of the socio-economic aspect of the SCP scenarios. The inclusion in the cost function of the ciguatera risk follows the same logic.

Fourth, here, we emphasised ciguatera as a critical input of the SCP scenarios. In our study, SCP design potentially decreased the risk for fishers to consume ciguatoxic products by providing wider access to fishing grounds with low risk of ciguatera (Figure 34). This strategy is relevant to identify reserves for an island that is severely impacted like Raivavae (André et al., 2021b), where it is an important component of livelihoods and fisheries. This can be also useful elsewhere, as the problem is widespread at least in the Indo-Pacific and the Caribbean regions. However, the ciguatera data set should be used with precaution. Indeed, ciguatera risk map was not inferred from fish toxicity survey data but from map-based interviews, i.e. it relied mainly on the population's local knowledge and perception of ciguatera risk, which is difficult to assess. However, this knowledge was shown to be quite accurate, as is also the case in other islands in French Polynesia (Chinain et al., 2010; Morin et al., 2016). Further, the map of ciguatera risk we used was generic and not species-specific, but actually, within a given area, it is well established that not all species are susceptible to cause ciguatera poisoning (Chinain et al., 2010; Morin et al., 2016). Thus, nuance is required as zones with high ciguatera risk could still be fished by targeting only low risk species.

Precaution must also be taken when putting ciguatera in perspective with conservation. Indeed, implementing reserves/ rāhui does not prevent ciguateric micro-algae development in protected areas, as evidenced by the severe mass-poisoning event in Rapa iti (Austral Archipelago, French Polynesia) in 2009-2010, which primarily involved an area subject to temporary rāhui (Chinain et al., 2020). This rather raises the point that when an area is under fishing ban for a while, fishers lose or cannot update locally their knowledge on ciguatera spatial risk, which is known to vary in time and space (Bienfang et al., 2008).



Finally, other aspects that interplay in a rāhui building process were obviously not captured by SCP. For a population, the interest of building and managing rāhui projects also lies in multifaceted social dimensions such as federating a community (Govan, 2009). Beyond fisheries management, these local, bottom-up initiatives often help strengthen social networks, raise awareness on the environment and ecological considerations through resource stewardship, and the feeling of responsibility for sustaining resources for next generations, as shown by the educative rāhui in Anaa Atoll, French Polynesia (Filous et al., 2021).

### 4.3 Practical recommendations

A number of pragmatic advice emerge from this study, which can be generalised to other contexts with a reef fishery component. First, integrating a SCP step in the rāhui process can increase efficiency of the traditional rāhui design, with local communities support, by decreasing the spatial extent of closures and the opportunity costs to fishers in terms of fishing ground access and exposure to ciguatera risks.

Second, for areas impacted by ciguatera, as ciguatera is variable in time and space, we recommend the continuous and systematic data collection of ciguatera poisoning cases and their spatial occurrence. A tool allowing the on-line report of poisoning cases is already in place in French Polynesia ([www.ciguatera.pf](http://www.ciguatera.pf)), but could be strengthened if the population perceive direct interest in sharing this information for their lagoon management and design of the next phase of rāhui rotation. An additional precious source of reliable information could be test on fish toxicity, but these are very costly.

Third, we recommend monitoring the marine resources on a regular basis (as in Gnanalingam et al., 2021). The Raivavae population expressed interest in assessing the impacts of rāhui implementation on the stocks/abundance of resources on a regular basis, so as to understand its impact *sensu* Smallhorn-West et al. (2019, 2020b). This encouraging initiative could benefit from technical support by local authorities with before–after, control–impact with paired series (BACI and BACIPS, the ‘impact’ being here the creation of the reserve) studies or other protocols (Smallhorn-West et al. 2020b). In return, a community-based participatory approach could help produce valuable spatialised and quantified long-term datasets for further management and adaptive conservation spatial planning.

## 5 Conclusion

In the present study we demonstrated the interest of SCP contribution to optimise traditional reserve designs for sustained fisheries, as occurring in French Polynesia and further in the Pacific Ocean, as well as globally in many indigenous communities from the poles to the equator. The Raivavae Island and French Polynesian rāhui case study provide one example of possible collaboration between traditional management practices and scientific, data-driven approaches. Considering the benefits of social cohesion brought by a rāhui, SCP prioritisation and planning should be seen, as usual, as one useful step in a suite of design and management process towards implementation in coordination with indigenous communities (Wendt et al. 2016; Watson et al. 2021). In our case study, the benefits are unequivocal in terms of resource representation *versus* cost ratio. Consequently, we strongly recommend for the benefits of all,

to be cautious when putting forward traditional practices without recommending in the same time possible pathways for objective diagnostics and optimisation, including through the collection of relevant data when it is imperative to use a sound accurate baseline, for instance in terms of stock levels. In the same time, it is necessary to remain aware of the limitations of the quantitative data-driven approach.

Basically, the work performed here prior to the re-establishment of traditional practices can be recommended to any locations where local indigenous traditions remain strong. The collaboration between approaches is a sound way to reinforce the confidence put into traditional approaches previously used when circumstances were very different from most modern situations. Despite the broad potential, geographically speaking, of this simple advice, the assessment, test and implementation phases of similar work should be necessarily very local in scope. Also, while a suite of SCP spatial tools were applied in this case study, alternative optimisation pathways exist if available data or management traditions are not spatially explicit and area-based.

### **Acknowledgements**

The study was funded by the MANA (Management of Atolls) project (grant ANR-16-CE32-0004), by the PANGEA project (grant from Délégation à la Recherche de Polynésie française to Institut Louis Malardé, Conv. N° 06575/MED of September 28th, 2018), and by a doctoral fellowship from Sorbonne Université to LVA. We thank the fishers and the population of Raivavae Island for the discussions on their fishing habits and ciguatera knowledge.



## Chapter V – Diversification options



## Chapter V – Diversification options

### Spatial solutions and their impacts when reshuffling coastal management priorities in small islands with limited diversification opportunities

Laure Vaitiare André <sup>1,2</sup>, Simon Van Wynsberge <sup>3</sup>, Mireille Chinain <sup>4</sup>, Clémence Mahana iti Gatti <sup>4</sup>, Vetea Liao <sup>5</sup>, Serge Andréfouët <sup>1</sup>

1 IRD Institut de Recherche pour le Développement – France, UMR 9220 Entropie (Institut de Recherche pour le Développement – France, Université de la Réunion, Université de la Nouvelle-Calédonie, Ifremer, Centre National de la Recherche Scientifique), BP A5, 98848 Nouméa cedex, New Caledonia

2 SU Sorbonne Université, 21, rue de l'école de médecine, 75006 Paris, France

3 Ifremer Institut Français de Recherche pour l'Exploitation de la Mer, UMR 9220 Entropie (Institut de Recherche pour le Développement – France, Université de la Réunion, Université de la Nouvelle-Calédonie, Ifremer, Centre National de la Recherche Scientifique), BP A5, 98848 Nouméa cedex, New Caledonia

4 ILM Institut Louis Malardé, Laboratoire des Biotoxines Marines, UMR 241 EIO (Ifremer, Institut Louis Malardé, Institut de Recherche pour le Développement, Université de la Polynésie française), BP 30, 98713 Papeete, Tahiti, French Polynesia

5 DRM Direction des Ressources Marines, Fare Ute, BP 20, 98713 Papeete, Tahiti, French Polynesia

#### Submitted to Journal of Applied Ecology

André, L. V., Van Wynsberge, S., Chinain, M., Gatti, C. M. I., Liao, V. and Andréfouët, S. A. Spatial solutions and their impacts when reshuffling coastal management priorities in small islands with limited diversification opportunities.

**Abstract:**

In small islands, potential for new coastal activities and management options are often spatially limited. To reduce dependence on external factors and increase resilience of the populations in the face of global changes and international market fluctuations, a recommended pathway consists in diversifying the activities, accounts for artisanal fisheries to ensure local food security, and reserves space for ecosystem conservation to sustain their functions. In this study, we used systematic prioritization tool with single and multi-objective zoning to explore the feasibility of various levels of spatial diversification scenarios in Gambier Island lagoon (French Polynesia). The island black pearl culture activity from *Pinctada margaritifera* oysters is world-famous and economically critical, but stakeholders are also committed to economic, livelihood and environmental sustainability. At their request; the scenarios allowed foreseeing diversification options in marine management including optimised reallocation of the marine farms, identification of conservation areas for the wild oyster stock and for remarkable live coral communities, while accounting for the juvenile spat collection zone and oyster restocking zones defined within historically traditional management zones. Various types of costs were applied to minimize impacts of the different solutions, including surface area and artisanal fisheries. In addition, ciguatera seafood poisoning risk was also accounted for, since it drives fishing ground selection by fishermen. Robustness was analysed with different boundary penalty and costs layers. Solutions were compared among scenarios and impacts of each zone on one another were quantified, which allows setting sound quantitative baselines for further discussions among stakeholders and with management governance entities. The Gambier case study shows that exploring diversification options in small islands using systematic prioritization tools is possible and can efficiently provide local managers with tailor-made plans adapted to very specific island development questions to face the challenges of our times

**Keywords**

Sustainable marine management, Multi-objective systematic prioritization, Artisanal fisheries, Aquaculture, French Polynesia, Coral reef lagoons

## 1 Introduction

Globally, marine ecosystems are home for a high biodiversity and provide vital services to humans. This is particularly true in small islands, where communities highly depend on marine resources (Cinner et al., 2012; Lau et al., 2019). Coastal ecosystems also face important pressures and degradations, both from local and global origins (Jupiter et al., 2014; He and Silliman, 2019; Payri and Vidal, 2019), and coastal management has evolved globally during the past decades toward more integrated approaches (Birch and Reyes, 2018), as there are increasing evidences that a better articulation between the various human activities help mitigate impacts on ecosystems and eventually improve benefits for human society.

In small islands, human uses of coastal areas are multiple, generally including recreational, food security and income-generating activities such as tourism, transport, fisheries or aquaculture. These activities are often dependant on global markets and can fluctuate due to outer factors such as politics, transport issues, pandemic situation, climate change, shortage of resources in isolated areas, and so on. Local factors such as ecosystem health and productivity can also directly affect these activities. These risk factors greatly threaten the sustainability of the activities and underline the vulnerability of the populations, especially when the community is organized around one single activity (Fenichel et al., 2016).

Diversifying the panel of activities is one way to secure communities' well-being, incomes and resilience in the face of global disturbances and risks (Barrett et al., 2001; Bowser and Nelson, 2012; Kasperski and Holland, 2013). For instance, in Asia, maintaining seaweed culture along with touristic zones is a precautionary back-up activity to balance tourism fluctuations and mitigate the risks of economic and livelihood collapse (Andréfouët et al., 2021). Securing space and time for multiple activities, including artisanal fisheries also provides fundamental services to the communities, such as food security (Bell et al., 2011; UN, 2015).

The development of activities, however, is often impeded by other factors. This is the case, for example, of ciguatera poisoning, which causes restrictions to reef-fisheries in many tropical islands and notably in the Pacific. Ciguatera is due to dinoflagellate micro-algae whose toxins accumulate in the marine food web. This can cause mild to severe poisonings in human consumers and lead to serious threats to food safety (Chinain et al., 2020). In small islands, this factor, as well as other activities that can be in competition or rely on the same resources, can generate spatial conflicts. Local management authorities, through public inputs, need in these situations to make plans for a wise, equitably shared and accepted use of the coastal domains. Moreover, local managers and stakeholders as well should also account for local conservations priorities, to efficiently protect representative habitats and species deemed of interest or endangered. In fact, in many places, urgent conservation matters have been the catalysers of spatial plans (reviewed for the Pacific islands in André et al., 2021a).

To help define spatial management plans, marine spatial planning can offer efficient ways to explore solutions. Marine spatial planning, which is promoted by the Intergovernmental Oceanographic Commission of the UNESCO (Ehler and Douvère, 2009), has already been useful in many different contexts for several non-governmental organisations and governance entities (from local to national). Most notably, systematic conservation planning (SCP) is a data-driven optimisation approach that allows for the identification of the best objective-cost

compromises in selection of priority sites (Margules and Pressey, 2000). Minimizing socio-economic costs generated by the management plan to local communities, is deemed necessary to increase acceptability of the plans and compliance of the populations while best fitting their needs. Several planning toolboxes are available and widely used including Marxan© and its extensions (Ball et al., 2009; Watts et al., 2009), Zonation© (Moilanen et al., 2009), C-Plan© (Pressey et al., 2005) and Prioritizr© R package (Hanson et al., 2021). Among the options, a multi-objective zoning approach allows identifying within the same plan different management zones with different status, such as strict protection with no access, recreational zones with no extractive activity, areas dedicated to aquaculture, and open zones. Incentives to design such spatial plans can also be prompted by new economic interests and constraints.

The value of SCP approaches in the case of communities willing to, or being forced by the circumstances, to shift into diversification of activities is certainly critical, but to the best of our knowledge, few case studies exist on planning for activities other than fisheries and conservation in the case of small islands (but see Delavenne et al., 2012; Venier et al., 2021 in continental European contexts). In this case, SCP objectives would be to maximize spatial uses without conflict, and conservation per se may not be a priority, although the plan can also include biological and fishery stock conservation objectives (Krueck et al., 2017, Cabral et al., 2020). Other criteria can include prioritization to maintain or enhance existing activities with environmental good practices, while allowing the development of other activities, either new or more traditional such as fisheries. Specifically in small tropical islands such as atolls and volcanic islands with steep slopes, usable land area and resources are generally limited and only marine area offer substantial pathways for viable diversification. Nevertheless, marine spaces that most island communities are able to easily access are mainly restricted to coastal shallow areas, which are relatively narrow and with limited carrying capacity. Thus, maintaining livelihood sustainability is capital but space limitation is very challenging (Cinner, 2014; Hurtado et al., 2013). Spatial optimization approach can be instrumental in helping to plan it.

Herein, we demonstrate through a south Pacific Island case study a SCP application to devise the diversification of activities in an island initially strongly devoted to aquaculture, in particular black pearl farming. This activity has now spatially reached its maximum capacity while in the same time the international trade has decreased, partly due to the Covid pandemic. At the request of the local stakeholders and governance entities (meeting in Nov. 2019 and web workshop in Oct. 2020), we propose to explore zoning plans integrating new priorities (such as leaving more room for traditional fishing), the spatial reshuffling of presently too extensive pearl farming-related concessions, the integration of pearl oyster restocking zones, and the environmental factors (ciguatera-prone areas, habitat quality and remarkable biodiversity) all at play in a multi-zone scenario. Finally, generalization from this case study to the broad problem of diversification of spatial activities that can be very specific in islands with low diversification potential is discussed.



## 2 Study site context and specific objectives

### 2.1 Pearl oyster farming in French Polynesia

We base our study on the income-generating case of pearl oyster *Pinctada margaritifera* farming in French Polynesia. Traditionally, this bivalve species was used for adornments and to carve fishing hooks. From the 1800's, the oysters were collected from mostly a dozen of productive islands for the international trade and button industry, which significantly contributed to the economic growth of French Polynesia, leading to significant decrease of stocks that was observed as early as the early 20<sup>th</sup> century. Demand and collecting dropped after the Second World War due to the plastic revolution and new economic opportunities and developments took place in French Polynesia following the settlement of nuclear weapons test sites in the Tuamotu-Gambier archipelago (Le Pennec, 2009).

Natural pearls were only occasionally found in oysters before the government promoted programs in the 1960's to produce cultured black pearls, following practices already in use in Asia. As a result, pearl production grew exponentially in the 1980-1990's due to initial high prices that quickly made pearl farming the second source of income for French Polynesia after tourism. However, financial gains for individual farmers soon dropped due to overproduction, decreased selling prices, and anarchic sales; consequently, the whole sector has been in crisis for more than 20 years now. For now, pearl farming remains a valuable resource but is dependent on international market fluctuations, government management (or lack of decisions, for instance to limit production and monitor quality), and local lagoon disturbances such as oyster mortalities.

In a nutshell, quality pearl production takes 3 to 4 years and relies on two distinct activities: (i) spat (juvenile) collection and (ii) oyster (adult) farming. Harvesting wild adult oysters is banned in French Polynesia, in order to protect wild stocks. Due to the high demand, and presence of fertile wild stocks, farmed oysters come from spat collection achieved with lines of collectors deployed in the water column. Spat collection success is however erratic in time and space, and depends on reproductive wild oyster stock abundance in the lagoon, hydrodynamic circulation and suitable environmental conditions at all oyster life stages (Sangare et al., 2020). Then, oyster farming includes : i) managing spat growth until they reach sufficient size to be grafted, ii) grafting of a bead nucleus, and then iii) monitoring the growth of grafted stocks until, eventually, iv) pearl harvesting. Farms are organized through central working building on stilts above the lagoon, in which manipulations and grafting take place, after spats and oysters get transported back and forth from hectares of immersed lines of spats collectors and baskets of adult oysters. Lagoon space is thus a critical resource. A public technical service, the *Direction des Ressources Marines* (DRM), controls the farmed areas through the delivery of yearly marine concessions, which are subjected to a fee. Conversely, spat collecting lines can be deployed anywhere in lagoon areas, except in Gambier Island and Ahe atoll (Tuamotu archipelago) where it is authorized only in a single area.

In the face of the pearl market crisis and environmental risks such as mass mortality events (Andréfouët et al., 2015), DRM manages the activity to improve sustainability of both farmers' income and ecosystem quality. This strategy translates into reducing exploited surface areas, to eventually reduce production and pressure on the exploited lagoon ecosystems. An

additional measure is restocking the lagoon with adult oysters after pearl harvest as broodstock instead of killing them, preferably in favourable, dedicated areas at high density to maximize reproduction and, eventually, ensure sustainable spat production. At the same time, decreasing pressure on the ecosystems, in addition to establishing conservation zones, is expected to benefit other activities such as artisanal fisheries.

## 2.2 Specificities of the Gambier

In French Polynesia, among the 31 islands of Tuamotu-Gambier and Society's archipelagos, where spat collection and pearl oyster farming activities take place, the Gambier is the most productive island (with 1.7 million pearls in 2020, i.e. more than 25% the country's production (DRM, 2020a)). Some Gambier's pearl producers organized themselves into an economic interest group, committed towards the best quality, and keen on managing the sustainability of the activity.

Gambier is located at 135°W longitude and 23.20°S latitude, at 1,650 km from Tahiti, the main island in French Polynesia (Figure 35). It is a small archipelago with seven high islands within a single lagoon of 486 km<sup>2</sup> bordered by a discontinuous barrier reef. Not all islands are inhabited and Mangareva Island is home to the majority of the 1530 inhabitants (based on the 2017 census). The lagoon is one of the most complex across all French Polynesia due to the diversity of its geomorphological and benthic habitats, which includes remarkable live coral assemblages and notably *Fungia* spp. communities that are unique in French Polynesia (Hoekseman and Benzoni, 2013; Chevalier, 1974). The lagoon still presents a high stock of wild *P. margaritifera* oysters, although limited to several locations nearby the center of the lagoon (Andréfouët et al., in prep.).

As in many Pacific Ocean tropical islands, fishing is widespread in French Polynesia as a cultural heritage, recreational activity and for food provision in every households (Bell et al., 2011; André et al., 2021a). However, ciguatera poisoning outbreaks occurred in Gambier, and it still represents a significant issue (Chinain et al., 2020). Ciguatera causative agent is a dinoflagellate in the genus *Gambierdiscus* named after the Gambier Islands, where it was first discovered back in the early 1970s (Yasumoto et al., 1977). Consequently, local fishers are particularly aware of ciguatera risk and local knowledge on areas and species at risk is an important driver for fishing ground selections based on personal perception and shared information of previous poisoning events (Chinain et al., 2020). Today, the whole lagoon area is theoretically open to fisheries, but in practice, some areas are less fished or totally avoided and then 'protected' *de facto* due to ciguatera risk.

In addition, in the past, Gambier inhabitants used to temporarily ban fishing, including wild oyster harvest, in rotating delimited areas (a practice named *rāhui* in Polynesia (Bambridge, 2016)). This was deemed necessary to sustain fishery resources in difficult times and in preparation of special events requiring lots of catches. The four historical traditional management areas around Mangareva Island are still vivid in inhabitant's memory. Lagoon users and the population in general would strongly welcome and endorse a revival of these traditions. Building upon this, DRM proposed to implement oyster restocking programs in sub-areas within these four traditional areas, and prohibit fishing any resource.

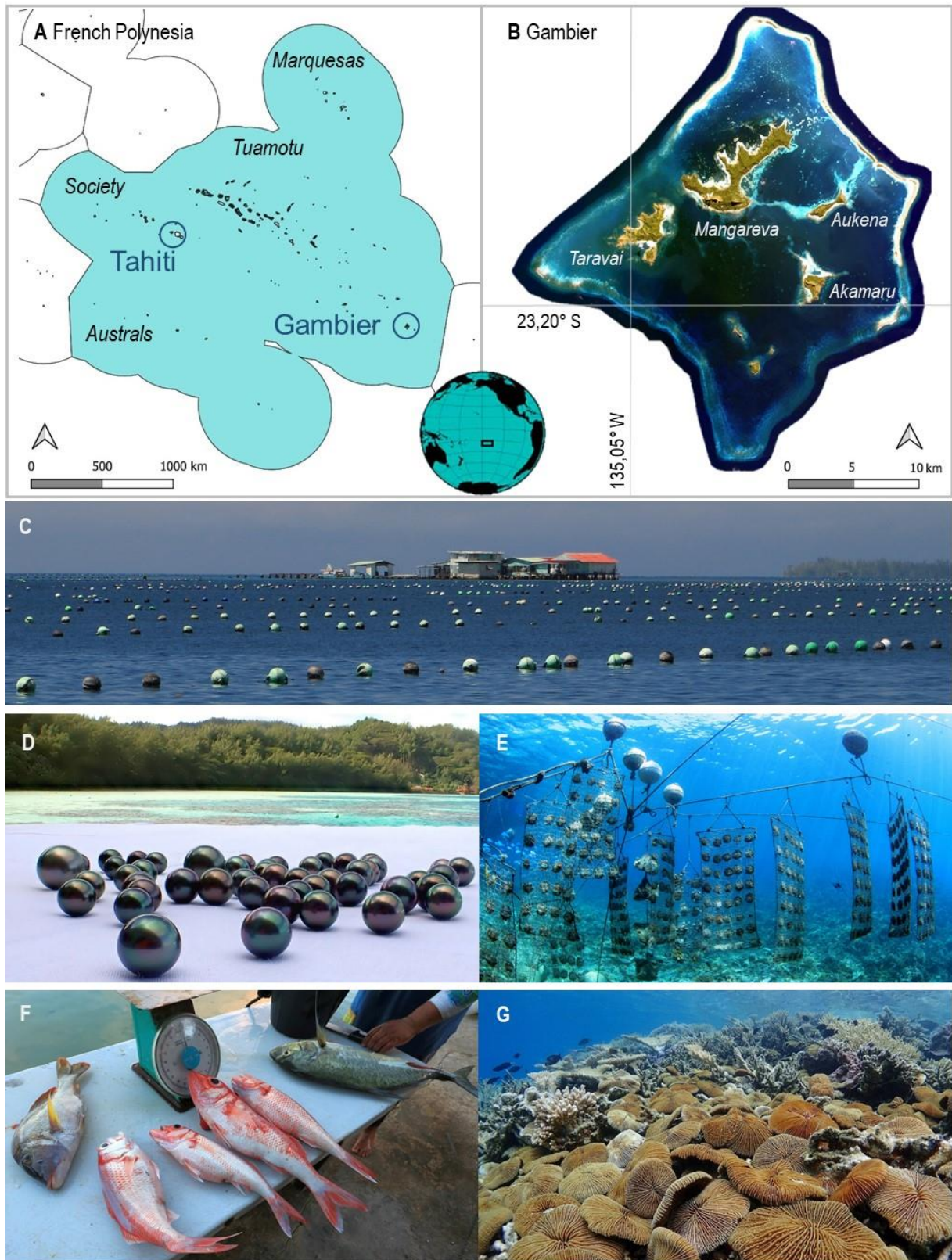


Figure 35. Study-site characteristics.

A. Location of Gambier in French Polynesia. B. Gambier lagoon and islands. C. Concessions for pearl oyster farming. D. Black pearls harvested in Gambier. E. Baskets of adult pearl oysters. F. Local catches and fishery for livelihood. G. Remarkable *Fungia* coral communities. (All photos S. Andréfouët apart from photo D: V. Liao).

### 2.3 Diversification objectives

In the Gambier lagoon, inhabitants need to live and work in a space that currently prioritizes black pearl production for the international jewelry market, but where artisanal fisheries also take place (mainly subsistence fishing) taking into account ciguatera poisoning risk. DRM wishes to work options away from this ‘business-as-usual’ scenario by reducing the extent of areas devoted to pearl farming *per se* (i.e., spat collection and farm concessions), while leaving open more areas for restocking and diversification into other activities including fishing.

Here, the idea is to compare this business-as-usual scenario and these diversification options with also a no-farming, ‘back-to-tradition’ scenario that would only account for fisheries and a rāhui resource management scheme. The main objectives of this study are to evaluate what are the spatial trade-offs required to allow, and maximize, each activity within these different scenarios, considering the major socio-economic and ecological components at play, and to what extent their relative importance may vary between scenarios and options.

Practically, we first translated the present situation into a ‘business-as-usual scenario’ (BAU). Then we conceived two multi-zone systematic prioritization problems. The first one gave priority to the current income-generating activity, pearl farming, as well as conservation, as a first degree of diversification (Scenario 1). The second one further integrated fisheries while also mitigating ciguatera risks, as a second degree of diversification (Scenario 2). Finally, a ‘back-to-tradition’ option focused only on fisheries and conservation for resource management (Scenario 3), banning pearl farming activities. This last one was conceived as a one-zone systematic prioritization problem. For each option, the costs generated (i) for fishers (through the loss of fishing grounds), (ii) for pearl producers (through the loss and spatial change of farmed areas) and (iii) for the remarkable benthic assemblages (through the overlap of remarkable habitat with impacting activities) were quantified. Finally, the likely impacts of these diversification strategies for sustainable livelihoods were discussed.

## 3 Methods

### 3.1 Study design

The Gambier lagoon study area extends from the various islands coastlines to the barrier reef crest and covers 486 km<sup>2</sup>. The study design consists in four main steps. Firstly, we collected spatialized data at relevant resolution sourced from either previous studies, local geographic information system (GIS) services, or specifically generated for the purpose of this study. Secondly, we spatially aggregated the layers in data layers and formats suitable for systematic planning analyses. Thirdly, we translated the scenarios introduced in Section 2.3 into explicit problems to solve with a SCP optimization software (Scenario 1-3). The BAU simply represents the current situation and is not the result of any optimization. The spatial use corresponding to the BAU was mapped with a GIS. Then we compared the BAU to optimized scenario solutions in terms of areas devoted to different activities and costs implied by the solutions. Lastly, for each optimization scenario, an analysis of sensitivity of the solutions to input data layers and to a compacity parameter was conducted, as recommended by André et al. (2021a).

### 3.2 Collection of spatial data

We updated spatially-explicit information layers on marine biodiversity, pearl oyster exploitation, artisanal fisheries and ciguatera risk, at high spatial resolution.

- **Layer 1:** a habitat map of high thematic resolution with 77 geomorphologic and benthic classes, from resampled QuickBird and IKONOS imagery at 4 m. resolution spatial imagery. This product is an original work made for this study after recent benthic surveys performed in 2019-2020. It was built following the Millennium Coral Reef Mapping Project principles (Andréfouët et al., 2006; Andréfouët and Bionaz, 2021), with a hierarchical classification scheme describing first three levels of detailed geomorphological features, followed by, when suitable for our scenario, benthic information in particular the type of coral communities. This Gambier habitat map included from 7 classes of coarse geomorphological description at level 1, to 77 classes at level 5, the finest level of description mixing fine geomorphology and benthic coral information;
- **Layer 2:** a refined map of fishing grounds, from a map-based questionnaire survey on the fishing grounds completed by 42 artisanal fishers conducted in November 2019. Each fishing ground was characterized by an annual level of catch. Using GIS tools, each fishing ground delimitation was then refined according to the limits of the geomorphological features that were compatible with a given fishing gear, following the methodology detailed in André et al. (2021b);
- **Layer 3:** a ciguatera risk map, from local knowledge on poisoning events and on areas suspected at risk. This information was collected during the same surveys. This also followed the methods described in André et al. (2021b). Another series of ciguatera data came from toxicity analyses on fish tissue samples performed in 2017 by Institut Louis Malardé (Darius, unpublished data);
- **Layer 4:** a wild oyster stock abundance map, achieved from densities measured between 0 and 30 m. in 64 stations surveyed in November 2019 and February 2020 (Andréfouët, Liao, unpublished data), and generalized according to the distribution of densities per type of mapped habitats and depth as done previously in other site for benthic invertebrate stock assessment (Andréfouët et al., 2016) (see above for habitat map);
- **Layer 5:** a map of the area reserved for spat collection by legal decree, from the DRM GIS database;
- **Layer 6:** a map of the existing concessions authorised for pearl oyster farming as of 2019, from the DRM GIS database;
- **Layer 7:** a map of the four traditionally managed sectors, provided by DRM.

These maps were used as foundations to compute the additional layers required for the systematic prioritization scenarios.

### 3.3 Spatial data aggregation

The study area was overlaid and segmented with hexagonal planning units (PU). This shape presents an optimal ratio between surface area and boundary length (Ardron et al., 2010). Planning unit size was 10 ha to best fit the mean data spatial variations (Van Wynsberge et al., 2015), including the mean concession size in Gambier and feature patterns of the high-resolution habitat map. Since all data need to be aggregated under the set of PUs for scenario analysis purposes, the spatial resolution of the analysis thus corresponds to the PU sizes. Aggregation can refer to a specific algebraic operation (sum, average, weighted sum, etc.), as detailed below for each set of data.

Four additional layers were produced, by data aggregation per PU:

- **Layer 8:** a fishery catch map, used as a simple opportunity cost layer in the optimized scenarios. It consisted, for each PU, in the sum of catches from all individual refined fishing grounds intersecting the PU (Léopold et al., 2014; André et al., 2021b);
- **Layer 9:** a ‘fishery-ciguatera’ index map, used as a cost layer. This layer was based on the fishery catch map modulated by the ciguatera risk map as in André et al (2021b). In short, for a given level of fishing, fishery opportunity cost was lowered proportionally to the increasing risk in ciguatera-prone PU. Values of fish harvest and coefficient of ciguatera risk per PU were first normalised and then combined following the method developed in André et al. (2021b), with a relative weight coefficient for ciguatera of  $a = 0.25$ ;
- **Layer 10:** oyster restocking zones were identified within the four traditional management (rāhui) sectors. They consisted of 160 to 760-ha zones with favourable habitats for oyster fixation (hard-bottom geomorphological unit, from the habitat map at level 2), excluding existing farm concessions. The area of oyster restocking zones were constrained to remain below 10 % of the surface area of each traditional management sector;
- **Layer 11:** a concession suitability index: specifically produced to guide the selection of optimal places to locate oyster concessions and also taking into account the farming history. For each PU ( $i$ ), the farm suitability index ( $S$ ) was defined as the surface area of geomorphological features suitable for oyster concessions (i.e., all features except barrier reef and fringing reef) ( $F_s$ ). Since existing concessions are easy to access (short distance from shore) and benefit from already built infrastructures, the surface area of existing concessions ( $E_s$ ) was also considered to compute, following [Equation (1)]:

$$S_i = F_s i + E_s i \quad (1)$$

### 3.4 Scenarios of spatial marine management and their related zones

Among the four scenarios, the three systematic prioritization ones are detailed below (Figure 36).

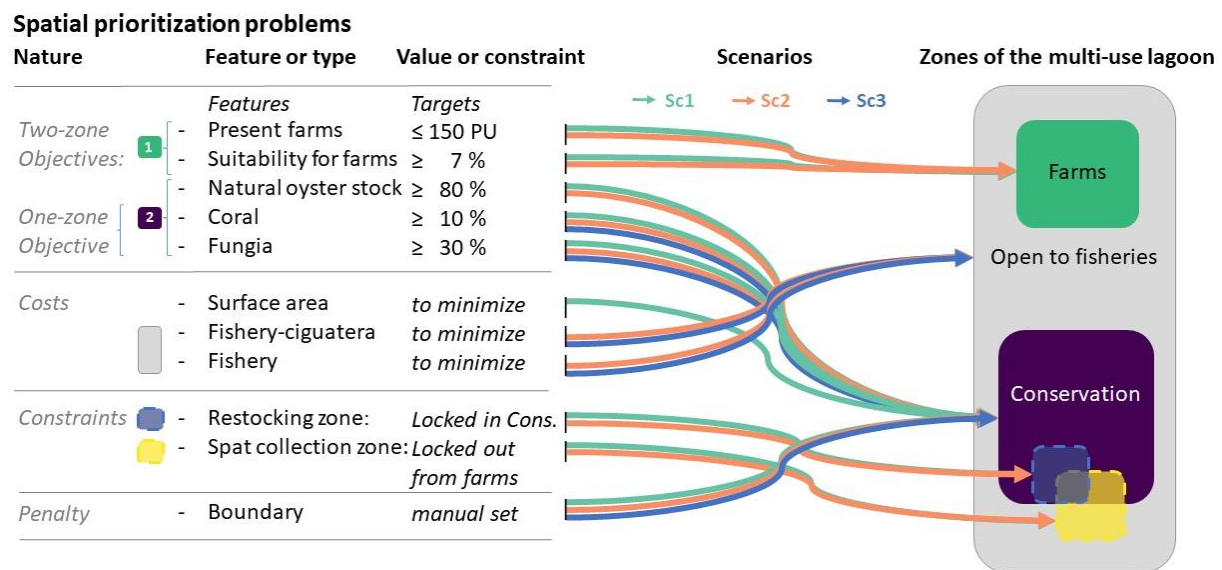


Figure 36. Graphical description of the three types of optimization scenarios.

Optimal farm concession zones are in green, conservation zones in purple, oyster restocking zones in blue, spat collection zone in yellow and the remaining area (open to fishing) in grey.

It should be noted that in this multi-use lagoon, some zones mutually exclude each-others (farms, fishery and conservation zones) while others can overlap, either partially (spat collection zone with conservation zone) or totally (restocking zones included in conservation zone). Not all zones are present in all scenarios (e.g., no farms nor spat collection nor restocking zones in scenario 3). Before detailing the scenarios, we first describe the different zones:

- **Optimal farm concession zone** in suitable environments (using layer 11, the concession suitability index previously described), with absolute target set at 1500 ha maximum, following a DRM specification;
- **Conservation zone**, including at least 30% of surface area of remarkable coral communities, namely *Fungia spp.* community and at least 10% of surface area of the remaining live coral assemblage (based on classes in the habitat map, level 5 of layer 1). Similar habitat representation objectives are recommended to protect biodiversity (e.g., in the Aichi Target 11) and sustain fisheries. Depending on the scenarios (see below), conservation zone can also include wild oyster stock areas (protecting at least 80% of the habitat where wild stocks occur (layer 4), for a sustained spat supply). A boundary penalty was affected to the conservation zone to avoid the over-fragmentation of this zone with isolated PUs. This factor minimizes the sum of the perimeters of the prioritized zones;

- **Oyster restocking zones** that were previously identified by DRM (layer 10). They are included in the overall conservation zone as they protect oyster settlements and integrity. They can also include potential *Fungia* and other live coral features, and wild oyster stock as well, and contribute to fulfil the conservation targets;
- **Spat collection zone**, already delimited by decree. As spat collection lines do not densely cover the whole area presently, we consider it open to fishers. We do not aim to completely re-design its location here, but small changes in its boundaries are allowed if it contributes to general optimization. In particular identification of conservation areas is authorised within that zone, and if so, these conservation zones become closed to fisheries. Allocation of farms was excluded from the spat collection zone;
- **Fishery zone**, which is the whole remaining area, using both the fishery catch map (layer 8) and the fishery-ciguatera index map (layer 9).

The whole set of the four scenarios were transcribed as follows:

- **Business-as-usual** scenario (BAU) describes the present use of the lagoon with oyster culture and fisheries;
- **Sc1 first level of diversification. Priority to oyster farming and conservation:** this multi-zone scenario aims at meeting a double objective of oyster culture and conservation. For both objectives, the cost to minimize was the surface area of the solution. Fishery opportunity costs are not taken into account in this scenario;
- **Sc2 second level of diversification. Priority to oyster farming and conservation while minimizing costs for fisheries:** this multi-zone scenario has the same double objective as Sc1 but considers fishery activity as a cost to minimize for both zones, in order to improve fishery opportunities in the area remaining open;
- **Sc3 back-to-tradition. Priority to fisheries and conservation:** this simple scenario has a habitat conservation objective that minimizes costs for fisheries. In this case, the conservation zone was considered also consistent with a rāhui tradition of sustaining fisheries since it provides protection of the fish stock associated with the targeted coral habitats.

To run these scenarios, the *Prioritizr* R package (Hanson et al., 2021) was used as a systematic site-prioritization tool to solve minimum-set problems of multi-zone spatial management. *Prioritizr* is a recent tool based on mixed integer linear programming. Unlike other widely used marine systematic conservation planning tools such as *Marxan* and its extensions which relies on simulated annealing, from meta-heuristics (Ball et al., 2009), *Prioritizr* provides exact optimization solution but may fail with large problems that are better studied with (meta-)heuristics (Beyer et al., 2016; Possingham et al., 2000). The Gambier scenarios fall *a priori* in the low complexity categories (Figure 36) and *Prioritizr* proved to be a suitable toolbox (see Results).



### 3.5 Comparison of solutions

First, solutions of the three optimized scenarios were compared, using the BAU scenario as standard. To this end, the relative surface area ( $RSA_{z,sci}$ ) of each zone type ( $z$ ) solved by each scenario ( $sci$ ), was standardized by the surface area of the corresponding zone type of the BAU reference scenario ( $A_{z,BAU}$ ), following [Equations (2)]:

$$RSA_{z,sci} = \frac{A_{z,sci}}{A_{z,BAU}} \quad \text{with } z \in \{ \text{Fishery zone; Conservation zone; Oyster restocking zone; Farm zone; Spat collection zone} \} \text{ and } sci \in \{ \text{Sc1; Sc2; Sc3} \} \quad (2)$$

The same procedure was implemented to compare solutions on the basis of a relative cost (RC) derived from fishery-ciguatera index ( $fc$ ) [Equations (3)].

$$RC_{z,sci} = \frac{fc_{z,sci}}{fc_{z,BAU}} \quad (3)$$

As the conservation and oyster restocking zones was absent from BAU, comparisons were made using Sc1 values as the reference for that zone.

Second, for each scenario we estimated the amount of 1) surface area, 2) fishery-ciguatera index, 3) fishery-catch, 4) concessions as in BAU and 5) Coral-*Fungia* communities in each of the zones (namely, fishery zone, farm zone, spat collecting zone and conservation zone, when they exist). To compare the proportions of each of these indicators between scenarios, for a given scenario they were expressed in percent of the total value of the indicator across the lagoon (i.e., sum of values over all zones).

In other words, if  $n$  is the number of zones, for an indicator  $Ind$  of each zone  $z$  in scenario  $sci$ , we calculated the standardized value of each indicator ( $\overline{Ind}_{z,sci}$ ) following [Equation (4)]:

$$\overline{Ind}_{z,sci} = \frac{Ind_{z,sci}}{\sum_{z=1}^n Ind_{z,sci}} \quad (4)$$

It should be noted that for a given scenario, the sum of standardized indicators is equal to 1 [Equation (5)] because the fishery zone will be assigned to all areas not used by any other zones, i.e. the lagoon is always fully occupied.

$$\sum_{z=1}^n \overline{Ind}_{z,sci} = 1 \quad (5)$$

### 3.6 Sensitivity analyses

Two sensitivity analyses were conducted to assess the variability of the solutions to: i) the use of either the fishery catch or the fishery-ciguatera index as input cost-layer for scenarios 2 and 3; ii) the boundary penalty for the conservation zone solutions. For the latter, an optimal boundary penalty value was sought for each scenario following Ardron et al. (2010), based on iterations with a factor-10 increased penalty value. For each value, when plotting the cost of the solution against the sum of the perimeters of the solution zones, the optimal boundary penalty value was the point that defined the inflexion point of the curve.

## 4 Results

### 4.1 Spatial data collection and aggregation

The Gambier lagoon appeared to be characterised by:

- *a high diversity of habitats* (Figure 37A) in the 48,560 ha lagoon, including 5,920 ha of coral-dominated benthos, which were distributed on fringing reefs, patch reefs and lagoon floors geomorphological units; in addition to 747 ha of remarkable *Fungia spp.* communities, which were distributed on the North-West of the main island Mangareva (Figure 37B);
- *an extensive fishery activity*, estimated to 63.5 t. annual catch based on the fishers surveys, which identified 252 overlapping individual fishing grounds covering 33,845 ha, or 70% of the lagoon surface area. A total of 128 individual zones of moderate to high level of ciguatera risk were identified based on the fishers' knowledge, and supplemented with five locations of multiple fish tissue ciguatera analysis. The resulting risk map, combined to the fishery catch map, reflected the areas most favourable for fishing activity at a lower risk of ciguatera (Figure 37C and D). These favourable areas for fishing were mainly located in the North coast of Mangareva, the West end of Aukena, in a specific location in the middle of the North-West barrier reef near a small pass and, to a lesser extent, all along the North-East barrier reef.
- *a well-established black pearl oyster farming activity*, with 2,253 ha of maritime concessions, mainly on the North-West of Mangareva island and to a lesser extent, in the South and near Aukena island. Concessions overlapped 358 ha of *Fungia spp.* communities (48%). The lagoon also presents 780 ha with abundant wild oyster stock, which is mainly distributed on the shallow terraces between Mangareva and Aukena Islands, between Aukena and the eastern barrier reef, and on the summit of deep patch reefs in the centre of the lagoon. The collecting zone overlapped some of these oyster stock habitats (Figure 37E). The farm suitability index highlighted the suitable farming areas (Figure 37F).

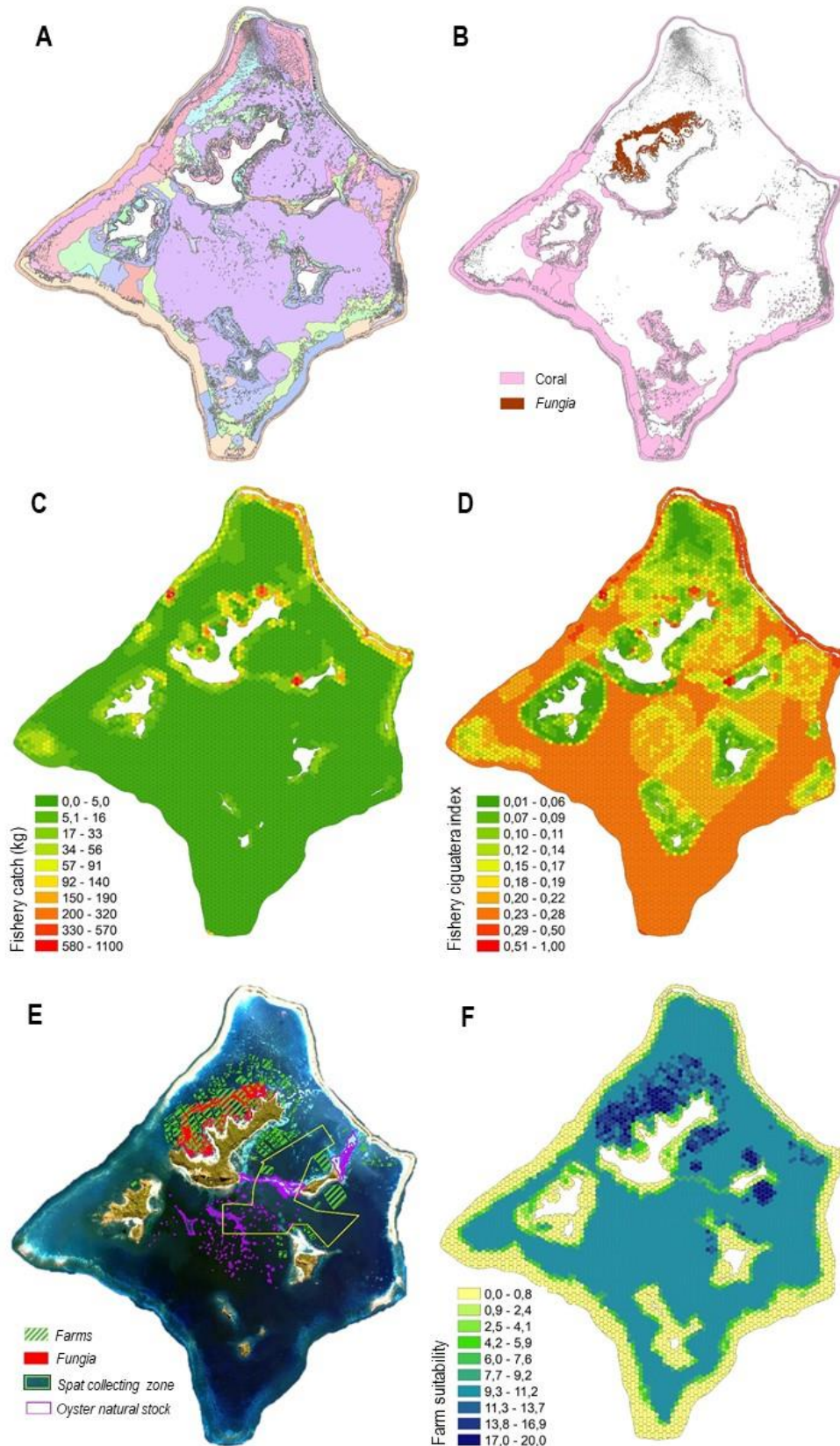


Figure 37. Spatial information on Gambier lagoon.

A. Gambier habitat map of 77 classes. Complete legend in Appendix 4. B. Distribution of live coral benthos and Fungia communities. C. Fishery catch aggregated by planning unit (PU). D. Fishery-

ciguatera index aggregated by PU. E. Extent of present farm concessions and their overlap with *Fungia*; extent of spat collecting zone and its overlap with wild oyster stock. F. Farm suitability index calculated by PU.

## 4.2 Scenarios solutions

Best solutions with optimized penalty value were found for each scenario. They were characterized by different distribution and surface areas associated to the zone types (Figure 38).

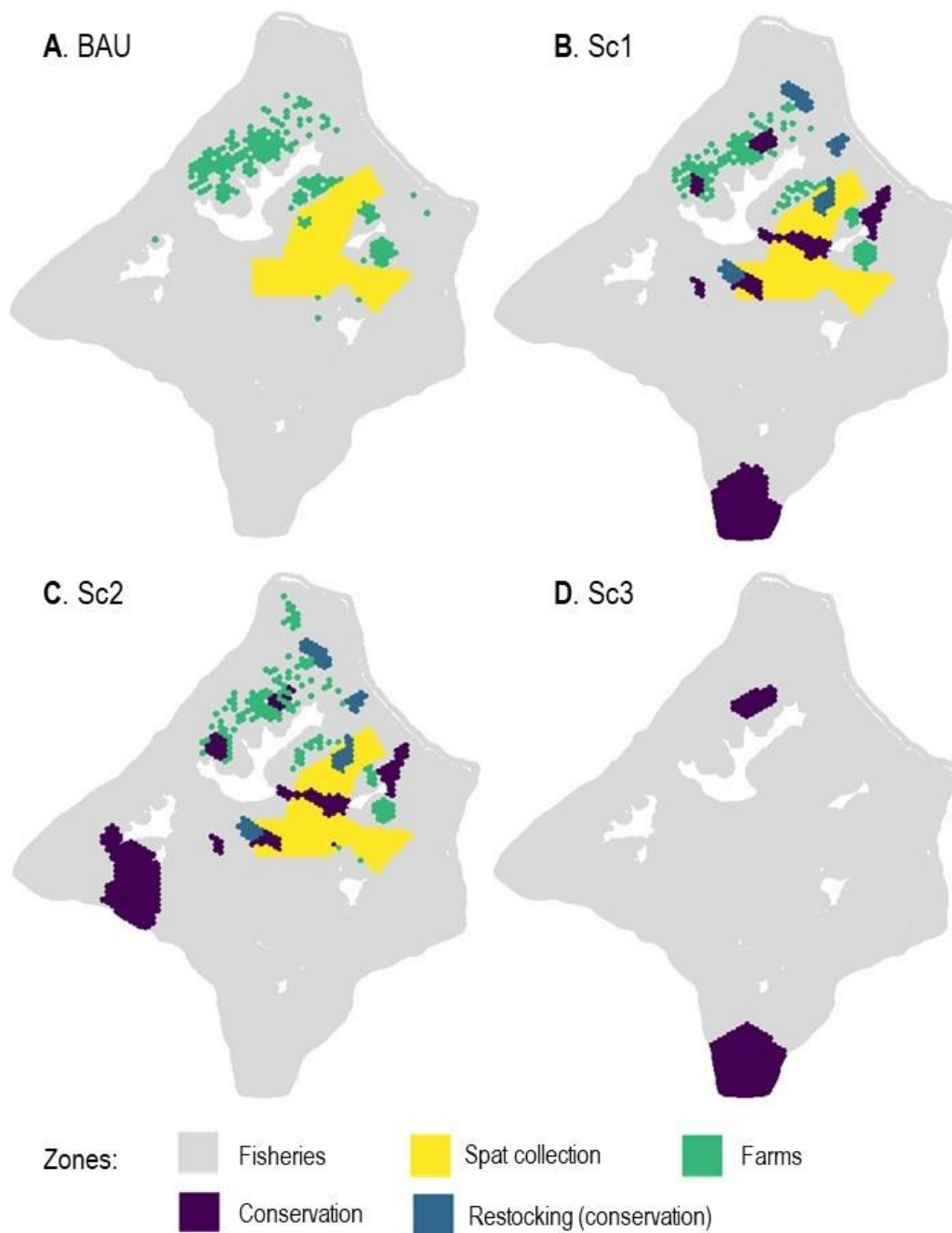


Figure 38. The 'Business as Usual' (BAU) situation and the best solutions in term of zones distribution for each optimized scenario.

The ‘business-as-usual’ scenario displayed a large farming activity with 2,253 ha of concessions mainly on the North-West of Mangareva and to a lesser extent, on the South-East and around Aukena (Figure 38A). Since it reflects the present situation, there are neither conservation nor restocking zones, and the distribution of farms do not take into account the fishers’ interests.

Sc1 displayed a first level of diversification through conservation zones. These include 2,961 ha of conservation for remarkable coral communities and oyster stock, distributed in two *Fungia spp.* zones on the North-West of Mangareva, one large (1,363 ha) coral zone on the South of the lagoon, and 750 ha of oyster restocking zones within the four traditional sectors (Figure 38B). Total surface area allocated to farm concessions was distributed broadly in the same locations as for the BAU scenario, but decreased down to 1,400 ha.

Sc2 displayed an increased diversification scenario that built on Sc1 by maximizing fishery activity. The conservation surface area slightly grew to 3,008 ha, and this time, the large coral conservation zone was located on the West, near Taravai island. This location was less costly for fishers than in the South, as previously identified in Sc1. As for the 1,500 ha farms concessions, minimizing the opportunity cost to fishers led to an optimal distribution extending towards the far North lagoon (Figure 37AC).

Sc3 displayed a mono-activity emphasizing the traditional fisheries with 2,149 ha for the conservation of remarkable coral communities, implicitly protecting fishery stocks associated to these productive habitats (Figure 38D). It allowed estimating the space left by oyster culture, henceforth leaving 46,411 ha open to fisheries.

### 4.3 Comparison of solutions

Figure 39 provides the comparison of each scenario in terms of relative values of surface area (A) or fishery-ciguatera index (B) for each zone.

The diversification options (Sc1 and 2) slightly decreased the zone open to fisheries compared to BAU, while it was logically increased by the mono traditional-activity (Sc3). These results remain valid either in terms of surface area (A) or fishery-ciguatera index (B). Indeed, the decrease in  $RSA_{Fishery,sci}$  and  $RC_{Fishery,sci}$  resulted from the creation of restocking and conservation zones on Sc1 and 2, which did not exist in BAU. By contrast, their increase under Sc3 was due to the loss of concessions and spat collection that existed in BAU.

Compared to BAU, the diversification options (Sc1 and 2) led to an important decrease in the surface areas of concessions zones (62 and 67% of BAU’s surface area for Sc1 and 2, respectively) and in terms of fishery-ciguatera cost (64 and 55%, respectively). The interesting point is that despite surface area of concessions was slightly higher in Sc2 than in Sc1, the cost for fishers was lower in Sc2 than in Sc1. Similar results occurred for conservation zones, showing equivalent areas for Sc1 and Sc2, but at notably lower cost for fishers under Sc2 than Sc1 (20% lower). Spat collection zones also decreased, in area and cost, due to the inclusion of restocking and conservation zones.



Figure 39. Comparison of the generated impacts for each scenario and each zone.

Relative surface areas (RSA<sub>z,sci</sub>) (A) and fishery-ciguatera index (RC<sub>z,sci</sub>) (B) of each zone *z* (x-axis) and each scenario *sci* (colors) as standardized by the BAU scenario when suitable, or by the Sc1 for Conservation and Oyster Restocking zones, when BAU was not available.

Results from the second comparison approach are transcribed in Figure 40. Here, the comparison between scenarios *sci* allows for quantifying the weight of each zone *z* relative to the others, using the objectives and costs indicators  $\overline{Ind}_{z,sci}$  as weights.

Surface areas dedicated to fishery (grey bar) decreased with diversification (Sc1 and 2), but increased under Sc3 compared to BAU. Focusing on Sc1 and 2, the option of minimizing cost

for fisheries-ciguatera (Sc2) did not bring more surface area available for fisheries (column 1). Measured in Fishery-ciguatera index, it increased only very slightly the fishery zone (column 2) from 83 % in Sc1 to 85 % in Sc2, which reflects the slight increase of maintained opportunity with lower ciguatera risk for fishers, in that open zone. Spat collection area slightly decreased in Sc1 and 2, compared to the BAU option, in either Surface area or Fishery-ciguatera index (columns 1-2) due to the inclusion of some conservation areas within spat collection zone.

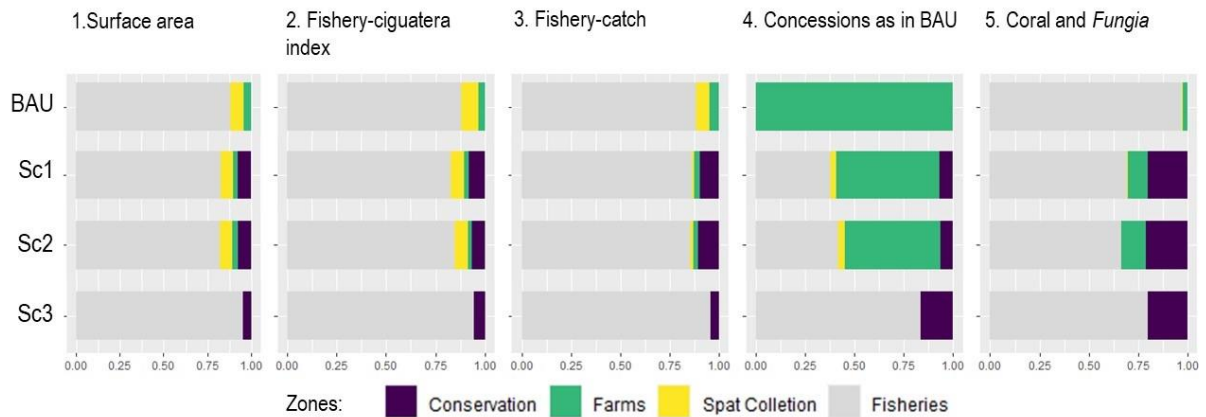


Figure 40. Relative impacts of the scenarios.

Differences between scenarios (in rows) on the repartition of the zones (identified by their colors), as measured using different indicators (in columns) related to the objective (Surface area, Concessions as in BAU and Coral-Fungia) or cost layers (Fishery-ciguatera and Fishery-catch).

Comparison of zone ratios measured in Fishery-ciguatera index and Fishery-catch indicators (columns 2-3) showed that spat collection zones in Sc1 and 2 had virtually no cost in terms of Fishery catch, compared to an increased cost in terms of Fishery-ciguatera index. It means that almost no fishers used that zone, although it would likely be quite safe regarding ciguatera risk. On the opposite, the opportunity cost of conservation zones was higher in terms of Fishery-catch than in terms of Fishery-ciguatera index. This shows that accounting for ciguatera risk reduces the opportunity cost to fishers.

Regardless of the scenario, the zone remaining open to fishers was finally significant, whether in terms of surface area (82% to 88% of the lagoon), or in terms of maintained opportunity to fish while integrating the ciguatera risk (82% to 94% fishery-ciguatera index) or not (85% to 96% of fishery-catch).

Optimised farms (Sc1 and 2) overlapped with only about the half of the BAU concessions (column 4), resulting from both a change in location and a reduced surface area of optimized farms. We also noticed that 7% (Sc1 and 2) to 17% (Sc3) of BAU concessions surface areas were reallocated to conservation in optimized scenarios. This is due to the overlap of BAU concessions with coral communities, which were assigned to conservation zones in the optimization scenarios.

Interestingly, among the total surface area of Coral-*Fungia* communities (column 5) deemed of interest for conservation, the overlap by farms was higher in optimised scenarios (Sc1 and 2) than in BAU. However, while the remaining surface area of Coral-*Fungia* communities was

entirely exposed to fishery related impacts in BAU, we noted that at least 20 % surface area was protected by conservation zones in the three optimized scenarios (Sc1 to 3).

#### 4.4 Sensitivity analyses

Throughout the different tests of sensitivity to boundary penalty applied on conservation zones, we noticed some common patterns (Figure 41). Generally, at low penalty, we could easily identify which conservation zone was explained by which feature, as some have restricted distributions such as the wild oyster stock sub-zone, and the *Fungia* sub-zone. On the opposite, the coral feature was widely distributed in the lagoon and the relatively low target (10%) allowed the possibility to prioritize zones in different parts of the lagoon. In addition to reducing the scattering of PU assigned to conservation zones (as in Figure 41J, K and L), the increasing penalty mainly induced two changes: (i) it created one large clustered conservation zone that connected together wild oyster stock, oyster restocking (B and C) and eventually *Fungia* zones (A), and (ii) it shifted the coral conservation zone from West to South. This was true for all scenarios except when using Fishery-catch cost layer (columns 3 and 5), where the coral conservation zone remained located in the West (in Sc2) or in the South (in Sc3) whatever the boundary penalty.

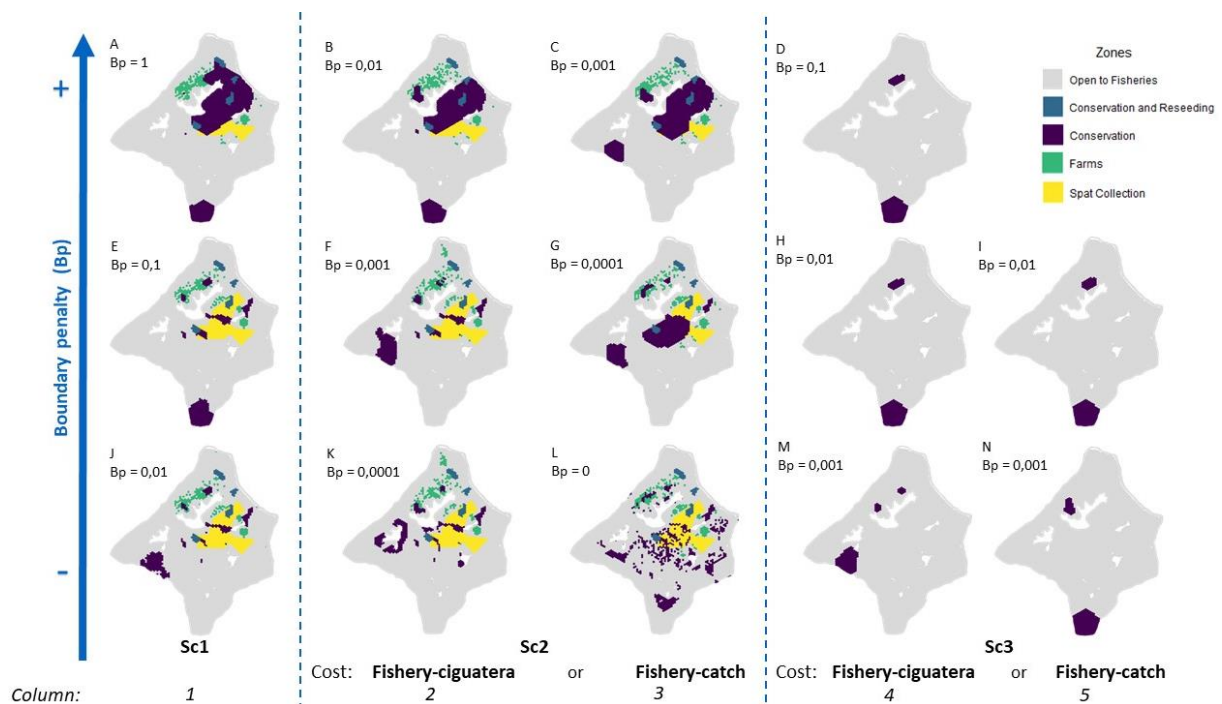


Figure 41. Sensitivity analysis of the optimization scenario solutions.

Sensitivity to the cost layer fishery-ciguatera or fishery-catch (in columns) and boundary penalty increase (in rows).



## 5 Discussion

In small islands, where available land areas are limited, activities are very much oriented towards marine areas, and guidance on spatial management of these spaces is helpful. In these coastal environments, it is necessary to interconnect spheres of economic and food security activities to ensure livelihood resilience, while preserving biodiversity and sustain ecosystem services. The present study conducted in a French Polynesian island highlights that it is possible to reconsider a 'business as usual' situation geared towards one single activity (namely, black pearl oyster farming activity) towards a more diverse portfolio leaving room for fishery activities and conservation as well. Different options for spatial management were explored and their respective impacts were compared

The results showed that diversifying the activities was feasible, with all the different investigated options and targets fitting within the lagoon space. Many different zone configurations could be tested, as shown in the sensitivity analysis. Generally, satisfactory solutions were found, including conservation areas and optimized farm activity, with or without fisheries optimization (respectively scenario 1 and 2). Diversification solutions allowed keeping productive fishing grounds open (from 85% to 96% catch maintained, depending on scenarios) and the still wide areas open to fishing (from 82% to 88% of the lagoon) leave room for potential future further diversification.

The diversification scenarios highlight that a new spatial organisation that better integrates the cycle of oyster culture is feasible in theory. Indeed, the lagoon can accommodate new restocking zones in the four traditionally managed areas, the existing wild stocks, the existing spat collecting zone, and a suitable area for farming (1,500 ha) as defined by DRM. However, the different options, and their solutions, remains to be discussed with local stakeholders, and tested in real conditions. For instance, we observed that in the most diversifying scenario (Sc2), locations for farms were suggested in the North of the lagoon, to decrease opportunity cost for fishers since they do not use much this area. However, for oyster farmers, this solution increases distances from the shore and will then induces larger operational costs for transports. Distance to mainland was not accounted for here because the studied zone was relatively small. It is however a typical socio-economic cost used in many systematic conservation plans in islands (Cheok et al., 2016, Kabbadj et al., 2018) and for continental coasts (Venier et al., 2021) and it could be profitably integrated in a second draft if stakeholders object to these solutions. Objections can be expected from particular farmers that could be impacted the most. In fact, any changes that could be implemented is likely to be heavily discussed should DRM moves forward to discuss with the stakeholders some of the options we highlight here. Additional aspects concern protecting specifically the zones of high abundance of wild oyster stock and planning for new restocking zones. Indeed, health and abundance of wild stocks are critical to sustain the black pearl activity. Keeping the oldest oysters alive and thus restocking some specific zones may have a positive impact on the wild stock sex-ratio, which is critical for spat production, as demonstrated in a modelling and genetic study of larval dispersal and recruitment in Ahe atoll, Tuamotu (Reisser et al., 2020).

Other aspects specific to pearl farming can be investigated further if new scenarios are developed. For instance; spat collection, that strongly constrains the entire pearl production,

was used here as a locked-in criteria since area for spat collection is officially delimited by decree. We did not investigate other possibilities for spat collection zones, however, it could be interesting to do so if relevant data became available, such as larval dispersal data from biophysical models. These models can provide insights on what are the best spat collection locations in different weather regimes, including for future climate conditions (Thomas et al., 2016, Dutheil et al., 2020).

The 'back to the tradition' scenario defines the maximum surface area and fishery opportunity cost that can be gained by the fishers, compared to the business-as-usual farming activity, or allocated to zones for conservation or stock replenishment. It served as an extrema in diversification options. As such, this scenario might not be realistic because oyster farming is not likely to be abandoned in Gambier anytime soon. If this happens, this would bring important changes in the local community such as potential emigration of farmers to other productive islands, or professional retraining of farmers to become fishers inducing higher fishing pressure and changes in fishing ground locations.

The annual fishery catch in Gambier was estimated around 63.5 t. for a 485-km<sup>2</sup> lagoon. This is ten-times lower than in Raivavae (120 t. for a 86-km<sup>2</sup> lagoon), another ciguatera-prone island of French Polynesia (André et al., 2021b). This lower rate of catch per km<sup>2</sup> in Gambier is likely due to the strong focus on black pearl farming activity. In Raivavae, despite a smaller population, islanders are mainly oriented towards fishery and agriculture activities. More generally, the role that non-commercial fisheries play in food provision is often underappreciated in policies and development programs due to limited information available in rural and remote zones (Jacquet and Pauly, 2008; FAO, 2018). In Hawaii State, which represents another Pacific island context, the importance of artisanal fisheries was evaluated in terms of monetary income, food security and cultural values associated with nearshore fisheries (Grafeld et al., 2017). Non-commercial catches appeared to be three times higher than commercial ones. This example, among others (Zeller et al., 2006; Bell et al., 2009; Kronen et al., 2012; Cinner et al., 2014; Thiault et al., 2017; André et al., 2021b) highlights the essential role that artisanal fisheries play in Oceania. We stress the importance to account for them when making plans of diversification (Aswani et al., 2006; Léopold et al., 2019), even in situations where artisanal fisheries are not the main activity, as in Gambier, because it can return to the forefront and buffer the socioeconomic collapse in case of disruption of the economic activities.

To alleviate pressure on coral reef fisheries in light of climate change and population growth drivers, which are recognized as some of the main future threats for the Pacific Islands (Bell et al., 2011), options of diversification of the fisheries themselves have been recommended. Indeed, the resort to fish aggregation devices was identified to sustain local food security and diversify the sources of marine proteins towards offshore resources like tuna, *mahi mahi* and *wahoo* while alleviating fishing pressure on coral reef resources (Bell et al., 2015, 2018). Typically, such fish aggregation devices are anchored nearshore on the external slope after the barrier reef. Some, anchored further from the reef and deeper (800-1500 m), are already implemented and used in Gambier, as well as in other French Polynesian islands (99 in total in French Polynesia as of 2020 (DRM, 2020b)). Further development of systematic planning

studies on fisheries could focus on that point by extending the study-zone to the external slope to include this fishery activity and the associated habitats.

In French Polynesia, diversification from mainly fishery activity towards more lucrative activities such as black pearl production as it occurred in the years 1980-1990 concerns many island lagoons, particularly in the remote and rural islands of Tuamotu Archipelago. Other diversification pathways could include tourism or aquaculture and collection for the aquarium trade, for example, which bring additional incomes (Remoissenet & Wabnitz, 2009; IUCN, 2021). After spatially assessing the current situation, systematic planning could highlight options of spatially sound diversification integrating environmental and socio-economic aspects. It is a useful tool to help design an integrated approach for sustainable development and management of activities, spaces and resources. Indeed, international and local governance as well as scientific research are called upon to integrate more and more sustainability science principles taking into account society, culture, economy and the environment systems (Duvat et al., 2008; Eger and Courtenay, 2021). For this, systematic planning can be used as a transdisciplinary tool that can thrive on, and be applied to, these different spheres in a dynamic adaptive planning process involving the different stakeholders. Adaptive management is crucial to integrate new knowledge and the changing society and environments (Mills et al., 2015; Winter et al., 2020), particularly in the context of small and isolated islands, that have limited diversification opportunities, compared to continental coastal zones. In this study, we focused on islands, which should actually be further understood *sensu lato*, as patches with a certain degree of isolation that can be geographic or biogeographic in remote regions, but also social, cultural or administrative, in any regions.

So all in all the Gambier case study takes into account several of the recommendations that we put forward after the review of 34 SCP cases studies in the Pacific (André et al. 2021a). Specifically, it takes into consideration aquaculture (pearl farming), the impact of ciguatera on fisheries, and focuses on an invertebrate resource. It also generated spatialized fishery atlas data (all data not shown here, as details per fishing gear for instance are available) and provides sensitivity analyses to different input factors including SCP optimisation parameters (boundary penalty). As such, it fills several gaps to represent better Indo-pacific tropical island configurations and specificities never or poorly considered thus far in SCP work.

## 6 Conclusion

In the context of integrated coastal management, leaving ‘business-as-usual mentality’ (Eger and Courtenay, 2021) and heading to diversification of activities is challenging but a sound way leading to sustainability (Fenichel et al., 2016) by mitigating of pressures on the environment and increasing resilience of the populations. Through this case study we explored and compared different options for reshuffling management priorities for an island representative of a system with limited diversification options to adapt to socio-economic and environmental changes, in the future or already happening. More broadly, it addresses the questions of resilience of populations as a balance between food security and income generating activity dependant on international markets. It also addresses the question of ecosystem and resource management in terms of carrying capacity, conservation of biodiversity and resource stock management. To chart pathways for diversification, the use of

systematic planning approach ensured objectivity and data-based solutions, where existing measures could be maintained (spat collection zone) or improved (oyster farms and lower ciguatera risk fishery grounds), and where optimal places for new activities could be identified (conservation of remarkable coral communities and wild oyster stock, oyster restocking zones). This empirical study evidences options of diversification that provide public policies with avenues through decision support products to build integrated management measures at the local scale.

### **Acknowledgements**

The study was funded by the MANA (Management of Atolls) project (grant ANR-16-CE32-0004), by the PANGEA PhD project (grant from Délégation à la Recherche de Polynésie française to Institut Louis Malardé, Conv. N° 06575/MED of September 28th, 2018), and by a doctoral fellowship from Sorbonne Université to LVA.

We acknowledge all the people of Gambier including fishers and black pearl farmers, as well as Rikitea city council representatives for taking the time to reply to our questions and for their inputs. We thank Jeffrey Hanson for his advice on Prioritizr code, Taiana Darius for providing data on ciguatera field sample analysis and Solène Derville for tips in data visualization. We thank the urbanization service of French Polynesia for providing the Gambier QuickBird and IKONOS imagery.



## General discussion



## General Discussion

Systematic conservation planning is a mature scientific tool that has demonstrated high flexibility in the accommodation of a variety of data, features and processes relevant to conserve and sustain ecosystems while minimizing the impacts for stakeholders.

### 1 Synthesis of the contributions

This thesis addressed the general question of how and to what extent we can better integrate the Pacific Ocean tropical Islands' specifics in systematic planning for conservation and management of coastal areas. We contributed to enhance SCP in the conservation and management of POTIs lagoons by proposing original approaches to answer different management issues that have emerged in specific French Polynesia island contexts, and by developing methods to better take into account several factors and processes that are themselves generically important to Pacific Islands but had never been considered into previous SCP studies. More specifically, the following sections summarize the main contributions made to our four research topics: (1.1) Accounting for ciguatera risk in SCP scenarios; (1.2) Planning for the sustainability of pearl oyster farming; (1.3) Fostering collaboration between SCP and a traditional approach of fishery management design; and (1.4) Planning for multiple activities and economic diversification. We then discuss the transversal contributions made by this study (1.5) and its limitations (1.6).

#### 1.1 Accounting for ciguatera risk in SCP scenarios

When planning for the management of marine areas, the plan must take into account all the main features involved. Some may have been seen as minor beforehand, but can be blocking factors down the line. Indeed, in regions affected by ciguatera, if the marine plan incidentally leaves only ciguatera-prone areas as open for fishers, they will probably not approve it. By contrast, areas perceived at risk regarding ciguatera poisoning are *de facto* avoided by some fishers. Therefore, these areas represent good candidate areas for implementing strict reserves while minimizing opportunity costs generated by the closure of fishing grounds.

In order to account for ciguatera in SCP scenarios, we built a methodological framework to integrate spatialized and quantified information on perceived ciguatera poisoning risk that we applied in Chapters 2. The results of the Raivavae and Gambier case studies evidenced that ciguatera was a critical piece of information to incorporate to fisheries management, as part of SCP, towards ensuring that areas open to fishing are relatively safe, or less risky, with respect to ciguatera (Chapter 2, 4 and 5). Not taking into account ciguatera risk would have potentially closed valuable fishing grounds that were safe from ciguatera while leaving open areas at risk. Therefore, omitting ciguatera risk when planning for fisheries can actually result in a significant increase of opportunity cost for fishers.

However, information on ciguatera is not easy to gather. For further use, we suggest the methodological framework described in Chapter 2 to collect and produce spatialized and quantitative information on ciguatera risk from fishers' local knowledge. This is described in

detail for Raivavae Island (Chapter 2) and was subsequently applied on the two other sites (Chapters 4 and 5) to answer other specific questions. However, local knowledge can have limitations, inherent to human perceptions with varying levels of precision (Lauer and Aswani, 2010), although fishers in French Polynesia Islands have quite an accurate perception of the ciguatera risk, at least at very local scale (Chapter 2; Chinain et al., 2010).

The maps of ciguatera risk that we produced for the three study sites should be used for the purpose of spatial planning, and not for human health-related programs. For this, precise and validated information should be collected from biotoxin-testing on *in situ* fish samples or *Gambierdiscus* populations. However, collecting this information require substantial time and budget, and is difficult to implement at the scale of the whole lagoon. Moreover, ciguatera is acknowledged to vary in time and space (Bienfang, 2008), as illustrated by the record of ciguatera poisoning occurrences and outbreaks of varying intensity in many sites (Chinain et al., 2021). In this context of changing socio-environmental systems, we highly recommend to revise datasets periodically, every 5-10 years, conduct temporal follow-up, regular monitoring, and adaptive planning strategies.

## 1.2 Planning for the sustainability of pearl oyster farming

After a golden age of black pearl farming in French Polynesia where it expanded rapidly and densely in many lagoons, the sector has undergone several crises. To address some of these issues and foster sustainability, the DRM marine management technical service is seeking to implement several spatial measures, such as decrease surface areas allocated to rearing oyster (concessions), establish sanctuaries for wild oyster populations, and implement restocking measures to enhance the wild oyster stock. Systematic prioritization was used to spatially manage specific black pearl farming activities (Chapters 3 and 5).

To enhance the sustainability of pearl oyster farming, several scenarios were explored in the Gambier lagoon (Chapter 5), through multi-use designs that included the different facets of pearl farming. Sustainable management approach has raised questions about how to spatially optimize a reduction of the total concessions surface areas to reduce pressure on the Gambier lagoon's carrying capacity. This was done in Chapter 3 using a variety of information (collecting zone, areas of high-density wild oyster stocks, suitable restocking zones within a traditional management scheme, etc.). The help of SCP tool has proven useful in considering spatial arrangements in such a context of multiple uses, interests and constraints, since sustainable management deals with both environmental and socio-economic domains. Over the different scenarios, the solutions allowed measuring the distribution of space allocated to each activity and the relative costs induced, including in terms of socio-economic costs.

The cornerstone for maintaining the pearl farming activity is the supply of oyster spats, which depends on the reproductive success of the wild stock, and the success of spat collection. In particular, in order to cope with the issue of wild stocks with low fitness levels, the study conducted in Takaroa focused on oyster restocking and identification of suitable zones (Chapter 3). Based on features related to dispersal potential, environmental suitability, and socio-economic parameters, the systematic prioritization tool allowed identifying potential adequate sites to release reared oysters into the natural environment.



Although not originally motivated by conservation objectives, but rather by maintaining mariculture production, these prioritization exercises shared several common principles with conservation-oriented SCP scenarios. First, the scenario addressed the preservation and enhancement of a natural stock, which could be applied to other reared marine resources (holothurians, giant clams (IUCN, 2021)) but could also interest the field of biodiversity restoration, for some coral species of high ecological value for example. Second, connectivity between sub-zones in the lagoon was also considered. Although the hydrodynamic model has been used to study larval broadcast only for *Pinctada margaritifera* oysters, it remains relevant for a variety of spawning species within the lagoon. Finally, the planning exercise has also integrated fisher's opportunity costs, as daily users of the lagoon, which was also the most frequent socio-economic variable used to minimize costs of conservation scenarios in the Pacific Ocean (André et al., 2021a).

### 1.3 Integrating SCP to traditional fishery management design

The revival of traditional and community management of the marine environment is ongoing in French Polynesia. During the investigations to assess fishery and ciguatera specific to the Raivavae Island, we were informed that a project of traditional rāhui was emerging. As fishers questioned the rāhui design itself, the opportunity came up to translate the objective of this traditional closure into SCP problems to find out ways to optimize the design (Chapter 4). The question was not to evaluate the rāhui, but rather to look for ways to make the design less restrictive for fishers. For this, the main traditional principles were kept, namely, conserve the marine resources by avoiding overfishing, particularly the giant clam stock, and share equally the areas of closed lagoon among the different districts. Spatially explicit data on giant clam stock were used, in addition to the information from the surveys concerning opportunity cost to fishers and local knowledge on ciguatera risk, to decrease the constraints induced by the closures.

The SCP results identified solutions far less restrictive in terms of surface area and opportunity cost while reaching the same objective of giant clam stock protection, and limiting ciguatera risk in areas open to fishery. We concluded that SCP provided insights to optimize the traditional design, integrating a number of environmental factors, and socio-economic information from aggregated local knowledge. Spatial analysis could also help gauge the outcomes of the different designs in terms of measurable benefits and costs.

Beyond spatially measurable benefits, traditional management is widely recognized to foster local buy-in, and raise a sense of responsibility and stewardship in fisheries management. This is typical of bottom-up initiatives (Gurney et al., 2015; Smallhorn-West, 2019). While each individual approach has strengths and weaknesses, this hybrid example of potential collaboration between approaches illustrated the opportunity to adapt some aspects of the initial traditional design using SCP through numerical optimization, with measured outcomes.

### 1.4 Planning for multiple activities

In a changing world, global crises affect even remote islands, with a severity that depends on their degree of exchanges and dependencies with the outer world. In Gambier, black pearl farming is a major economic activity but this already-weakened sector was further affected by

the Covid-pandemic (IEOM, 2020). Diversification strategies are classically promoted to mitigate the risks of collapse of the local socio-economic balance (Barrett et al., 2001; Bowser and Nelson, 2012; Kasperski and Holland, 2013).

Regarding Gambier, SCP was used to assess the spatial feasibility of a diversification strategy, downplaying the pearl farming spatial extent and leaving more room to new or existing activities, according to socio-economic and environmental factors. SCP compared new plans with the business-as-usual present, pearl farming dominant configuration (chapter 5). New diversification scenarios included several criteria such as reduction of the extent of pearl farming concessions, new restocking areas set within historical traditionally managed areas, productive fishing grounds for fishers preferentially in areas less affected by ciguatera, and protection of remarkable coral communities. The results showed that diversification was possible in this lagoon; the different scenarios displayed various possible spatial arrangements, measuring the associated extents and costs for each activity.

For governance entities and stakeholders, the demonstration that diversification strategies are feasible based on the criteria we used, can be a motivation to start an actual plan towards diversification in the 5 to 10-year time range.

As we step back to look at the contribution of this thesis to the overall themes addressed by SCP in the POTIs (Figure 42), we note it has substantially increased Polynesia weigh and nearly doubled the number of contributions to the topics related to local knowledge, adaptive management, and stakeholder integration.

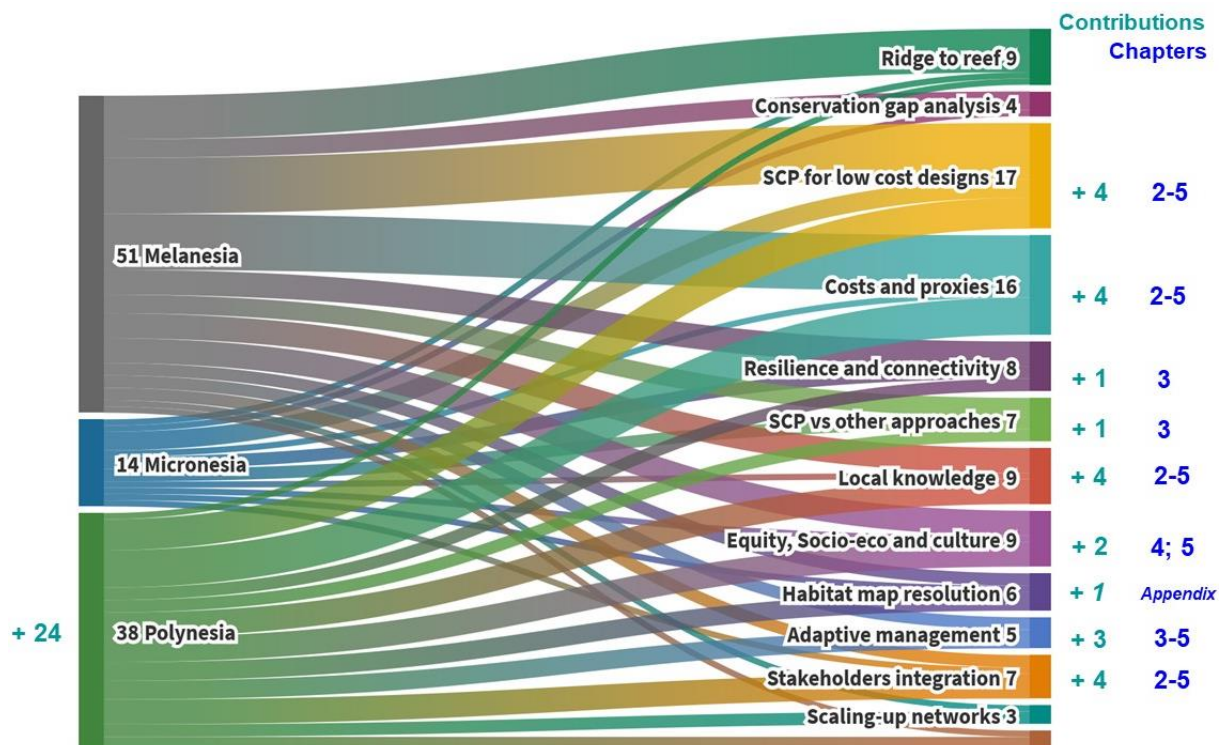


Figure 42. Update of the previous state of the art (Figure 9), summarizing the themes addressed by the SCP case studies across the POTI regions after integration of the contributions from this thesis, as reported on the right, along with the chapters.

## 1.5 Transversal contributions across all systematic planning exercises

### Data quality

The approach taken in this thesis to use adequate data led us to produce new artisanal fishery information on fishing grounds, catch, species, fishing gears and seasonality. Naturally, the quantity and reliability of the information remained dependent on the time allocated to fieldwork and the availability and willingness of the fishers to share information. Although more extensive data collection with repeated missions at different periods of the year and covering a greater proportion of the population would have been ideal, the artisanal fishery data on Takarua, Raivavae and Gambier provided much needed updated and reliable spatial information, critical to reach conclusions with confidence. Using these datasets to quantify opportunity costs to fishers in SCP scenarios was more robust and reliable than the various proxies commonly used, such as distance to ports or population density (Government of PNG, 2015; Makino et al., 2013b; Mills et al., 2012), which may not be adapted to small islands.

### Tailor made scenarios

Trying to translate the local questions of conservation and management as accurately as possible into the SCP framework led us to mobilize and conceive original information layers and to use several settings offered by the SCP tools.

Beyond habitat maps classically used in SCP (André et al., 2021a), we used spatial data on invertebrates: reared (concessions) and wild oyster stocks of *Pinctada margaritifera* (in Chapters 3 and 5) and giant clams stocks of *Tridacna maxima* (Chapter 4) to reflect, respectively, mariculture management questions, and the design of a traditional fishery closure. Additionally, attention was paid to defining cost layers best adapted to the context, where the opportunity cost to fishers was derived from local and updated information. It could include ciguatera risk when critical, and account for improved accuracy of the fishing ground delimitations according to the geomorphological units adequate to each fishing gear. This allowed us diversifying the usual biodiversity and cost criteria, as highlighted in the introduction.

Regarding technical aspects, the main SCP parameterizations and setting adjustments that we used, were:

- the level of representation of the target(s) with various tests;
- Boundary Length Modifier (BLM) to foster compactness of the solution network;
- Species Penalty Factor (SPF) to ensure reaching the target; and its optimal value compared to the costs generated;
- the application of lock-in and lock-out functions to include or exclude specific PU from the solution;
- the use of different spatial scales (each district versus whole lagoon);
- the design of multiple zones with associated targets, costs and compactness;
- the use of different tools that are based on different solving methods.

These parameters are rather standard in SCP developments. This shows that specific relevant scenario can be explored using standard existing tools; without specific developments. SCP

toolbox has developed significantly in the last decades (cf. the development of PrioritizR or different extensions of Marxan to better integrate multiple zones, connectivity and threat probability (Ball et al., 2009)) and it is likely that developments will continue. We expect that real-world complex situations will continue to benefit from the most recent developments, but the existing toolbox is already adequate for useful island scenarios, of various complexities as we have shown here.

### *Sensitivity analyses and implications for management*

Across all optimizations performed here, we contributed to test the robustness of the output solutions by investigating the sensitivity of the results to input data (biodiversity and cost criteria) and to optimization parameters. We showed that solutions could vary from little to a lot due to changes of input features (Appendix 5) such as opportunity cost to fishers modulated by ciguatera (Chapter 2 and 5), and due to parameter settings: compactness of the solutions (Chapters 2, 4 and 5), and penalty to reach the target (Chapters 2 and 4). The results demonstrated that it was always possible to meet the objectives through multiple arrangements of the spatial solutions.

The sensitivity of the results to some SCP criteria and parameters (i.e., notably Boundary Length Modifier) highlights the need for conducting thorough sensitivity analyses to these parameter settings, and to document them, which we have done throughout the different case studies, to allow for comparison and replicability. When such sensitivity analyses are performed, the panel of solutions also offers a range of options for managers, which in practice is more useful than a single “best” solution.

Since small differences in input layers (e.g., opportunity costs) may generate different solutions, it is necessary to remind the reader that a thorough exchange with the stakeholders is necessary to fine-tune the plans iteratively when using them for real decision support. Integrating feedbacks from manager’s and stakeholders on SCP solutions at some point should be more frequent, for example at the beginning, during and at the end of the SCP tests (Cheok et al., 2017; Flower et al., 2020).

### *From systematic conservation planning to systematic planning?*

Here, we used the SCP tools to address issues of either conservation or exploitation, or both. As an echo to the conservation science debate mentioned in the general introduction, on how to balance conservation between natural and social systems, here we explored the application of SCP tools primarily towards specific objectives geared for the sustainability of economic and extractive activities and adequate allocation of multi-use spaces, and not only for objectives of biodiversity (habitat or species) conservation.

This can be put in perspective with initiatives that are multiplying to move ‘Other effective area-based Conservation Measures’ (OECM) towards the recognition of their contribution to reaching the global conservation targets (Gurnay et al., 2021; UICN, 2019) as OECM can primarily be aimed for sustainable exploitation activities. Similar context is the exploration of potential synergies between aquaculture and marine protected areas (Laffoley et al., 2017). In addition, marine spatial planning is being promoted globally (through the IOC’s MSPGlobal program) and specifically, the Marxan systematic conservation planning tool (IPBES, 2021;

NOAA, 2021). It is therefore likely that the use of systematic, or at least spatial planning will increase and develop accordingly.

The management questions addressed in this study were driven by discussions and workshops with the local *Direction des ressources marines* (DRM) (Chapters 3 and 5) and the population (Chapter 4), during which ideas and needs emerged. By being connected to the partners needs and by addressing trade-off issues between objectives and costs, our applications are typical of SCP core decision-support missions. We confirmed this way that the future of SCP for island management is not necessarily condemned to go towards increasingly complex scenarios such as those that have emerged in the scientific literature in the past few years (André et al., 2021a). Basic trade-off assessments remain extremely valuable for management decisions, yet they may need adequate data.

## 1.6 Limitations

In this section, we address how we could improve the study, and what practical and conceptual limitations were identified.

### Data limitations

We identified several practical limitations that could affect the validity of the results.

#### *In situ additional data collection*

Quality of the collected information could have been improved by additional survey fieldtrips to gather the information over a longer period of time and confirm catch periodicity patterns, share additional fishing trips with the fishers and conduct underwater visual fish census surveys for the targeted resources. These developments were considered as possibilities at the beginning of the thesis, but the travel limitations after March 2020 due to covid-19 pandemic ended any thoughts of returning to the sites for additional surveys, or direct discussions with islanders. As a minimum feedback to the communities, mission reports were shared with the staff from the three town halls and part of the results have been discussed remotely with DRM. On-site presentation of the results and new data acquisition could be possible, should travels open again in 2022.

#### *Ciguatera information framework*

Integrating ciguatera information from local knowledge into SCP raised some warnings and perspectives. As highlighted above, ciguatera risk maps produced from local knowledge are relevant for spatial planning but not for health-related programs, where ecotoxicological analyses would better fit the need.

Assuming fishers had described consistently and precisely their knowledge on ciguatera risks, the main challenge to further enhance the developed methodology (Chapter 2) should be now to include separately the groups of species that are ciguatera-prone. Indeed, ciguatera risk varies spatially within a lagoon, but also from one species to another (Chinain et al., 2021). Being able to record and use precisely this information would increase the relevance of the methodology applied here (Chapter 2).

### *Connectivity information*

The connectivity matrices used for Takaroa to identify candidate sites for oyster restocking, and subsequently, for spat collection, could be refined, spatially and temporally. The small size of Takaroa and the distribution of suitable habitats for wild oysters allow us to state that we are not expecting substantial changes in terms of connectivity patterns even at refined resolution, yet a hydrodynamic model with enhanced precision, additional wind regimes and more detailed connectivity matrices is currently producing enhanced data for Takaroa, within the MANA Project. This will allow being a little more specific on the best restocking zones. These refinements are however useful to develop in the case of additional, larger, lagoons.

### *Conceptual limitations*

We describe here some conceptual limitations that we have identified regarding SCP itself, conservation and planning in general.

#### *SCP cannot handle a temporal dimension*

While SCP offers numerous options to parameterize scenarios, we faced a structural limitation when searching to select two different sets of optimal solutions using a single dataset, to mirror the rāhui temporal design, which is based on periodic rotational closures. In SCP literature, the temporal dimension is only mentioned from the perspective of adaptive planning, to make iterative plans with new sets of data to better adapt to changing situations (Cheok et al., 2017; Grantham et al., 2008; Weeks and Jupiter, 2013). Explicitly taking into account the temporal dimension and dynamic nature of socio-ecosystems (and notably fisheries) into a single SCP scenario is currently not possible. Potential future development of SCP tools may solve this type of restriction, but this is not addressed in the SCP literature for now. Besides, when the temporal dimension is as important as the spatial dimension, other tools could help solve this problem, including spatial modelling approaches such as spatial population model or multiagent based modelling. However, these approaches require temporal information (and validation), which were not available here.

#### *SCP solutions are driven by opportunity costs*

Another point to highlight is that SCP site selection is, by design, highly driven by the cost minimization. In our context, this translates into avoiding selecting the most fished zones for conservation. Nevertheless, empirical observations show that locally managed marine areas are often situated next to villages (Cinner & Aswani, 2007; Smallhorn-West et al., 2019), where fishing pressure is expected to be high. In these cases, the management rationality may have prioritized locations that are easy to control by the communities. This could lead us to put into question the common initial assumption that minimizing costs for stakeholders in a fishery context, solely relies on potential catch loss. Nevertheless, for SCP applications, it is impossible to anticipate in a generic way the willingness of a community to give priority to strengthening control on the reserve or minimizing catch loss, while reaching the objectives. In such situations, only case-by-case involvement of the community during the SCP process is likely to provide such indications to guide SCP parameterizations. During field studies, we actually noticed that some fishers could virtually use the whole lagoon, showing quite high spatial mobility, to adapt to weather conditions, gear type choice or the fish wished for the daily menu. This adaptability might be linked to the size of the lagoon and the near-absence

of marine tenure in Polynesia, contrary to examples in Melanesia (Deas et al., 2014; Gruby and Basurto, 2013). Indeed, in such cases, future adaptations for SCP designs should take into account, to some extent, locating reserves near villages to better support the need for local enforcement.

### *SCP cannot integrate all the parameters at play*

In principle, SCP relies inherently on spatial and quantified information, thus the realistic nature of the scenarios is usually limited by the availability of such data. While a typical design usually claims to account for socio-economic factors, these may not reflect exactly human reality, which may be difficult to capture and / or not always suitable for spatialisation, as many facets are at play (stakeholder rationalities, cultural values, unsaid or *tapu* subjects, gender issues, governance aspects, etc.). As a limit of the tool itself, this reminds us of the need to situate SCP as just one step in the overall conservation project process, and to take into account the subsequent steps that are necessary to SCP results: validation and implementation by the involved stakeholders (Pressey and Bottril, 2009).

### *Other limitations to planning*

Reserve planning tends to focus on the benefits of removing anthropogenic pressure (fishery, multiple uses) from the protected area. However, some aspects are less studied regarding the impacts that reserves can cause beyond their boundaries, such as fishing pressure displacement and if the expected biomass export can balance it (but see Babcock et al., 2005, Halpern et al., 2004). Although these consequences induce planning issues, they have never been integrated to a SCP process, to our knowledge (but see Chollet et al. (2016), a non-SCP study).

## **2 Generalization to other POTIs**

The approach we have undertaken to focus on a context-specific angle has strengths and weaknesses. Some concepts can be generalized to other study sites, but any practical planning exercise will need to remain locally grounded, to answer adapted questions and use adequate data.

### **2.1 Small-scale fisheries and ciguatera information**

Coastal small-scale fisheries are widely practiced across the POTIs (Gillett and Tauati, 2018), for leisure, sport and food security, as a way of life and a cultural heritage. Nevertheless, fishing practices have evolved with new equipments, fishing pressure has increased and, combined with population growth, resources are being overexploited, which affects the ecosystems. Precise and recent knowledge on the practices and levels of catch are required to run SCP with robust baseline, for every island taking part in this activity. However, small-scale fisheries are usually poorly reported and quantified (FAO CWP Secretariat, 2019; Zeller et al., 2007).

The dinoflagellates producing ciguatoxins are endemic to the Pacific Ocean zone, as well as the Indian Ocean and the Caribbean, and we now find them in additional regions such as in Asia, India and Atlantic Ocean (cases reported in Canary and Madeira Islands) (Friedman et al., 2008) (Figure 43). Ciguatera poisoning occurrences were recorded in 22 POTIs with high

to very high incidence rates (up to 1,300-1,400 cases/100,000 inhab. in Kiribati and Cook Islands) despite difficulties to estimate them (Chinain et al., 2020). Thus, taking into account ciguatera when undertaking marine planning should be extremely useful for most POTIs, highly relying on small-scale fisheries for local food security. Precise spatial and updated information is necessary to integrate ciguatera risk into SCP application. In our studies, we used map-based fisher surveys to gather local knowledge and use it as a proxy to ciguatera risk. This generic method, provided in the framework (Chapter 2), can be used and adapted to other POTIs to account for ciguatera risk when planning for conservation and fisheries management.

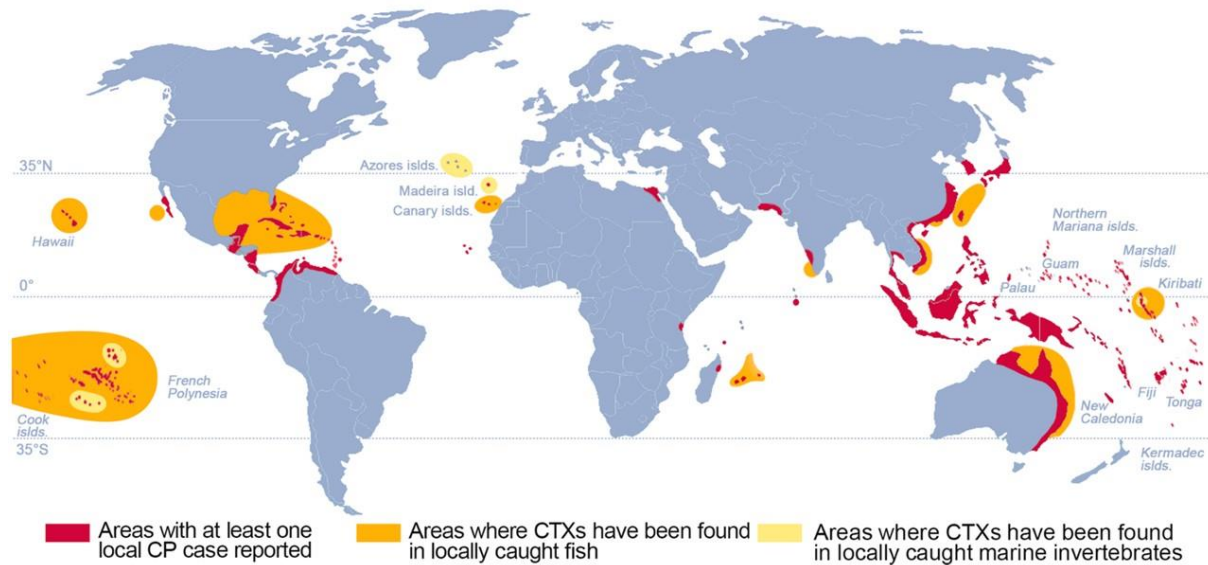


Figure 4.3. The regions where ciguatera poisoning (CP) occurrences have been documented at a global scale (Chinain et al., 2021).

However, some aspects can hinder the generalization of this method to other sites. First, of course using this approach is not justified in a site where there is little or no ciguatera (such as in Takaraoa, where we did not take it into account for this reason). In addition, in sites where ciguatera risk is low, local knowledge on spatial risk may not be accurate. Second, basing the survey approach on fisher's local knowledge worked well at our study sites, but it can be more complicated in other sites where fishers may not share as easily the information about their fishing grounds and practices. Lastly, although Pacific islanders are generally recognized to easily find their bearings on a geographical map (Lauer and Aswani, 2009), some respondents might have difficulties to find their way on the satellite view map. More generally, analyses of ciguatoxin levels in finfish and invertebrates should advantageously complement the characterization of local risk.

As a perspective, a large project is being prepared by Institut Louis Malardé (ILM) as part of the Ciguawatch initiative to build an online training and data-sharing platform accessible by all the Pacific countries and territories: among other benefits, this platform will allow health care workers and individuals to declare and localize poisoning events. Data feeding into this platform through a citizen science approach has the potential to yield precious data on the current epidemiological ciguatera status in a given country. In a SCP perspective, this



information would be valuable, as a first step assessment information prior to considering complementary field surveys among the fishers, which remains recommendable.

## 2.2 Traditional management

Traditional management, including community-based fisheries management (CBFM) and locally managed marine areas (LLMA), is widely shared among the POTIs, in its many different forms (Bell et al., 2018). It has regained importance since the 1980's (Gruby and Basurto, 2013; Johannes, 2002; Ruddle, 2008), and is increasingly recognized and promoted (Sangha et al., 2019) at regional and international levels (PIRT, 2020; Payri and Vidal, 2019). Integrating this dimension or at least consultation with local stakeholders when building any new SCP project in the POTI region, is thus warmly recommended.

In many places in the POTIs, it is known that overfishing is occurring (Gillett and Tauati, 2018) but detailed knowledge is lacking on stocks, species, distribution, pressure etc. Due to wide dispersion of the islands and limited resources of the governments preventing them from sending a monitoring authority to each site, the enforcement of fisheries regulations, when existing, is often lacking. In this context, strengthening local and community-based management are key levers to raise awareness, promote and sustain fisheries management.

However, articulating community-based management with national legal frameworks remains challenging, as it requires governance to be shared and partially decentralized (Kuemlangan, 2004). The ongoing recognition of customary law in country's legislations systems such as in New-Caledonia, Cook, Solomon and Vanuatu, among others (Graham and D'Andrea, 2021; FAO, 2020) is a step in that direction. Some achievements should be highlighted, such as the Tonga's Special Management Area Program, where the government recognizes communities' responsibility in local management (Smallhorn-West et al., 2020), the Palau's national MPA network implementation that induced institutional changes and multi-level governance system including with NGOs (Gurby and Basurto, 2013), or the Fijian adaptive co-management of flexible customary governance with long-term partners (Weeks and Jupiter, 2013). Co-management of natural resources is a governance scheme now widely recognized as fair and effective to governing complex socio-ecosystems, as are fisheries. Based on flexible and adapted levels of accountability between local entities, managers and governing partners, these arrangements raise institutional challenges but are promising to enforce local conservation measures and secure food security (Cohen et al., 2021). The *rāhui* initiative in Raivavae (Chapter 4) falls within this context, as well as the integration of a traditional design for the oyster restocking, in Gambier (Chapter 5).

Co-management approach, operating at multiple scales of governance, can be beneficial in improving the effectiveness of resilience to climate change. In Reao Atoll, French Polynesia, the articulation of different levels of legal and local management and science frameworks (at the international, national, territorial and atoll levels) resulted in a successful coordinated decision-making process to respond to a mass-bleaching event of reared giant clams (Andréfouët et al., 2018). To increase buy-in from the communities, a solution is the scaling-up of local reserve networks through SCP design, which requires articulating local governance scale with national levels (Horrigue et al., 2015). For this, social network analysis can greatly help (Mills et al., 2014). Indeed, local communities in peripheral communities are

not always aware of ecological processes or climate change threats and the necessary complex design required (Nunn et al., 2014). Thus planning at regional scales would spread the risk for local reserves to be impacted by the same disturbance (Andréfouët et al., 2013; Green et al., 2014; Kabbadj et al., 2018; Mills et al., 2010).

Another point is that SCP relies on scientific paradigm with standards, methods and measurable information, whereas traditional knowledge of the environment and management schemes may include other paradigms of values that can vary across Oceania, including cultural practices and spiritual heritage, along with empirical observations and long term perception of the environment. As culture is in perpetual evolution and adaptation, in contact with globalization and foreign power influences, we assist to both hybridization of views and increased awareness of cultural identity, exemplified by the renaissance of community-based management initiatives (Johannes, 2002). While these initiatives were primarily motivated by marine fisheries management, many tend to adapt to contemporary context and expectations, including conservation principles, sometimes hybridizing with research and/or education programs (Delevaux et al., 2018; Filous et al., 2019; Hinchley et al., 2007; Reimaanlok Nat'l planning team, 2008; Smallhorn-West et al., 2020; Wendt et al., 2016). In return, an emergent recommendation to integrate in reserve designs, is how people are attached to their environment (Buijs, 2009; Charles and Wilson, 2009). Incorporating how people value their environment and fishing grounds into SCP designs was shown to bring significant changes in the locations of protected areas, as evidenced in Papua New Guinea (Hamel et al., 2018) and in Fiji (Gurney et al., 2015). Beyond SCP solutions, the planning process itself with local stakeholders can reap invaluable benefits, such as combining traditional knowledge with ecosystem-based approach (Weeks and Jupiter, 2013; Wendt et al., 2016).

As a decision science asset to rigorously set conservation priorities (Klein et al., 2014), SCP can definitely act as a tool to inform stakeholder's decisions and feed the management discussions, providing objective and quantified information on potential solutions. It could be a catalyzer to bridge gaps between community-based initiatives, such as OECM (Gurney et al., 2021; IUCN, 2019), and regional and international initiatives in the Pacific institutions, such as the South Pacific Community (The Vemööre Declaration (PIRT, 2020); IPBES Oceania (Payri and Vidal, 2019)). SCP could be placed at the crossroads of these different levels as a common forum to dialogue and find out aligned plans.

### 2.3 Mariculture, diversification and adaptive approach

#### *Mariculture*

In this thesis, integrating mariculture to SCP as an original POTI feature was declined around black pearl farming, as it is a preponderant activity in French Polynesia lagoons. Black pearl farming is also practiced at a smaller scale in Cook Islands and in Fiji, where spatial dispersal of larvae was recently modelled (Monal et al., 2020). SCP could also be used to address questions of management regarding other mariculture activities, if they are to develop, such as shrimp, invertebrate or seaweed farming (Adams et al., 2001; Bell et al., 2011a) given their potential spatial extent in coastal areas, and the associated status of exclusive use.

For example, in the Solomon Islands, a recent workshop training was held on local transformation of seaweeds to increase added value and revenues (Singh and Lulu, 2021). In the form of family businesses, seaweed farming is the main source of incomes in Wagina and Manaoba Islands, and this value chain development is likely to increase interest for this activity. In this context, if seaweed farming surface areas extend, a spatial management plan for sound development should be recommended.

Another example is the giant clam mariculture development during the past decade in the Tuamotu Archipelago, French Polynesia (Remoissenet and Wabnitz, 2012). In these remote atolls where few other income-generating activity exist, it offers promising prospect of income. Giant clam spat collecting rafts depend on the reproductive capacity of the wild (fished) brood stock, and are vulnerable to extreme temperature events (Andréfouët et al., 2018). Finding the best places for giant clam spat collecting rafts therefore depends on a panel of criteria, including intra-lagoon connectivity patterns and exposure to high temperature events, as well as socio-economic factors such as fishery grounds to minimize spatial conflicts between mariculture farmers and fishers. In a near future, provided such information is available, SCP could give clues to identify suitable zones for spat collection.

Mariculture development (or reduction) can be considered in the context of diversification of the activities, and their spatial outcomes may need to be balanced with other activities such as fishing, conservation, tourism etc., while looking for sound development pathways that balance income-generating activities, with the need to ensure food security through local fisheries, and to conserve functional ecosystems through reserves. SCP proved to be a useful tool to foresee spatial arrangements between multiple uses, such as in Gambier (Chapter 5). It should be a valuable tool for other POTIs, for potential mariculture development, but also in the context of demographic growth inducing an increasing demand for marine resources and recreational activities.

### *Diversification beyond mariculture*

Besides demographic growth, external factors are at play: in a changing world, global crises affect even remote islands, with a severity that depends on their degree of exchanges and dependencies with the outer world. Island economies that rely strongly on a single, productive or extractive activity that is outward oriented, may be at risk in case of a global crisis or change in the external demand for this resource, or in case of resource depletion. An emblematic (and extreme) example in the Pacific is the Nauru's economy that has been exclusively based on phosphate extraction with no alternative economy development (Connell, 2006). Other examples are the recent Kiribati's spectacular GDP growth, exclusively from purse seine fishing rights revenues in its EEZ, contributing to 70 % of its income, and reaching 84% for Tokelau (Bell et al., 2021; Webb et al., 2020).

Diversification strategies are classically promoted to mitigate the risks of collapse in the local socio-economic balance (Barrett et al., 2001; Bowser and Nelson, 2012; Kasperski and Holland, 2013). Dominant activities often have a spatial dimension and an ecological footprint on the environment. In case the need for diversification is required, the spatial dimension can be addressed by sound multi-zone planning to help foresee spatial arrangements and integrate environmental factors to mitigate some of the risks. Other means, of course, can attenuate

socio-economic collapse. For example, the Covid crisis has hit the territories with a strong focus on tourism, such as French Polynesia, where tourism was the top export income (IEOM, 2020), and Palau, where the tourism sector accounted for 20% of GDP and 20% employment in 2019 (Joshua, 2020). However in these cases, the impacts were mitigated by aid from the privileged metropole counterparts.

Even though diversification has been largely promoted as alternative livelihoods in rural development projects (Haider et al., 2018), it must be considered carefully. Many factors interplay beyond spatial management and may hinder the project success if not adequate, such as fundamental alignment with actual local people aspirations, appropriate available skills, dependence to external subsidies, etc. (Gillett et al., 2008; Eriksson et al., 2020). Here we suggest SCP as an outlook when appropriate, where diversification is locally endorsed and underway. Some successful examples of diversification of the activities have been highlighted in the POTIs, such as successful seaweed farming in Kiribati, the Solomon Islands, and in the Autonomous region of Bougainville, Papua New Guinea (Gillett et al., 2008; Singh, 2015). Collecting or rearing species for aquarium trade is another alternative livelihood, such as growing “living stones” for aquarium trade in Fijian reefs, based on arrangements with coastal communities, or fishing the popular flame anglefish, mainly in Marshall Islands and Kiribati, but also in Vanuatu, Cook Islands and Federated States of Micronesia (Gillett et al., 2008; Wabnitz, 2015a). Nevertheless, not all sites have sufficient levels of resource abundance to allow for sustainable resource harvest, such as observed in Samoa (Wabnitz, 2015b) and fishing for aquarium trade must remain in a regulated framework within the international legal standards of the Convention of International Trade in Endangered Species (CITES).

One avenue often raised in the Pacific to diversify fishing activities, enhance food security and income in the POTI islands, is the use of nearshore low cost and rustic fish aggregating devices (FADs) to target tuna and coastal pelagic fishes (Bell et al., 2015, 2018; Hanich et al., 2018). In French Polynesia, FADs located much further offshore have already been implemented and used successfully, accompanied by government support for the acquisition of adapted equipment such as ‘*poti marara*’ type vessels (Gillett, 2008; DRM, 2019). In this case, FADs are aimed for professional fishers. In the case of nearshore FADs, although their development depends primarily on government investment and monitoring, and on the small-scale fishers’ adherence and empowerment, SCP tool could also help optimize the location of FADs as well as conservation zones on the outer slope and in the lagoon. If FADs actually alleviate lagoon fishing pressure and the fishing grounds change accordingly, iterative plans should be conducted to integrate these changes, under an adaptive approach. Besides, another fishing technique, traditional this time, concerns the fish parks. They consist in a labyrinth built with stones where the fish are trapped, carried by the currents of the passes or *hoa*. SCP could also help planning for the location of these fish parks in lagoons.

### *Adaptive approach and fishers adaptability*

Considering a wider geographical scope in the Asia-Pacific region, a switch on the main income-generating activities was evidenced in Bali, Indonesia, from widespread seaweed farming towards tourism-only economy. However, in front of the 2017 active volcanism of mount Agung and subsequent tourism drop, the inhabitants wanted to switch back to seaweed farming but they had no more adequate equipment. Future oscillations between these two

dominant activities are likely to repeat according to local and global conjectures, such as the Covid crisis. To help communities bounce back and be able to undertake one activity or the other, it was recommended to maintain a minimum level of effective seaweed farming activity and the associated means to ensure the continuation of know-how, seaweed strains and essential gears (Andréfouët et al., 2021). In such case, a coastal management zoning plan should set a minimum space for seaweed farming to maintain active this ‘diversification option’. It is a good example where SCP could provide base plans with variable levels of activities’ extents, and better integrate the adaptability needed.

In Tonga, small-scale fishers affected by the Covid crisis proved adaptable and engaged in diversification of the activities, especially women, including towards handicrafts. Fishery habits have changed and induced less fishing at night, and more nearshore holothurians species targeted (Marre and Garcia Imhof, 2021). These changes evidence great flexibility, widely shared among the Pacific islanders, but also the need for adequate adaptive management and planning to adjust to new challenges (Ban et al., 2011; Weeks and Jupiter, 2013) and mitigate impacts from global origin.

Stepping back, it may be noted that artisanal fishery activity has mainly been considered as a single activity in this thesis, but it actually can be understood as a remarkable pattern of diversification itself, already implemented and empirically optimized by the fishers themselves. Indeed, small scale fisheries are often based on diversified means of production, using different fishing gears (such as spear gun, line, gillnet, ‘*pātia*’, downrigger and hand harvest) (i.e. the results of our surveys in the three islands, and as mentioned in Adams et al., 2011; Deas et al., 2014; Van Wynsberge et al., 2015), which are adapted to the fishers’ needs, means and wants. It allows fishers to target different species and zones, either selected or in a rather opportunistic approach, according to weather conditions, seasonality, means of transport etc. (Figure 44). This flexibility makes them very adaptable and constitutes in itself a form of diversification. SCP projects should ensure that the use of different fishing gears are documented and mapped, so as to authorize a variety of diversification and spatial uses with a number of opportunity costs options, depending on the local gear portfolio (Deas et al; 2014).

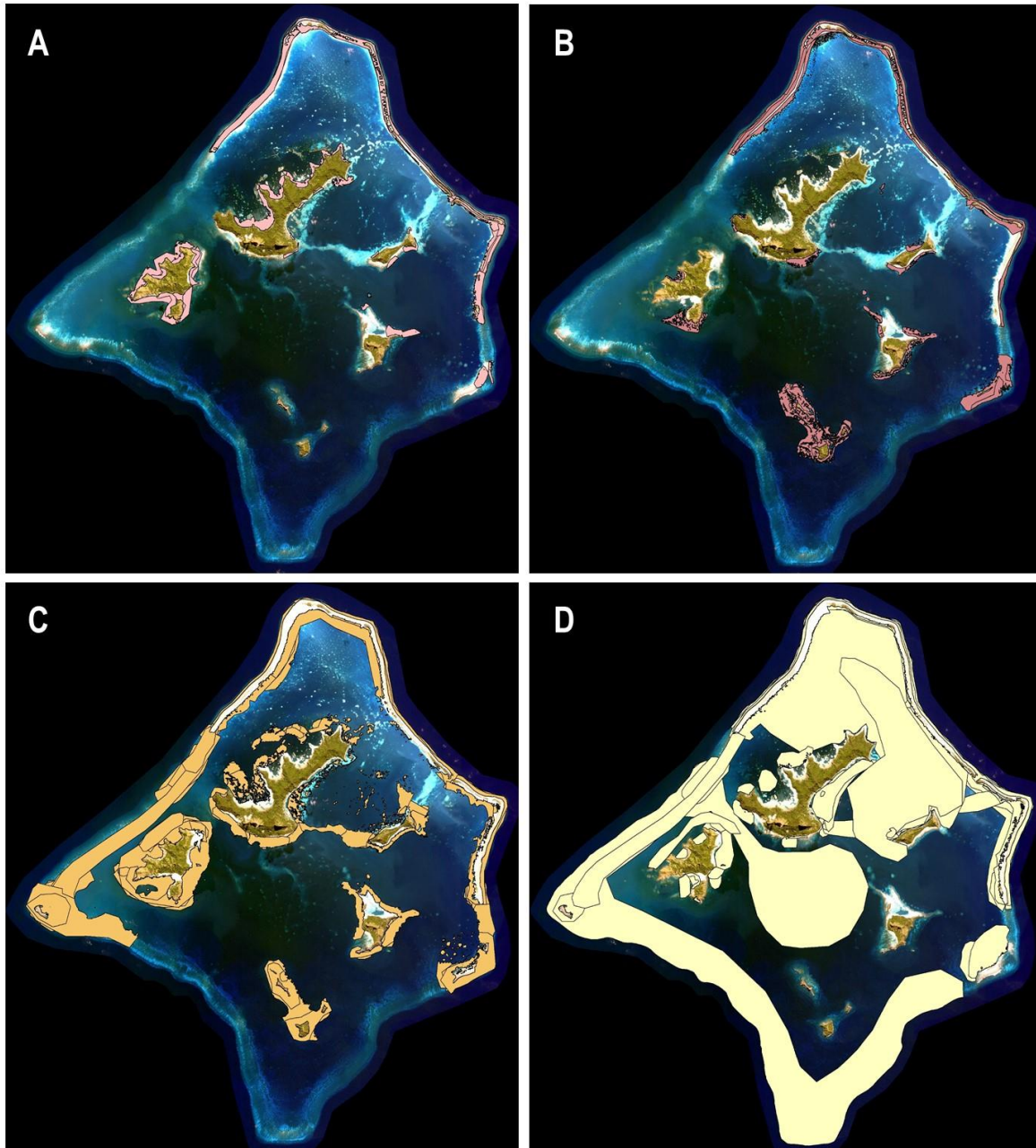


Figure 44. Distribution of fishing grounds in the Gambier lagoon, according to the fishing gear used (A) gillnet; (B) gathering seafood by hand (mainly lobsters); (C) spear gun fishing; (D) hook-and-line fishing.

#### 2.4 Additional avenues for SCP use

Many other activities and development projects having spatial outcomes and footprints are likely to occur across the POTIs and induce potential spatial conflicts with existing or future activities. Thus, some planning is required and SCP could bring useful insights to support management, provided feasibility in terms of available spatial data, their quality, and attention paid to the sensitivity of the results from initial parameterization. As a lesson-learned from this thesis, where we partially based the choice of relevant criteria on empirical observation, we

could state: every situation is different. Indeed, a case-by-case approach is necessary to tailor spatial plans for development or change in activities.

## 2.5 Tourism

Substantial tourism infrastructures imply developments on the shore or in lagoon habitats (wharfs or buildings on stilts over sandy bottoms, seagrass beds, mangroves or coral cays) and can induce degradation of fragile environments, aggravated by crowding in some places, such as in Micronesia, increasingly targeted by Chinese tourism. Tourism activity has been very important for a number of POTI Islands, with near 900,000 total visitor arrivals in 2017 in Fiji, above 200,000 in Vanuatu and French Polynesia, etc. (Cheer et al., 2018; IEOM, 2020). Any change in tourism intensity due to the international conjecture or increasing trend such as cruise ship, may translate into requirements for spatial adaptations that could be supported with SCP.

## 2.6 Coastal development

Many POTIs have high population density in their capitals and main urban centers. For example, seven countries have more than half their population living in urban centers (Cook Islands, Fiji Islands, the Marshall Islands, Nauru, Niue, Palau, and Tuvalu) (ADB, 2020), which raises issues of infrastructure development, environmental protection, and wastewater management. As inhabited zones concentrate on coastal strip, with consequent port infrastructures, airport strip frequently reclaimed from the sea and multiple marine uses including the need for seawater quality suitable for bathing and for safe fishing, a SCP component could provide useful hints in urban contexts.

However, planning may be very complex and take a long time if the situation is complicated, with multiple uses, increased demographic pressure and stakeholders with divergent interests (ex. 25 years planning PGEM before implementation in Moorea, French Polynesia).

## 2.7 Very large MPAs

A recent dynamic to create very large MPAs emerged across the POTIs, which was impulsed by the Hawaiian Papahānaumokuākea Marine National Monument in 2000. Most have not been the subject of a real design that would have explicitly integrated ecosystem-based design and human dimensions, but were rather likely 'residual reserves' that are declared on areas 'by default', where it does not bother (Devillers et al., 2015).

Nevertheless, recent guidelines paved the road for sustainable management design, such as the IUCN WCPA's Guidelines for Design and Management of Large-Scale MPAs (Lewis et al., 2017), and guidelines for ocean governance (Christie et al., 2017). Some case studies such as for the Pitcairn Island Marine Reserve (Nikitine et al., 2018) highlight the importance of data quality and ecosystem-based design. Recently, some research have precisely produced a comprehensive map on bioregions for coastal and oceanic waters at EEZ scale (economic exclusive zone), for the whole Southwest Pacific region (Beger et al., 2020). It is likely that this piece of work will unlock SCP use for large MPA design at the EEZ scale in the near future. Depending on the SCP focus, for applications to conservation or management, complementary information could be used, e.g. physical data: seabed geomorphology, depth,

seamounts, volcanic activity (i.e. for Vanuatu, Tonga's submarine volcanoes, PNG), seabed mining exploration zones or oceanic fisheries. Nevertheless, for the latter, given the very mobile character of tuna fisheries in connection with the dynamic warm pool shift following El Niño Southern Oscillations, SCP may not be appropriate to integrate such mobile and temporal component. Other measures, including quotas as already implemented, may be more relevant.

These examples thus suggest that SCP is able to bring tangible analysis to support negotiation processes, at the POTI region scale or even at international level for conservation by the High Seas Treaty, for example (Visalli et al., 2020). However, the real challenge lies in the implementation of such regional plans. Indeed, translating the regional design into local actions requires good communication between the levels of governance, and continuous adaptive planning between the local and regional scales. Indeed, regional plan must be compatible with the local situations, and additional studies of local SCP may be needed to validate the feasibility of implementation and coordinate the spheres of decision-making to achieve wider objectives (Mills et al., 2010; Pressey et al., 2013).

### 3 Perspectives

#### 3.1 Extending our SCP use of connectivity models to additional marine resources

Future developments of our SCP simulations may benefit from the lagoon hydrodynamic circulation models that are currently being developed for oyster larvae dispersal in several lagoons in French Polynesia, in the MANA project framework. In order to extend their use to other marine resources that would be representative for local fisheries management, research should be directed towards coupling these site-relevant hydrodynamic models to biological information on larval behavior from other taxon. We acknowledge that larval connectivity is only one of many facets of population connectivity (Green et al., 2015; Magris et al., 2016; 2021; Thomas et al., 2014), and the MANA models are only built at a lagoon scale although connectivity among islands also occurs through oceanic dispersion (such as modelled for oyster larvae in Fiji, e.g. Monal et al., 2020). Nevertheless, spatial planning for sustainable fisheries using such intra-lagoon connectivity model could make a useful contribution to plan for fishery stock management, as conducted elsewhere (i.e. Nicolle et al., 2017).

Genetic data could provide complementary information, when available at relevant scales and resolution, by using estimation of the degree of genetic differentiation between sites, to infer connectivity among populations, and thus provide useful data for MPA planning (Jenkins and Stevens, 2018). Further, if combined with biophysical models, it improves knowledge on marine connectivity and provides connectivity data on both demographic and genetic levels (Jenkins and Stevens, 2018). Such an example was conducted on pearl oyster model in Ahe Atoll, French Polynesia, where data on genomics, demographic and biophysical parameters were combined to infer population dynamics and oyster connectivity within the lagoon. It revealed strong spatial discrepancy and the need for sound management with protection measures (Reisser et al., 2020). These studies on genetic connectivity are very costly, but if



they are conducted, as here, or in other atolls where hydrodynamic models are operational, this will produce valuable information potentially useful for further SCP planning.

### 3.2 Implementation of the SCP solutions in our study sites

After the design step of systematic planning, possibly including co-construction with the involved stakeholders, subsequent steps include implementation by transferring these findings to the partners, potentially from multiple levels of governance. These transfers can be dynamic in two ways and conduct to re-iterate a cycle of discussions and SCP scenarios, potentially with new indications to refine the process each time until the design is satisfactory for all parties (Weeks and Jupiter, 2013). This is an ideal adaptive process implementation and has been studied through some examples in Fiji or New Zealand (Geange et al., 2017; Weeks and Jupiter, 2013; Wendt et al., 2016). Sometimes, SCP step is only conducted early in the process, then, subsequent modifications are brought to the design but the plan is not re-evaluated (Flower et al., 2020). It is not the ideal situation but the plan was at least elaborated from a clear data-driven baseline. However, in case of co-management, implementation success is also function of the adaptive capacity of the local community, thus fostering communities' engagement and leadership should be one of the institutional priorities (O'Leary et al., 2020).

Indeed, beyond planning, the effectiveness of a reserve crucially depends on effective management, which key pillars seem to converge towards local endorsement, enough means allowed to maintain it and follow-up on the long run, and good articulation between the different levels of policy makers involved (Ban et al., 2011; Gruby and Basurto, 2013; Weeks and Adams, 2018).

In the case of the islands we studied, we hope that the stakeholders will appropriate the SCP findings. DRM's involvement throughout the process provided significant insights on the needs and expectations from the plans, to guide co-construction of the scenarios during the SCP process. Further collaborations may enable to fine-tune the reasoning and sharpen up the plans, integrating additional feedbacks from the local stakeholders such as pearl oyster farmers in the case of Gambier, and new data such as enhanced connectivity matrices, in the case of Takaroa restocking project.

Working with Raivavae fishers was less interactive, except during the initial discussions and field trip, given the people were less familiar with emails and videoconferencing to be able to interact during the pandemic travel bans. However, considering our results, future partnership and interactions are not excluded, within a clear institutional framework, if the rāhui is eventually implemented. Under DRM approval and marking, monitoring the impacts of the rāhui will undoubtedly be scientifically interesting in relation to its spatial and temporal scheme, and the community's buy-in.

### 3.3 Beyond the SCP horizon

Besides SCP, alternatives to area-based management measures exist. For instance, expert-driven *ad hoc* solutions can emerge more easily and simplify the work of managers, although this approach has limitations (Allnutt et al., 2012; Keppel, 2014; Keppel et al., 2012; Klein et al., 2014a). The potential, pros, and cons of the various approaches remain a matter of debate

and this will likely continue in the future, however, as exemplified throughout this thesis, SCP provides useful advantages. Spatial planning has recently be promoted globally through the Marine Spatial Planning global initiative, supported by the IOC-UNESCO, and in the context of Blue economy (Figure 45).



Figure 45. Blue growth and blue justice display here ten challenges for the ocean economy that interconnect with marine spatial planning (adapted from Bennett et al., 2021).

Area-based management tools, and *a fortiori* SCP tools, are only one part of the conservation and management toolbox. A whole lattice of rules and fishery management strategies exist and can also work quite well (Weeks et al., 2016) such as fishing quotas, size limits (minimum size to protect juveniles and maximum size to protect the highly productive spawners), gear restrictions when they are destructive or too effective (such as mosquito net to catch juveniles). Fishery management can also recommend temporal restrictions to protect spawning aggregations or release egg-bearing females (lobster hand harvest). Another measure consists in decreasing pressure on herbivorous fishes, to preserve their function and mitigate risk for coral reef recovery after a major perturbation, via favoring coral recruitment (Chung et al., 2019).

However, institutional and financial means of regulation and controls are often lacking, all the more in remote islands and despite high pressure in densely populated zones. Therefore, complementary effort to manage fisheries and conservation should be directed towards preventive measures to inform and raise awareness. Essential tools include active communication by various means (radio, TV, informative billboards at strategic sites), education programs in schools, promotion of environmental association fostering engagement in resource stewardship and monitoring, etc. In line with the developments set out above, local levels and communities taking part in the implementation process are key levers to promote and sustain fisheries and the environment.

Interestingly, beyond the technical data-driven solutions, the mapping instrument can also serve other strategies such as giving more visibility to some aspects or a segment of the population, such as artisanal fishers. Iterative discussions and knowledge sharing between them, scientists and managers can contribute to their empowerment, the co-development of sound data production and subsequent active participation in debates, such as exemplified by Trouillet et al. (2019).

#### 4 Conclusion – take home messages

In the field of conservation science, Systematic Conservation Planning (SCP) is a tool based on mathematical solving methods used to identify, among multiple possible combinations, the areas that will optimally address the problem at hand. Classically, the goal is to achieve a conservation representation objective while minimizing the socio-economic costs induced by the reserve. This tool aims at providing decision support to managers.

Through a state of the art of the use of SCP in the coastal environments of the Pacific Ocean Tropical Islands (POTI), we have noted various uses of SCP tools, but also some gaps. Indeed, SCP studies have often been oriented towards increasingly complex issues, firstly seeking originality for scientific publications. This leads to a lower number of SCP studies responding to real needs for concrete applications locally to contribute to the decision-making process. There are several aspects common to many POTIs that have not been addressed or have been poorly addressed in the POTI SCP studies. This state of the art helped to formulate the main research question (Q0) addressed in this thesis: "how can we better integrate the POTI's specifics into SCP for the conservation and management of marine areas?"

Working in French Polynesia with local partners (DRM, DREC, and ILM), we have identified four main lines of research on features that make sense at the local level, and the associated questions have been developed in consultation with stakeholders. Thus, we examined how to use SCP to address the following issues: (Q1) **ciguatera**, which strongly affects French Polynesia populations, especially when they are dependent on lagoon fishery for food security; when known, areas at risk for ciguatera are avoided by fishers and thus become restricted access areas for fishing, which is to be considered in lagoon spatial planning; (Q2) **pearl farming**, widely developed in French Polynesia, is an economic pillar that helps maintain an activity in remote islands, but is now facing a multifactorial crisis, this points a need to identify management options in the lagoons; (Q3) **traditional management of marine resources**, which is experiencing a revival in recent decades, but faces optimization needs and (Q4) **diversification** of the activities as a means of reducing risks related to the variability of external factors, particularly in the case of pearl farming when it is dominant in a lagoon thus other sea use options need to be considered.

The main results from this thesis study are:

- 1) Ciguatera can indeed be integrated into the SCP framework. To do this, building up an information database by collecting local knowledge is a satisfactory and relatively low-cost solution. It makes it possible to obtain a spatialized and quantified representation of the risk of ciguatera within a lagoon. We then proposed a method for integrating this information into the opportunity cost of fishing. According to our approach, the higher the risk of ciguatera, the lower the opportunity cost, thus favoring the closure of areas that are high-risk with low fishing activity. This methodology was applied to the Raivavae lagoon in the Austral Islands and the results show that taking into account the risk of ciguatera leads to solutions with 24-38% decrease in the opportunity cost for fishers (Chapter 2).
- 2) Sustainable management issues in pearl farming, particularly with regard to the spatial component, are successfully addressed by SCP. It has been used to identify suitable areas for the reintroduction of spawning adults to increase the natural stock of pearl oysters in the lagoon and thus revitalize the collection of juveniles in Takaroa, Tumaotu. Site selection was based on socio-economic and environmental parameters specific to the pearl oyster resource, including habitat and lagoon connectivity (Chapter 3).
- 3) The traditional management design, which appeared to be restrictive for fishers in Raivavae, was considered by the SCP to seek alternative solutions. Numerical optimization was carried out to meet the same objectives of preservation of the giant clam resource as the rāhui, and to reflect the spatial distribution of the closures across the four large areas in the lagoon. It also aimed at minimizing the opportunity costs for fishers, while taking into account the risk of ciguatera, to which the population has been heavily exposed (Chapter 4). The SCP solutions identified designs that were respectively 7 and 5 times lower in size and cost for the fishers.
- 4) Finally, spatial options for diversification of activities were explored using the SCP in the Mangareva lagoon, where pearl farming, the dominant activity, is threatened by the economic difficulties experienced by this sector. The managers wish to decrease the spatial extent of pearl farming concessions in order to leave more room for fisheries, to set up sanctuaries for adult oysters restocking according to a traditional management zone scheme, and to identify conservation areas for remarkable coral communities. Scenarios were designed for the spatial distribution of activities through various degrees of diversification and to maximize areas of interest to fishers, including considering the risk of ciguatera (Chapter 5). The multi-zone SCP results have shown that diversification scenarios are possible in the Gambier lagoon and the comparison of solutions can serve as a basis for management discussion.

Until now, SCP had never integrated the risk of ciguatera and impacts on fishing grounds, nor addressed the management and sustainable exploitation issues raised by pearl farming. By studying how SCP can respond to some specificities of POTIs, in particular the risk of ciguatera associated with artisanal fisheries, the management of pearl farming, the management of traditional reserves and diversification strategies in a lagoon, this thesis has contributed to demonstrate the potential of tailor-made SCP scenarios to respond as closely

as possible to the needs of managers and to reflect local logics and constraints. Thus, this thesis contributed to develop the field of possible uses of SCP and demonstrated that this tool could answer very pragmatic questions, in concrete cases of coastal space management, which are actually common to many POTIs.

Lastly, this thesis increases the contribution of French Polynesia to the total number of SCP case studies in the POTIs, and slightly counterbalance the polarization by Fiji (Figure 46).

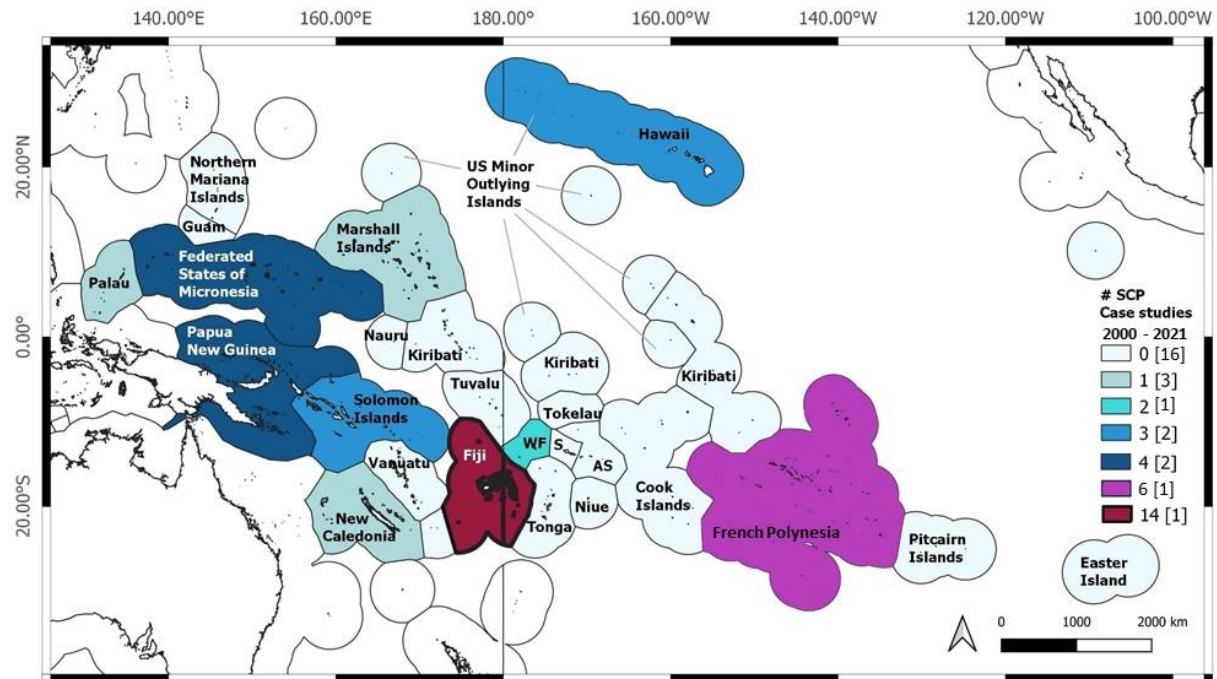


Figure 46. Summary of the number of SCP case studies in the POTI, with the contribution from this thesis, as an update of Figure 7.

In conclusion, the specificities examined here in the context of French Polynesia can be extrapolated to many POTIs. Indeed, generalizing a methodology that integrates the risk of ciguatera will be useful for guiding SPC exercises in all areas where ciguatera causes problems for fisheries and consumers. However, such information derived from local knowledge should not be used in the context of public health measures, where environmental toxicological analyses are recommended. Furthermore, a hybrid approach of traditional management and SCP could advantageously be extrapolated to all the POTIs, which are experiencing a revival of interest in traditional management. One limitation, however, is that SCP has difficulty integrating a temporal dimension, which is often encountered in traditional management schemes. It should be noted that traditional schemes, however socially beneficial, generally do not incorporate ecological or resilience principles, which yet they should now address. The value of collaboration between the two approaches is therefore emphasized here, as well as the value of involving stakeholders from the planning design stage, as illustrated in this thesis.

Finally, SCP can be seen and used as a tool that has the potential to bring together, at different spatial and governance scales, a multi-stakeholder participatory process to move towards protecting our environment and managing our resources in a sustainable manner.

## References

- Adams, T., Bell, J.D., Labrosse, P., 2001. Current status of aquaculture in the Pacific Islands, in: Subasinghe, R.P., Bueno, P., Phillips, M.J., Hough, C., McGladdery, S.E., Arthur, J.R. (Eds.), *Technical Proceedings of the Conference on Aquaculture in the Third Millennium*. NACA, Bangkok and FAO, Rome, Bangkok, Thailand., pp. 295–305.
- Adams, V.M., Mills, M., Jupiter, S.D., Pressey, R.L., 2011. Improving social acceptability of marine protected area networks: A method for estimating opportunity costs to multiple gear types in both fished and currently unfished areas. *Biol. Conserv.* 144, 350–361. <https://doi.org/10.1016/j.biocon.2010.09.012>
- Adams, V.M., Mills, M., Weeks, R., Segan, D.B., Pressey, R.L., Gurney, G.G., Groves, C., Davis, F.W., Álvarez-Romero, J.G., 2018. Implementation strategies for systematic conservation planning. *Ambio* 48, 14. <https://doi.org/10.1007/s13280-018-1067-2>
- ADB - Asian Development Bank, 2020. Pacific urban update 2020. Manila Philippines.
- Alati, V.M., Olunga, J., Olendo, M., Daudi, L.N., Osuka, K., Odoli, C., Tuda, P., Nordlund, L.M., 2020. Mollusc shell fisheries in coastal Kenya: Local ecological knowledge reveals overfishing. *Ocean Coast. Manag.* 195, 105285. <https://doi.org/10.1016/j.ocecoaman.2020.105285>
- Allnutt, T.F., McClanahan, T.R., Andréfouët, S., Baker, M., Lagabrielle, E., McClennen, C., Rakotomanjaka, A.J.M., Tianarisoa, T.F., Watson, R., Kremen, C., 2012. Comparison of marine spatial planning methods in madagascar demonstrates value of alternative approaches. *PLoS One* 7. <https://doi.org/10.1371/journal.pone.0028969>
- Álvarez-Romero, J.G., Mills, M., Adams, V.M., Gurney, G.G., Pressey, R.L., Weeks, R., Ban, N.C., Cheok, J., Davies, T.E., Day, J.C., Hamel, M.A., Leslie, H.M., Magris, R.A., Storlie, C.J., 2018. Research advances and gaps in marine planning: towards a global database in systematic conservation planning. *Biol. Conserv.* 227, 369–382. <https://doi.org/10.1016/j.biocon.2018.06.027>
- Anderson, A.B., Bonaldo, R.M., Barneche, D.R., Hackradt, C.W., Félix-Hackradt, F.C., García-Charton, J.A., Floeter, S.R., 2014. Recovery of grouper assemblages indicates effectiveness of a marine protected area in Southern Brazil. *Mar. Ecol. Prog. Ser.* 514, 207–215. <https://doi.org/10.3354/meps11032>
- André, L.V., Van Wynsberge, S., Chinain, M., Andréfouët, S., 2021a. An appraisal of systematic conservation planning for Pacific Ocean Tropical Islands coastal environments. *Mar. Pollut. Bull.* 165, 20. <https://doi.org/10.1016/j.marpolbul.2021.112131>
- André, L.V., Van Wynsberge, S., Chinain, M., Gatti, C.M.I., Dempsey, A., Andréfouët, S., 2021b. A framework for mapping local knowledge on ciguatera and artisanal fisheries to inform systematic conservation planning. *ICES J. Mar. Sci.* 78, 1357–1371. <https://doi.org/10.1093/icesjms/fsab016>
- Andréfouët, S., Adjeroud, M., 2019. French Polynesia, in: Sheppard, C. (Ed.), *World Seas: An Environmental Evaluation* (Second Edition). Elsevier, pp. 827–854. <https://doi.org/10.1016/B978-0-08-100853-9.00039-7>
- Andréfouët, S., Bionaz, O., 2021. Lessons from a global remote sensing mapping project. A review of the impact of the Millennium Coral Reef Mapping Project for science and management. *Sci. Total Environ.* 776, 145987. <https://doi.org/10.1016/j.scitotenv.2021.145987>
- Andréfouët, S., Cabioch, G., Flamand, B., Pelletier, B., 2009a. A reappraisal of the diversity of geomorphological and genetic processes of New Caledonian coral reefs: A synthesis from optical remote sensing, coring and acoustic multibeam observations. *Coral Reefs* 28, 691–707. <https://doi.org/10.1007/s00338-009-0503-y>

- Andréfouët, S., Dewantama, I.M.I., Ampou, E.E., 2021. Seaweed farming collapse and fast changing socio-ecosystems exacerbated by tourism and natural hazards in Indonesia: A view from space and from the households of Nusa Lembongan island. *Ocean Coast. Manag.* 207, 1–8. <https://doi.org/10.1016/j.ocecoaman.2021.105586>
- Andréfouët, S., Dutheil, C., Menkes, C.E., Bador, M., Lengaigne, M., 2015. Mass mortality events in atoll lagoons: Environmental control and increased future vulnerability. *Glob. Chang. Biol.* 21, 195–205. <https://doi.org/10.1111/gcb.12699>
- Andréfouët, S., Friedman, K., Gilbert, A., Remoissenet, G., 2009b. A comparison of two surveys of invertebrates at Pacific Ocean islands: The giant clam at Raivavae Island, Australes Archipelago, French Polynesia. *ICES J. Mar. Sci.* 66, 1825–1836. <https://doi.org/10.1093/icesjms/fsp148>
- Andréfouët, S., Genthon, P., Pelletier, B., Le Gendre, R., Friot, C., Smith, R., Liao, V., 2020. The lagoon geomorphology of pearl farming atolls in the Central Pacific Ocean revisited using detailed bathymetry data. *Mar. Pollut. Bull.* 160, 111580. <https://doi.org/10.1016/j.marpolbul.2020.111580>
- Andréfouët, S., Muller-Karger, F.E., Robinson, J.A., Kranenburg, C., Torres-Pulliza, D., Spraggins, S.A., Murch, B., 2006. Global assessment of modern coral reef extent and diversity for regional science and management applications: a view from space, in: Suzuki, Y., Nakamori, T., Hidaka, M., Kayanne, H., Casareto, B.E., Nadaoka, K., Yamano, H., Tsuchiya, M., Yamazato, K. (Eds. . (Eds.), *Proceedings of 10th International Coral Reef Symposium*, Japanese Coral Reef Society. Okinawa, Japan, pp. 1732–1745.
- Andréfouët, S., Tagliaferro, A., Chabran-poete, L., Campanozzi-tarahu, J., Haumani, G., Stein, A., 2019. An assessment of commercial sea cucumber populations in French Polynesia just after the 2012 moratorium. *SPC Beche-de-mer Inf. Bull.* 39, 8–18.
- Andréfouët, S., Thomas, Y., Dumas, F., Lo, C., 2016. Revisiting wild stocks of black lip oyster *Pinctada margaritifera* in the Tuamotu Archipelago: The case of Ahe and Takaroa atolls and implications for the cultured pearl industry. *Estuar. Coast. Shelf Sci.* 182, 243–253. <https://doi.org/10.1016/j.ecss.2016.06.013>
- Andréfouët, S., Thomas, Y., Lo, C., 2014. Amount and type of derelict gear from the declining black pearl oyster aquaculture in Ahe atoll lagoon, French Polynesia. *Mar. Pollut. Bull.* 83, 224–230. <https://doi.org/10.1016/j.marpolbul.2014.03.048>
- Andréfouët, S., Van Wynsberge, S., Gaertner-Mazouni, N., Menkes, C., Gilbert, A., Remoissenet, G., 2013. Climate variability and massive mortalities challenge giant clam conservation and management efforts in French Polynesia atolls. *Biol. Conserv.* 160, 190–199. <https://doi.org/10.1016/j.biocon.2013.01.017>
- Andréfouët, S., Van Wynsberge, S., Kabbadj, L., Wabnitz, C.C.C., Menkes, C., Tamata, T., Pahuatini, M., Tetairekie, I., Teaka, I., Scha, T.A., Teaka, T., Remoissenet, G., 2018. Adaptive management for the sustainable exploitation of lagoon resources in remote islands: Lessons from a massive El Niño-induced giant clam bleaching event in the Tuamotu atolls (French Polynesia). *Environ. Conserv.* 45, 30–40. <https://doi.org/10.1017/S0376892917000212>
- Ardron, J.A., Possingham, H.P., Klein, C.J., 2010. *Marxan Good Practices Handbook, Version 2*. Pacific Marine Analysis and Research Association, Victoria, BC, Canada.
- Aswani, S., Hamilton, R.J., 2004. Integrating indigenous ecological knowledge and customary sea tenure with marine and social science for conservation of bumphead parrotfish ( *Bolbometopon muricatum* ) in the Roviana Lagoon, Solomon Islands. *Environ. Conserv.* 31, 69–83. <https://doi.org/10.1017/s037689290400116x>
- Aswani, S., Lauer, M., 2006. Incorporating Fishermen's Local Knowledge and Behavior into Geographical Information Systems (GIS) for Designing Marine Protected Areas in Oceania. *Hum. Organ.* 65, 81–102. <https://doi.org/10.17730/humo.65.1.4y2q0vhe4l30n0uj>

- Aylesworth, L., Phoonsawat, R., Suvanachai, P., Vincent, A.C.J., 2017. Generating spatial data for marine conservation and management. *Biodivers. Conserv.* 26, 383–399. <https://doi.org/10.1007/s10531-016-1248-x>
- Babcock, E.A., Pikitch, E.K., Mcallister, M.K., Apostolaki, P., Santora, C., 2005. A perspective on the use of spatialized indicators for ecosystem-based fishery management through spatial zoning. *J. Mar. Sci.* 62, 469–476. <https://doi.org/10.1016/j.icesjms.2005.01.010>
- Bacchet, H., Zysman, T., and Lefèvre, Y. 2010. Guide des poissons de Tahiti et ses îles. Au vent des îles. Tahiti
- Baker, N., Beger, M., McClennen, C., Ishoda, A., Edwards, F., 2011. Reimaanlok : A National Framework for Conservation Area Planning in the Marshall Islands. *J. Mar. Biol.* 2011, 11. <https://doi.org/10.1155/2011/273034>
- Ball, I.R., Possingham, H.P., Watts, M.E., 2009. Marxan and relatives: Software for Spatial Conservation Prioritization, in: Moilanen, A., Wilson, K.A., Possingham, H.P. (Eds.), *Spatial Conservation Prioritization. Quantitative Methods & Computational Tools*. Oxford university Press, pp. 185–195.
- Ballu, V., Bouin, M.-N., Siméoni, P., Crawford, W.C., Calmant, S., Boré, J.-M., Kanas, T., Pelletier, B., 2011. Comparing the role of absolute sea-level rise and vertical tectonic motions in coastal flooding, Torres Islands (Vanuatu). *Proc. Natl. Acad. Sci.* 108, 13019–13022. <https://doi.org/10.1073/pnas.1102842108>
- Bambridge, T., 2016. *The Rāhui: Legal pluralism in Polynesian traditional management of resources and territories*. ANU-Press.
- Bambridge T., Gaulme, F., Montet, C. & Paulais T. 2019. *Communs et Océans, Le rāhui en Polynésie*. Auvent des îles. 175 p.
- Ban, N.C., Adams, V.M., Almany, G.R., Ban, S., Cinner, J.E., McCook, L.J., Mills, M., Pressey, R.L., White, A., 2011. Designing, implementing and managing marine protected areas : Emerging trends and opportunities for coral reef nations. *J. Exp. Mar. Bio. Ecol.* 408, 21–31. <https://doi.org/10.1016/j.jembe.2011.07.023>
- Ban, N.C., Davies, T.E., Aguilera, S.E., Brooks, C., Cox, M., Epstein, G., Evans, L.S., Maxwell, S.M., Nenadovic, M., 2017. Social and ecological effectiveness of large marine protected areas. *Glob. Environ. Chang.* 43, 82–91. <https://doi.org/10.1016/j.gloenvcha.2017.01.003>
- Ban, N.C., Hansen, G.J.A., Jones, M., Vincent, A.C.J., 2009. Systematic marine conservation planning in data-poor regions : Socioeconomic data is essential. *Mar. Policy* 33, 794–800. <https://doi.org/10.1016/j.marpol.2009.02.011>
- Ban, N.C., Klein, C.J., 2009. Spatial socioeconomic data as a cost in systematic marine conservation planning. *Conserv. Lett.* 2, 206–215. <https://doi.org/10.1111/j.1755-263X.2009.00071.x>
- Barrett, C.B., Clay, D.C., Reardon, T., 2001. *Working Paper Income Diversification Strategies in Rural Africa*, New York.
- Bartlett, C.Y., Maltali, T., Petro, G., Valentine, P., 2010. Policy implications of protected area discourse in the Pacific islands. *Mar. Policy* 34, 99–104. <https://doi.org/10.1016/j.marpol.2009.04.021>
- Beger, M., Selkoe, K.A., Treml, E., Barber, P.H., von der Heyden, S., Crandall, E.D., Toonen, R.J., Riginos, C., 2014. Evolving coral reef conservation with genetic information. *Bull. Mar. Sci.* 90, 159–185. <https://doi.org/10.5343/bms.2012.1106>
- Beger, M., Wendt, Hans K.Sullivan, J., Mason, C., LeGrand, J., Davey, K., Jupiter, S., Ceccarelli, D.M., Dempsey, A., Edgar, G., Feary, D.A., Fenner, D., Gauna, M., Grice, H., Kirmani, S.N., Mangubhai, S., Purkis, S., Richards, Z.T., Rotjan, R., Stuart-Smith, R., Sykes, H., Yakub, N., Bauman, A.G., Hughes, A., Raubani, J., Lewis, A., Fernandes, L., 2020. National-scale marine



- bioregions for the Southwest Pacific. *Mar. Pollut. Bull.* 150, 13. <https://doi.org/10.1016/j.marpolbul.2019.110710>
- Bell, J.D., Adams, T.J., Johnson, J.E., Hobday, A.J., Gupta, A. Sen, 2011a. Chap. 1. Pacific communities, fisheries, aquaculture and climate change: An introduction, in: Bell, J.D., Johnson, J.E., Hobday, A.J. (Eds.), *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 1–48.
- Bell, J.D., Albert, J., Andréfouët, S., Andrew, N.L., Blanc, M., Bright, P., Brogan, D., Campbell, B., Govan, H., Hampton, J., Hanich, Q., Harley, S., Jorari, A., Lincoln Smith, M., Pontifex, S., Sharp, M.K., Sokimi, W., Webb, A., 2015. Optimising the use of nearshore fish aggregating devices for food security in the Pacific Islands. *Mar. Policy* 56, 98–105. <https://doi.org/10.1016/j.marpol.2015.02.010>
- Bell, J.D., Andrew, N.L., Batty, M.J., Chapman, L.B., Dambacher, J.M., Dawson, B., Ganachaud, A.S., Gehrke, P.C., Hampton, J., Hobday, A.J., Hoegh-Guldberg, O., Johnson, J.E., Kinch, J.P., Le Borgne, R., Lehodey, P., Lough, J.M., Pickering, T.D., Pratchett, M.S., Vunisea, A., Waycott, M., 2011b. Chap. 13. Adapting tropical Pacific fisheries and aquaculture to climate change: management measures, policies and investments, in: Bell, J.D., Johnson, J.E., Hobday, A.J. (Eds.), *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 803–876.
- Bell, J.D., Cisneros-Montemayor, A., Hanich, Q., Johnson, J.E., Lehodey, P., Moore, B.R., Pratchett, M.S., Reygondeau, G., Senina, I., Viridin, J., Wabnitz, C.C.C., 2018. Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands. *Mar. Policy* 88, 303–314. <https://doi.org/10.1016/j.marpol.2017.05.019>
- Bell, J.D., Kronen, M., Vunisea, A., Nash, W.J., Keeble, G., Demmke, A., Pontifex, S., Andréfouët, S., 2009. Planning the use of fish for food security in the Pacific. *Mar. Policy* 33, 64–76. <https://doi.org/10.1016/j.marpol.2008.04.002>
- Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S., Dessert, M., Gehlen, M., Gorgues, T., Hampton, J., Hanich, Q., Harden-Davies, H., Hare, S.R., Holmes, G., Lehodey, P., Lengaigne, M., Mansfield, W., Menkes, C., Nicol, S., Ota, Y., Pasisi, C., Pilling, G., Reid, C., Ronneberg, E., Gupta, A. Sen, Seto, K.L., Smith, N., Tai, S., Tsamenyi, M., Williams, P., 2021. Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nat. Sustain.* <https://doi.org/10.1038/s41893-021-00745-z>
- Bennett, N.J., Blythe, J., White, C. S., Campero, C. 2021. Blue growth and blue justice: Ten risks and solutions for the ocean economy. *Marine Policy*, 125, 104387. <https://doi.org/10.1016/j.marpol.2020.104387>
- Beyer, H.L., Dujardin, Y., Watts, M., Possingham, H.P., 2016a. Solving conservation planning problems with integer linear programming ( appendices ). *Ecol. Modell.* 1–16.
- Beyer, H.L., Dujardin, Y., Watts, M.E., Possingham, H.P., 2016b. Solving conservation planning problems with integer linear programming. *Ecol. Modell.* 328, 14–22. <https://doi.org/10.1016/j.ecolmodel.2016.02.005>
- Bienfang, P. K., Parsons, M. L., Bidigare, R. R., Laws, E. A., Moeller, P. D. R. 2008. Ciguatera Fish Poisoning: A Synopsis from Ecology to Toxicity. In: *Oceans and Human Health: Risks and Remedies from the Sea*. pp 257–270. Ed. by P. J. Walsh, S. L. Smith, L. E. Fleming, H. Solo-Gabriele, and W. H. Gerwick. Elsevier, New York, NY, USA. 672 pp. ISBN: 978-0-12-372584-4
- Birch, T., Reyes, E., 2018. Forty years of coastal zone management (1975–2014): Evolving theory, policy and practice as reflected in scientific research publications. *Ocean Coast. Manag.* 153, 1–11. <https://doi.org/10.1016/j.ocecoaman.2017.12.003>
- Bosserelle, P., Singh, N., Fred, I., Hedson, C., Moses, P., Ladore, R., Damian, D., Dewey, J., Alfred, M.,

- Santos, T., Malakai, S., Elias, B., Mathias, D., Martin, V., Moore, B., 2017. The status of sea cucumbers at Pohnpei Island and Ant Atoll , Federated States of Micronesia , in 2017. Nouméa, New Caledonia.
- Bowser, W., Nelson, C.H., 2012. Land Institutions , Investments , and Income Diversification: Pathways to Economic Development for Brazil ' s Quilombo Communities 44.
- Brennan, M., Chan, J., Hini, D., Esslemont, D., 1996. Improving the accuracy of recall data: A test of two procedures. *Mark. Bull. Mark. Massey Univ.* 7, 20–29.
- Buijs, A.E., 2009. Lay People's Images of Nature: Comprehensive Frameworks of Values, Beliefs, and Value Orientations. *Soc. Nat. Resour. An Int. J.* 22:5, 417–432. <https://doi.org/10.1080/08941920801901335>
- Cabral, R.B., Bradley, D., Mayorga, J., Goodell, W., Friedlander, A.M., Sala, E., Costello, C., Gaines, S.D., 2020. A global network of marine protected areas for food. *Proc. Natl. Acad. Sci. U. S. A.* 117, 28134–28139. <https://doi.org/10.1073/pnas.2000174117>
- Carvalho, P.G., Jupiter, S.D., Januchowski-Hartley, F.A., Goetze, J., Claudet, J., Weeks, R., Humphries, A., White, C., 2019. Optimized fishing through periodically harvested closures. *J. Appl. Ecol.* 56, 1927–1936. <https://doi.org/10.1111/1365-2664.13417>
- CBD - Convention on Biological Conservation, 2019. Post-2020 global biodiversity framework: discussion paper.
- CBD - Convention on Biological diversity, 2010. Strategic Plan for Biodiversity 2011-2020 and the Aichi Targets. *Secr. Conv. Biol. Divers.* 4.
- CBD - Convention on Biological Diversity, 2020. Update of the zero draft of the Post-2020 global biodiversity framework.
- Charles, A., Wilson, L., 2009. Human dimensions of marine protected areas. *ICES J. Mar. Sci.* 66, 6–15. <https://doi.org/10.1093/icesjms/fsn182>
- Cheer, J.M., Pratt, S., Tolkach, D., Bailey, A., Taumoepeau, S., Movono, A., 2018. Tourism in Pacific island countries: A status quo round-up. *Asia Pacific Policy Stud.* 5, 442–461. <https://doi.org/10.1002/app5.250>
- Cheok, J., Pressey, R.L., Weeks, R., Andréfouët, S., Moloney, J., 2016. Sympathy for the devil: Detailing the effects of planning-unit size, thematic resolution of reef classes, and socioeconomic costs on spatial priorities for marine conservation. *PLoS One* 11, 1–25. <https://doi.org/10.1371/journal.pone.0164869>
- Cheok, J., Pressey, R.L., Weeks, R., VanDerWal, J., Storlie, C., 2017. The plans they are a-changin': More frequent iterative adjustment of regional priorities in the transition to local actions can benefit implementation. *Divers. Distrib.* 24, 48–57. <https://doi.org/10.1111/ddi.12660>
- Chevalier, J. P., 1974. Aperçu sur les Scléactiniaires des Iles Gambier. *Cahier du Pacifique* 18:615–627
- Chinain, M., Darius, H.T., Ung, A., Fouc, M.T., Revel, T., Cruchet, P., Pauillac, S., Laurent, D., 2010. Ciguatera risk management in French Polynesia: The case study of Raivavae Island (Australes Archipelago). *Toxicon* 56, 674–690. <https://doi.org/10.1016/j.toxicon.2009.05.032>
- Chinain, M., Gatti, C.M. i., Darius, H.T., Quod, J.-P., Tester, P.A., 2021. Ciguatera poisonings: A global review of occurrences and trends. *Harmful Algae* 102, 101873. <https://doi.org/10.1016/j.hal.2020.101873>
- Chinain, M., Gatti, C.M. iti, Darius, H.T., Quod, J.P., Tester, P.A., 2020a. Ciguatera poisoning: a global review of occurrences and trends. *Harmful Algae* 22. <https://doi.org/10.1016/j.hal.2020.101873>
- Chinain, M., Gatti, C.M. iti, Ung, A., Cruchet, P., Revel, T., Viallon, J., Sibat, M., Varney, P., Laurent,

- V., Hess, P., Darius, H.T., 2020b. Evidence for the Range Expansion of *Ciguatera* in French Polynesia: A Revisit of the 2009 Mass-Poisoning Outbreak in Rapa Island (Australes Archipelago). *Toxins* (Basel). 12, 759. <https://doi.org/10.3390/toxins12120759>
- Chollett, I., Box, S.J., Mumby, P.J., 2016. Quantifying the squeezing or stretching of fisheries as they adapt to displacement by marine reserves. *Conserv. Biol.* 30, 166–175. <https://doi.org/10.1111/cobi.12573>
- Christie, P., Bennett, N.J., Gray, N.J., Aulani Wilhelm, T., Lewis, N., Parks, J., Ban, N.C., Gruby, R.L., Gordon, L., Day, J., Taei, S., Friedlander, A.M., 2017. Why people matter in ocean governance: Incorporating human dimensions into large-scale marine protected areas. *Mar. Policy* 84, 273–284. <https://doi.org/10.1016/j.marpol.2017.08.002>
- Chung, A.E., Wedding, L.M., Green, A.L., Friedlander, A.M., Goldberg, G., Meadows, A., Hixon, M.A., 2019. Building Coral reef resilience through spatial herbivore management. *Front. Mar. Sci.* 6. <https://doi.org/10.3389/fmars.2019.00098>
- Ciarleglio, M., Barnes, J.W., Sarkar, S., 2010. ConsNet—A tabu search approach to the spatially coherent conservation area network design problem. *J. Heuristics* 16, 537–557. <https://doi.org/10.1007/s10732-008-9098-7>
- Cinner, J.E., 2014. Coral reef livelihoods. *Curr. Opin. Environ. Sustain.* 7, 65–71. <https://doi.org/10.1016/j.cosust.2013.11.025>
- Cinner, J.E., Aswani, S., 2007. Integrating customary management into marine conservation. *Biol. Conserv.* 140, 201–216. <https://doi.org/10.1016/j.biocon.2007.08.008>
- Cinner, J. E., Basurto, X., Fidelman, P., Kuange, J., Lahari, R., Mukminin, A., 2012. Institutional designs of customary fisheries management arrangements in Indonesia, Papua New Guinea, and Mexico. *Mar. Policy* 36, 278–285. <https://doi.org/10.1016/j.marpol.2011.06.005>
- Cinner, J.E., McClanahan, T.R., Daw, T.M., Graham, N.A.J., Maina, J., Wilson, S.K., Hughes, T.P., 2009. Linking Social and Ecological Systems to Sustain Coral Reef Fisheries. *Curr. Biol.* 19, 206–212. <https://doi.org/10.1016/j.cub.2008.11.055>
- Cinner, Joshua E., McClanahan, T.R., Graham, N.A.J., Daw, T.M., Maina, J., Stead, S.M., Wamukota, A., Brown, K., Bodin, Ö., 2012. Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. *Glob. Environ. Chang.* 22, 12–20. <https://doi.org/10.1016/j.gloenvcha.2011.09.018>
- Cleguer, C., Grech, A., Garrigue, C., Marsh, H., 2015. Spatial mismatch between marine protected areas and dugongs in New Caledonia. *Biol. Conserv.* 184, 154–162. <https://doi.org/10.1016/j.biocon.2015.01.007>
- Close, C.H., Hall, G.B., 2006. A GIS-based protocol for the collection and use of local knowledge in fisheries management planning. *J. Environ. Manage.* 78, 341–352. <https://doi.org/10.1016/j.jenvman.2005.04.027>
- Cohen, P.J., Foale, S.J., 2013. Sustaining small-scale fisheries with periodically harvested marine reserves. *Mar. Policy* 37, 278–287. <https://doi.org/10.1016/j.marpol.2012.05.010>
- Cohen, P.J., Roscher, M., Wathasala Fernando, A., Freed, S., Garces, L., Jayakody, S., Khan, F., Mam, K., Nahiduzzaman, M., Ramirez, P., Ullah, M.H., van Brakel, M., Smallhorn-West, P.F., DeYoung, C., 2021. Characteristics and performance of fisheries co-management in Asia - Synthesis of knowledge and case studies: Bangladesh, Cambodia, Philippines and Sri Lanka, Characteristics and performance of fisheries co-management in Asia. FAO and WorldFish, Bangkok, Thailand. <https://doi.org/10.4060/cb3840en>
- Comeros-Raynal, M.T., Lawrence, A., Sudek, M., Vaeoso, M., McGuire, K., Regis, J., Houk, P., 2019. Applying a ridge-to-reef framework to support watershed, water quality, and community-based fisheries management in American Samoa. *Coral Reefs* 38, 505–520. <https://doi.org/10.1007/s00338-019-01806-8>

- Connell, J., 2016. Last days in the Carteret Islands? Climate change, livelihoods and migration on coral atolls. *Asia Pac. Viewp.* 57, 3–15. <https://doi.org/10.1111/apv.12118>
- Connell, J., 2006. Nauru: The first failed Pacific State? *Round Table* 95, 47–63. <https://doi.org/10.1080/00358530500379205>
- Conte, E., Technical exploitation and ‘ritual’ management of resources in Napuka and Tepoto (Tuamotu Archipelago). In: Bambridge, T., 2016. *The Rahui: Legal pluralism in Polynesian traditional management of resources and territories.* ANU-Press. 282p.
- Dalleau, M., Andréfouët, S., Wabnitz, C.C.C., Payri, C.E., Wantiez, L., Pichon, M., Friedman, K., Vigliola, L., Benzoni, F., 2010. Use of Habitats as Surrogates of Biodiversity for Efficient Coral Reef Conservation Planning in Pacific Ocean Islands. *Conserv. Biol.* 24, 541–552. <https://doi.org/10.1111/j.1523-1739.2009.01394.x>
- DAM, 2015. Pêches professionnelles maritimes et aquaculture, de 2006 à 2015. Nouméa, New Caledonia.
- Darius, H.T., Roué, M., Sibat, M., Viallon, J., Gatti, C.M. iti, Vandersea, M.W., Tester, P.A., Litaker, R.W., Amzil, Z., Hess, P., Chinain, M., 2018. *Tectus niloticus* (Tegulidae, Gastropod) as a Novel Vector of Ciguatera Poisoning : Detection of Pacific Ciguatoxins in Toxic Samples from Nuku Hiva Island (French Polynesia). *Toxins* (Basel). 10, 1–22. <https://doi.org/10.3390/toxins10010002>
- Davies, H.N., Gould, J., Hovey, R.K., Radford, B., Kendrick, G.A., 2020. Mapping the Marine Environment Through a Cross-Cultural Collaboration. *Front. Mar. Sci.* 7, 1–15. <https://doi.org/10.3389/fmars.2020.00716>
- Davies, T.E., Maxwell, S.M., Kaschner, K., Garilao, C., Ban, N.C., 2017. Large marine protected areas represent biodiversity now and under climate change. *Sci. Rep.* 7, 1–7. <https://doi.org/10.1038/s41598-017-08758-5>
- Deas, M., 2013. Conservation des communautés coralliennes face au réchauffement climatique : le cas des îlots du lagon Sud-Ouest de la Nouvelle-Calédonie.
- Deas, M., Andréfouët, S., Léopold, M., Guillemot, N., 2014. Modulation of habitat-based conservation plans by fishery opportunity costs: A New Caledonia case study using fine-scale catch data. *PLoS One* 9, 1–13. <https://doi.org/10.1371/journal.pone.0097409>
- Delavenne, J., 2012. Conservation of marine habitats under multiple human uses : Methods , objectives and constraints to optimize a Marine Protected Areas network in the Eastern English Channel. Université du Littoral Côte d’Opale.
- Delevaux, J.M.S., Winter, K.B., Jupiter, S.D., Blaich-Vaughan, M., Stamoulis, K.A., Bremer, L.L., Burnett, K., Garrod, P., Troller, J.L., Ticktin, T., 2018. Linking land and sea through collaborative research to inform contemporary applications of traditional resource management in Hawai’i. *Sustain.* 10. <https://doi.org/10.3390/su10093147>
- Derville, S., 2018. Écologie spatiale des baleines à bosse en zone de reproduction : habitats, distribution et mouvements dans le Pacifique Sud. Thèse sous la direction de Claire Garrigue - Sorbonne université
- Devillers, R., Pressey, R.L., Grech, A., Kittinger, J.N., Edgar, G.J., Ward, T., Watson, R., 2015. Reinventing residual reserves in the sea: are we favouring ease of establishment over need for protection? *Aquat. Conserv. Mar. Freshw. Ecosyst.* 25, 480–504. <https://doi.org/10.1002/aqc.2445>
- Donner, S.D., 2015. The legacy of migration in response to climate stress: learning from the Gilbertese resettlement in the Solomon Islands. *Nat. Resour. Forum* 39, 191–201. <https://doi.org/10.1111/1477-8947.12082>

- DREC – Délégation à la Recherche de la Polynésie française, 2021. website: <<https://www.service-public.pf/voir/annuaire/rec-delegation-a-la-recherche/>> last accessed August 2021
- DRM Direction des Ressources marines, 2019. Bulletin Statistique, Synthèse des données de pêche professionnelle, de l'aquaculture et de la perliculture - Édition 2019.
- DRM, 2021 website: <http://www.ressources-marines.gov.pf/reglementation-rahui/>, (last accessed 22 february 2021)
- DRMM, 2017. Bulletin Statistique, Synthèse des données de la pêche professionnelle, de l'aquaculture et de la perliculture, Edition 2017. Papeete, French Polynesia.
- Dropsy, V., Montet, C., 2018. Economic growth and productivity in French Polynesia : a long- term analysis. *Econ. Stat.* 499, 5–27.
- Droxler, A.W., Jorry, S.J., 2021. The Origin of Modern Atolls: Challenging Darwin's Deeply Ingrained Theory. *Ann. Rev. Mar. Sci.* 13, 537–573. <https://doi.org/10.1146/annurev-marine-122414-034137>
- Dudley, N., 2008. Guidelines for applying protected area management categories. IUCN WCPA Best Practice Guidance on recognising Protected Areas and Assigning Management Catégories and Governance types., Guidelines for applying protected area management categories. IUCN, Gland, Switzerland. <https://doi.org/10.2305/iucn.ch.2008.paps.2.en>
- Dumas, F., Le Gendre, R., Thomas, Y., Andréfouët, S., 2012. Tidal flushing and wind driven circulation of Ahe atoll lagoon (Tuamotu Archipelago, French Polynesia) from in situ observations and numerical modelling. *Mar. Pollut. Bull.* 65, 425–440. <https://doi.org/10.1016/j.marpolbul.2012.05.041>
- Dumas, P., Jimenez, H., Léopold, M., Petro, G., Jimmy, R., 2010. Effectiveness of village-based marine reserves on reef invertebrates in Emau, Vanuatu. *Environ. Conserv.* 37, 364–372. <https://doi.org/10.1017/S0376892910000536>
- Dutheil, C., Andréfouët, S., Jullien, S., Le Gendre, R., Aucan, J., Menkes, C., 2020. Characterization of south central Pacific Ocean wind regimes in present and future climate for pearl farming application. *Mar. Pollut. Bull.* 160. <https://doi.org/10.1016/j.marpolbul.2020.111584>
- Dutheil, C., Bador, M., Lengaigne, M., Lefèvre, J., Jourdain, N.C., Vialard, J., Jullien, S., Peltier, A., Menkes, C., 2019. Impact of surface temperature biases on climate change projections of the South Pacific Convergence Zone. *Clim. Dyn.* 53, 3197–3219. <https://doi.org/10.1007/s00382-019-04692-6>
- Duvat, V., 2008. L'évolution de la recherche sur les systèmes coralliens (1960-2007). *VertigO* 8, 0–17.
- Duvat, V.K.E., Magnan, A.K., Perry, C.T., Spencer, T., Bell, J.D., Wabnitz, C.C.C., Webb, A.P., White, I., McInnes, K.L., Gattuso, J.P., Graham, N.A.J., Nunn, P.D., Le Cozannet, G., 2021. Risks to future atoll habitability from climate-driven environmental changes. *Wiley Interdiscip. Rev. Clim. Chang.* 12, 1–28. <https://doi.org/10.1002/wcc.700>
- Duvat, V.K.E., Magnan, A.K., Wise, R.M., Hay, J.E., Fazey, I., Hinkel, J., Stojanovic, T., Yamano, H., Ballu, V., 2017. Trajectories of exposure and vulnerability of small islands to climate change. *WIREs Clim Chang.* 8, 14. <https://doi.org/10.1002/wcc.478>
- Eger, S.L., Courtenay, S.C., 2021. Integrated coastal and marine management: Insights from lived experiences in the Bay of Fundy, Atlantic Canada. *Ocean Coast. Manag.* 204, 105457. <https://doi.org/10.1016/j.ocecoaman.2020.105457>
- Ehler, C.N., 2018. Marine spatial planning. *Offshore Energy Mar. Spat. Plan.* 6–17. <https://doi.org/10.4324/9781315666877-2>
- Eriksson, H., Sulu, R., Blythe, J.L., van der Ploeg, J., Andrew, N., 2020. Intangible links between

- household livelihoods and food security in solomon islands: Implications for rural development. *Ecol. Soc.* 25, 1. <https://doi.org/10.5751/ES-11709-250418>
- ETOPO1, 2011. Grid of Earth's surface depicting the top of the Antarctic and Greenland ice sheets (1-minute resolution) doi:10.7289/V5C8276M
- European Union. 2016. General Data Protection Regulation, GDPR. <<https://gdpr-info.eu/>> consulted on the 22.06.2020
- Fache, E., and Pauwels, S. 2020. Tackling coastal “overfishing” in Fiji: advocating for indigenous worldview, knowledge, and values to be the backbone of fisheries management strategies. *Maritime Studies*, 19: 41–52.
- FAO, 2018. The State of the World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals, Nature and Resources. Licence: CC BY-NC-SA 3.0 IGO., Rome.
- FAO, 2017. Workshop on improving our knowledge on small-scale fisheries: data needs and methodologies - Workshop proceedings. F 56, in: Fao Fisheries and Aquaculture Proceedings. Rome, Italy, p. 87.
- FAO - Food and Agriculture Organisation of the United Nations, 2020. Legislating for sustainable small-scale fisheries – A guide and considerations for implementing aspects of the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication in national legislat. FAO, Rome. <https://doi.org/10.4060/cb0885en>
- FAO CWP Secretariat, 2019. A matrix scoring approach to characterization of the scale of fishing units: Towards statistical definition of small-scale fisheries. Rome.
- Fenichel, E.P., Levin, S.A., McCay, B., St. Martin, K., Abbott, J.K., Pinsky, M.L., 2016. Wealth reallocation and sustainability under climate change. *Nat. Clim. Chang.* 6, 237–244. <https://doi.org/10.1038/nclimate2871>
- Fernandes, L., Day, J., Lewis, A., Slegers, S., Kerrigan, B., Breen, D., Cameron, D., Jago, B., Hall, J., Lowe, D., Innes, J., Tanzer, J., Chadwick, V., Thompson, L., Gorman, K., Simmons, M., Barnett, B., Sampson, K., De’ath, G., Mapstone, B., Marsh, H., Possingham, H., Ball, I., Ward, T., Dobbs, K., Aumend, J., Slater, D., Stapleton, K., 2005. Establishing Representative No-Take Areas in the Great Barrier Reef: Large-Scale Implementation of Theory on Marine Protected Areas. *Conserv. Biol.* 19, 1733–1744. <https://doi.org/10.1111/j.1523-1739.2005.00302.x>
- Filous, A., Lennox, R.J., Beaury, J.P., Bagnis, H., Mchugh, M., Friedlander, A.M., Clua, E.E.G., Cooke, S.J., Fuller, T.K., Danylchuk, A.J., 2021. Fisheries science and marine education catalyze the renaissance of traditional management (rahui) to improve an artisanal fishery in French Polynesia. *Mar. Policy* 123, 10. <https://doi.org/10.1016/j.marpol.2020.104291>
- Flower, J., Ramdeen, R., Estep, A., Thomas, L.R., Francis, S., Goldberg, G., Johnson, A.E., McClintock, W., Mendes, S.R., Mengerink, K., O’Garro, M., Rogers, L., Zischka, U., Lester, S.E., 2020. Marine spatial planning on the Caribbean island of Montserrat: Lessons for data-limited small islands. *Conserv. Sci. Pract.* 2, 1–14. <https://doi.org/10.1111/csp2.158>
- Foale, S., Cohen, P., Januchowski-Hartley, S., Wenger, A., Macintyre, M., 2011. Tenure and taboos: origins and implications for fisheries in the Pacific. *Fish Fish.* 12, 357–369. <https://doi.org/10.1111/j.1467-2979.2010.00395.x>
- Friedlander, A.M., 2018. Marine conservation in Oceania : Past, present , and future. *Mar. Pollut. Bull.* 135, 139–149. <https://doi.org/10.1016/j.marpolbul.2018.05.064>
- Friedlander, A.M., Golbuu, Y., Ballesteros, E., Caselle, J.E., Gouezo, M., Olsudong, D., Sala, E., 2017. Size, age, and habitat determine effectiveness of Palau’s Marine Protected Areas. *PLoS One* 12, 1–18. <https://doi.org/10.1371/journal.pone.0174787>
- Friedman, M.A., Fernandez, M., Backer, L.C., Dickey, R.W., Bernstein, J., Schrank, K., Kibler, S.,

- Stephan, W., Gribble, M.O., Bienfang, P., Bowen, R.E., Degrasse, S., Quintana, H.A.F., Loeffler, C.R., Weisman, R., Blythe, D., Berdalet, E., Ayyar, R., Clarkson-Townsend, D., Swajian, K., Benner, R., Brewer, T., Fleming, L.E., 2017. An updated review of ciguatera fish poisoning: Clinical, epidemiological, environmental, and public health management. *Mar. Drugs* 15, 41. <https://doi.org/10.3390/md15030072>
- Friedman, M.A., Fleming, L.E., Fernandez, M., Bienfang, P., Schrank, K., Dickey, R., Bottein, M.Y., Backer, L., Ayyar, R., Weisman, R., Watkins, S., Granade, R., Reich, A., 2008. Ciguatera Fish Poisoning: Treatment, Prevention and Management. *Mar. Drugs* 6, 456–479. <https://doi.org/10.3390/md20080022>
- Gaertner-Mazouni, N., Rodriguez, T., 2017. Note de synthese relative aux interactions perliculture - environnement.
- Gairin, E., Andréfouët, S., 2020. Role of habitat definition on Aichi Target 11: Examples from New Caledonian coral reefs. *Mar. Policy* 116, 103951. <https://doi.org/10.1016/j.marpol.2020.103951>
- Game, E.T., Grantham, H.S., 2008. Marxan User Manual: for Marxan version 1.8.10. University of Queensland and Pacific Marine Analysis and research association, St Lucia, Queensland, Australia and Vancouver, British Columbia, Canada.
- Garcia, J., Pelletier, D., Carpentier, L., Roman, W., Bockel, T., 2018. Scale-dependency of the environmental influence on fish  $\beta$ -diversity: Implications for ecoregionalization and conservation. *J. Biogeogr.* 45, 1818–1832. <https://doi.org/10.1111/jbi.13381>
- Garcin, M., Vendé-Leclerc, M., Maurizot, P., Le Cozannet, G., Robineau, B., Nicolae-Lerma, A., 2016. Lagoon islets as indicators of recent environmental changes in the South Pacific – The New Caledonian example. *Cont. Shelf Res.* 122, 120–140. <https://doi.org/10.1016/j.csr.2016.03.025>
- Gardon, T., El Rakwe, M., Paul-Pont, I., Le Luyer, J., Thomas, L., Prado, E., Boukerma, K., Cassone, A.-L., Quillien, V., Soyeux, C., Costes, L., Crusot, M., Dreanno, C., Le Moullac, G., Huvet, A., 2021. Microplastics contamination in pearl-farming lagoons of French Polynesia. *J. Hazard. Mater.* 419, 126396. <https://doi.org/10.1016/j.jhazmat.2021.126396>
- Gatti, C., Oelher, E., Legrand, A.M., 2008. Severe seafood poisoning in French Polynesia: A retrospective analysis of 129 medical files. *Toxicol.* 51, 746–753. <https://doi.org/10.1016/j.toxicol.2007.11.025>
- Geange, S.W., Leathwick, J., Linwood, M., Curtis, H., Duffy, C., Funnell, G., Cooper, S., 2017. Integrating conservation and economic objectives in MPA network planning: A case study from New Zealand. *Biol. Conserv.* 210, 136–144. <https://doi.org/10.1016/j.biocon.2017.04.011>
- Ghasarian, C., Protection of natural resources through a sacred prohibition: The rahui on Rapa iti. In: Bambridge, T., 2016. *The Rahui: Legal pluralism in Polynesian traditional management of resources and territories*. ANU-Press. 282p.
- Gillett, R., 2016. Fisherines in the Economies of Pacific Island Countries and Territories. <https://doi.org/10.1109/ICCT.2010.5689045>
- Gillett, R., Tauati, M.I., 2018. Fisheries of the Pacific Islands: Regional and national information, FAO Fisheries and Aquaculture Technical Paper. Apia, Western Samoa.
- Gnanalingam, G., Pritchard, D.W., Richards, D.K., Subritzky, P., Flack, B., Hepburn, C.D., 2021. Local management to support local fisheries: Rāhui (temporary closure) and bag limits for blackfoot abalone (*Haliotis iris*) in southern New Zealand. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 31, 2320–2333. <https://doi.org/10.1002/aqc.3662>
- Goñi, R., Adlerstein, S., Alvarez-Berastegui, D., Forcada, A., Reñones, O., Criquet, G., Polti, S., Cadiou, G., Valle, C., Lenfant, P., Bonhomme, P., Pérez-Ruzafa, A., Sánchez-Lizaso, J.L., García-Charton, J.A., Bernard, G., Stelzenmüller, V., Planes, S., 2008. Spillover from six western Mediterranean marine protected areas: Evidence from artisanal fisheries. *Mar. Ecol. Prog. Ser.* 366, 159–174.

<https://doi.org/10.3354/meps07532>

- Govan, H., 2009. Status and potential of locally-managed marine areas in the Pacific Island Region : meeting nature conservation and sustainable livelihood targets through wide-spread implementation of LMMAs. Suva, Fiji.
- Government of Papua New Guinea, 2015. National Marine Conservation Assessment for Papua New Guinea.
- Grafeld, S., Oleson, K.L.L., Teneva, L., Kittinger, J.N., 2017. Follow that fish: Uncovering the hidden blue economy in coral reef fisheries. *PLoS One* 12, 1–25. <https://doi.org/10.1371/journal.pone.0182104>
- Graham, A., D'Andrea, A., 2021. Gender and human rights in coastal fisheries and aquaculture: a comparative analysis of legislation in Fiji, Kiribati, Samoa, Solomon Islands, Tonga and Vanuatu, SCP. ed. SPC, Nouméa, New Caledonia.
- Grantham, H.S., Agostini, V.N., Wilson, J., Mangubhai, S., Hidayat, N., Muljadi, A., Muhajir, Rotinsulu, C., Mongdong, M., Beck, M.W., Possingham, H.P., 2013. A comparison of zoning analyses to inform the planning of a marine protected area network in Raja Ampat, Indonesia. *Mar. Policy* 38, 184–194. <https://doi.org/10.1016/j.marpol.2012.05.035>
- Grantham, H.S., Petersen, S.L., Possingham, H.P., 2008. Reducing bycatch in the South African pelagic longline fishery: The utility of different approaches to fisheries closures. *Endanger. Species Res.* 5, 291–299. <https://doi.org/10.3354/esr00159>
- Graviou, P., Nowak, E., Maury, R., Blais, S., 2013. *Curiosités géologiques de la Polynésie française*. BRGM Editions, Editions Orphie. 119 pp. ISSN: 2110-0381
- Green, A.L., Fernandes, L., Almany, G., Abesamis, R., McLeod, E., Aliño, P.M., White, A.T., Salm, R., Tanzer, J., Pressey, R.L., 2014. Designing Marine Reserves for Fisheries Management, Biodiversity Conservation, and Climate Change Adaptation. *Coast. Manag.* 42, 143–159. <https://doi.org/10.1080/08920753.2014.877763>
- Green, A.L., Maypa, A.P., Almany, G.R., Rhodes, K.L., Weeks, R., Abesamis, R.A., Gleason, M.G., Mumby, P.J., White, A.T., 2015. Larval dispersal and movement patterns of coral reef fishes, and implications for marine reserve network design. *Biol. Rev.* 90, 1215–1247. <https://doi.org/10.1111/brv.12155>
- Green, A.L., Smith, S.E., Lipsett-Moore, G., Groves, C., Peterson, N., Sheppard, S., Lokani, P., Hamilton, R., Almany, J., Aitsi, J., Bualia, L., 2009. Designing a resilient network of marine protected areas for Kimbe Bay, Papua New Guinea. *Fauna Flora Int.* 43, 488–498. <https://doi.org/10.1017/S0030605309990342>
- Grorud-Colvert, K., Sullivan-Stack, J., Roberts, C., Constant, V., Horta e Costa, B., Pike, E.P., Kingston, N., Laffoley, D., Sala, E., Claudet, J., Friedlander, A.M., Gill, D.A., Lester, S.E., Day, J.C., Gonçalves, E.J., Ahmadi, G.N., Rand, M., Villagomez, A., Ban, N.C., Gurney, G.G., Spalding, A.K., Bennett, N.J., Briggs, J., Morgan, L.E., Moffitt, R., Deguignet, M., Pikitch, E.K., Darling, E.S., Jessen, S., Hameed, S.O., Di Carlo, G., Guidetti, P., Harris, J.M., Torre, J., Kizilkaya, Z., Agardy, T., Cury, P., Shah, N.J., Sack, K., Cao, L., Fernandez, M., Lubchenco, J., 2021. The MPA Guide: A framework to achieve global goals for the ocean. *Science* (80-. ). 373. <https://doi.org/10.1126/science.abf0861>
- Gruby, R.L., Basurto, X., 2013. Multi-level governance for large marine commons: Politics and polycentricity in Palau's protected area network. *Environ. Sci. Policy* 33, 260–272. <https://doi.org/10.1016/j.envsci.2013.08.001>
- Guillemot, N., Leopold, M., 2009. Atlas Pêche non professionnelle de poissons du lagon dans la zone de Vook-Koohnê-Pwëëbuu (Voh-Koné-Pouembout), Nouvelle-Calédonie, données 2007. Nouméa, Nouvelle-Calédonie.



- Guillemot, N., Léopold, M., 2010. Atlas Non-professional reef fishing activities in the Vook-Koohné-Pwëëbuu (Voh-Koné- Pouembout) area , New Caledonia (2007 data). Nouméa, New Caldonia.
- Gurney, G.G., Darling, E.S., Ahmadi, G.N., Agostini, V.N., Ban, N.C., Blythe, J., Claudet, J., Epstein, G., Himes-cornell, A., Jonas, H.D., Armitage, D., Campbell, S.J., Cox, C., Friedman, W.R., Gill, D., Lestari, P., Mangubhai, S., Mcleod, E., Muthiga, N.A., Ranaivoson, R., Wenger, A., Yulianto, I., Jupiter, S.D., 2021. Biodiversity needs every tool in the box : use OECMs. *Nature* 595, 646–649.
- Gurney, G.G., Pressey, R.L., Ban, N.C., Álvarez-Romero, J.G., Jupiter, S., Adams, V.M., 2015. Efficient and equitable design of marine protected areas in Fiji through inclusion of stakeholder-specific objectives in conservation planning. *Conserv. Biol.* 29, 1378–1389. <https://doi.org/10.1111/cobi.12514>
- Haider, L.J., Boonstra, W.J., Peterson, G.D., Schlüter, M., 2018. Traps and Sustainable Development in Rural Areas: A Review. *World Dev.* 101, 311–321. <https://doi.org/10.1016/j.worlddev.2017.05.038>
- Halpern, B.S., Gaines, S.D., Warner, R.R., 2004. Confounding effects of the export of production and the displacement of fishing effort from marine reserves. *Ecol. Appl.* 14, 1248–1256. <https://doi.org/10.1890/03-5136>
- Hamel, M.A., Andréfouët, S., Pressey, R.L., 2013. Compromises between international habitat conservation guidelines and small-scale fisheries in Pacific island countries. *Conserv. Lett.* 6, 46–57. <https://doi.org/10.1111/j.1755-263X.2012.00285.x>
- Hamel, M.A., Pressey, R.L., Evans, L.S., Andréfouët, S., 2018. The Importance of Fishing Grounds as Perceived by Local Communities Can be Undervalued by Measures of Socioeconomic Cost Used in Conservation Planning. *Conserv. Lett.* 11, 1–9. <https://doi.org/10.1111/conl.12352>
- Hamilton, R.J., Hughes, A., Brown, C.J., Leve, T., Kama, W., 2019. Community-based management fails to halt declines of bumphead parrotfish and humphead wrasse in Roviana Lagoon, Solomon Islands. *Coral Reefs* 38, 455–465. <https://doi.org/10.1007/s00338-019-01801-z>
- Hanich, Q., Wabnitz, C.C.C., Ota, Y., Amos, M., Donato-hunt, C., Hunt, A., 2018. Small-scale fisheries under climate change in the Pacific Islands region. *Mar. Policy* 88, 279–284. <https://doi.org/10.1016/j.marpol.2017.11.011>
- Hanson JO, Schuster R, Morrell N, Strimas-Mackey M, Watts ME, Arcese P, Bennett J, Possingham HP (2021). prioritizr: Systematic Conservation Prioritization in R. R package version 7.0.1. Available at <https://CRAN.R-project.org/package=prioritizr> [last accessed: august 2021].
- HCRFP – Haut-Commissariat de la République française en Polynésie, 2021. <<http://www.polynesie-francaise.pref.gouv.fr/Services-de-l-Etat/Recherche-innovation-et-transition-ecologique/Recherche-et-innovation/DTRT>> last accessed August 2021
- He, Q., Silliman, B.R., 2019. Climate Change, Human Impacts, and Coastal Ecosystems in the Anthropocene. *Curr. Biol.* 29, R1021–R1035. <https://doi.org/10.1016/j.cub.2019.08.042>
- Hinchley, D., Lipsett-Moore, G., Sheppard, S., Sengebau, U.F., Verheij, E., Austin, S.C., 2007. Biodiversity Planning for Palau’s Protected Areas Network - An Ecoregional Assessment. Palau, Korrör.
- Hoeksema, B.W., Benzoni, F., 2013. Multispecies aggregations of mushroom corals in the Gambier Islands, French Polynesia. *Coral Reefs* 32, 1041. <https://doi.org/10.1007/s00338-013-1054-9>
- Horigue, V., Pressey, R.L., Mills, M., Brotánková, J., Cabral, R., Andréfouët, S., 2015. Benefits and challenges of scaling up expansion of marine protected area networks in the Verde Island Passage, Central Philippines. *PLoS One* 10, 1–28.

<https://doi.org/10.1371/journal.pone.0135789>

- Hurtado, A.Q., Gerung, G.S., Yasir, S., Critchley, A.T., 2014. Cultivation of tropical red seaweeds in the BIMP-EAGA region. *J. Appl. Phycol.* 26, 707–718. <https://doi.org/10.1007/s10811-013-0116-2>
- IEOM, 2020a. La perliculture en Polynésie Française - Etat des lieux d'une filière fragilisée. Papeete, French Polynesia.
- IEOM, 2020b. Panorama de la Polynésie française, Publications économiques et financières - Conjoncture économique. Papeete, French Polynesia.
- IEOM, 2015. Le tourisme en Polynésie française - En quête d'un second souffle, Insitut d'émission des départements d'Outre-Mer. Papeete, French Polynesia.
- IPBES, 2021. Policy support tool – Marxan. <https://ipbes.net/policy-support/tools-instruments/marxan> [last accessed: sept 2021]
- ISPF, 2018. Points forts de la Polynésie française - 07. Etudes. Le recensement de la population en Polynésie française en 2017. Papeete, French Polynesia.
- ISPF, Gauchenot, I., Breuilh, F., 2017. Recensement de la population 2017. Papeete, French Polynesia.
- IUCN, 2021. FRENCH POLYNESIA CASE STUDY. Sustainable Use, Mariculture and Conservation of Giant Clams in the Marine Regulated Fishing Area Reao Atoll, Tuamotu. Case study n° 4, Worldwide Catalogue of Case Studies on Aquaculture and Marine Conservation. Gland, Switzerland.
- IUCN - International Union for Conservation of Nature, 2020. IUCN Red List 2017 – 2020 Report.
- IUCN - WCPA (world commission on protected areas), 2019. Recognising and reporting other effective area-based conservation measures. IUCN. <https://doi.org/10.2305/iucn.ch.2019.patrs.3.en>
- Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A., Hughes, T.P., Kidwell, S., Lange, C.B., Lenihan, H.S., Pandolfi, J.M., Peterson, C.H., Steneck, R.S., Tegner, M.J., Warner, R.R., 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* (80- ). 293, 629–637. <https://doi.org/10.1126/science.1059199>
- Jacquet, J., Pauly, D., 2008. Funding priorities: Big barriers to small-scale fisheries. *Conserv. Biol.* 22, 832–835. <https://doi.org/10.1111/j.1523-1739.2008.00978.x>
- Jenkins, T.L., Stevens, J.R., 2018. Assessing connectivity between MPAs: Selecting taxa and translating genetic data to inform policy. *Mar. Policy* 94, 165–173. <https://doi.org/10.1016/j.marpol.2018.04.022>
- Johannes, R.E., 2002. The renaissance of community-based marine resource management in Oceania. *Annu. Rev. Ecol. Syst.* 33, 317–340. <https://doi.org/10.1146/annurev.ecolsys.33.010802.150524>
- Joshua, T., H. (2020) Initial Economic Impact of COVID-19 Reported for Micronesia, the Marshall Islands, and Palau. <https://www.doi.gov/oia/press/initial-economic-impact-covid-19-reported-micronesia-marshall-islands-and-palau> [last accessed: october 2021]
- Jupiter, S., Mangubhai, S., Kingsford, R.T., 2014. Conservation of biodiversity in the pacific islands of oceania: Challenges and opportunities. *Pacific Conserv. Biol.* 20, 206–220. <https://doi.org/10.1071/PC140206>
- Jupiter, S.D., Cohen, P.J., Weeks, R., Tawake, A., Govan, H., 2014a. Locally-managed marine areas: Multiple objectives and diverse strategies. *Pacific Conserv. Biol.* 20, 165–179. <https://doi.org/10.1071/PC140165>

- Jupiter, S.D., Mangubhai, S., Kingsford, R.T., 2014b. Conservation of Biodiversity in the Pacific Islands of Oceania : Challenges and Opportunities. *Pacific Conserv. Biol.* 20, 206–220.
- Jupiter, S.D., Wenger, A., Klein, C.J., Albert, S., Mangubhai, S., Nelson, J., Teneva, L., Tulloch, V.J., White, A.T., Watson, J.E.M., 2017. Opportunities and constraints for implementing integrated land-sea management on Islands. *Environ. Conserv.* 44, 254–266. <https://doi.org/10.1017/S0376892917000091>
- Justeau-Allaire, D., 2020. Constraint-based systematic conservation planning, a generic and expressive approach. *Montpellier 2*.
- Kabbadj, L., Van Wynsberge, S., Andréfouët, S., 2018. Scaling tropical island conservation planning to the regional level can lead to unbalanced ecological representation and poor social equity among islands. *Mar. Policy* 93, 31–39. <https://doi.org/10.1016/j.marpol.2018.03.024>
- Karcher, D.B., Fache, E., Breckwolfdt, A., Govan, H., Elías Ilosvay, X.E., Kam King, J.K., Riera, L., Sabinot, C., 2020. Trends in South Pacific fisheries management. *Mar. Policy* 118. <https://doi.org/10.1016/j.marpol.2020.104021>
- Kareiva, P., Marvier, M., 2012. What is conservation science? *Bioscience* 62, 962–969. <https://doi.org/10.1525/bio.2012.62.11.5>
- Kasperski, S., Holland, D.S., 2013. Income diversification and risk for fishermen. *Proc. Natl. Acad. Sci. U. S. A.* 110, 2076–2081. <https://doi.org/10.1073/pnas.1212278110>
- Keppel, G., 2014. The importance of expert knowledge in conservation planning - Comment to an article by C.J. Klein et al. *Mar. Policy* 48, 202–203. <https://doi.org/10.1016/j.marpol.2014.03.011>
- Keppel, G., Morrison, C., Watling, D., Tuiwawa, M. V, Rounds, I.A., 2012. Conservation in tropical Pacific Island countries : why most current approaches are failing. *Conserv. Lett.* 5, 256–265. <https://doi.org/10.1111/j.1755-263X.2012.00243.x>
- Klein, C.J., Jupiter, S.D., Possingham, H.P., 2014. Setting conservation priorities in Fiji: Decision science versus additive scoring systems. *Mar. Policy* 48, 204–205. <https://doi.org/10.1016/j.marpol.2014.03.008>
- Klein, C.J., Jupiter, S.D., Selig, E.R., Watts, M.E., Halpern, B.S., Kamal, M., Roelfsema, C., Possingham, H.P., 2012. Forest conservation delivers highly variable coral reef conservation outcomes. *Ecol. Appl.* 22, 1246–1256. <https://doi.org/10.1890/11-1718.1>
- Kleypas, J., Yates, K., 2009. Coral Reefs and Ocean Acidification. *Oceanography* 22, 108–117. <https://doi.org/10.5670/oceanog.2009.101>
- Kleypas, J.A., McManus, J.W., Meñez, L.A.B., 1999. Environmental Limits to Coral Reef Development: Where Do We Draw the Line? *Amer.Zool.* 39, 146–159.
- Knudby, A., Roelfsema, C., Lyons, M., Phinn, S., Jupiter, S.D., 2011. Mapping Fish Community Variables by Integrating Field and Satellite Data, Object-Based Image Analysis and Modeling in a Traditional Fijian Fisheries Management Area. *Remote Sens.* 3, 460–483. <https://doi.org/10.3390/rs3030460>
- Kool, J., Brewer, T., Mills, M., Pressey, R., 2010. Ridges to Reefs Conservation for Solomon Islands. *Townsville, QLD*.
- Kronen, M., Friedman, K., Pinca, S., Chapman, L., Awiva, R., Pakoa, K., Vigliola, L., Boblin, P., Magron, F., 2009. Polynésie française - Rapport de Pays : profils et résultats des enquêtes réalisées à Fakarava, Maatea, Mataiea, Raivavae et Tikehau (Septembre – Octobre 2003, Janvier – Mars 2004, Avril – Juin 2006), Programme régional de développement des pêches océaniques et côtières - PROCFish. Nouméa, New Caldonia.
- Kronen, M., Pinca, S., Magron, F., McArdle, B., Vunisea, A., Vigliola, L., Kulbicki, M., Andréfouët, S.,

2012. Socio-economic and fishery indicators to identify and monitor artisanal finfishing pressure in Pacific Island countries and territories. *Ocean Coast. Manag.* 55, 63–73. <https://doi.org/10.1016/j.ocecoaman.2011.07.011>
- Krueck, N.C., Ahmadi, G.N., Possingham, H.P., Riginos, C., Treml, E.A., Mumby, P.J., 2017. Marine Reserve Targets to Sustain and Rebuild Unregulated Fisheries. *PLoS Biol.* 15, 1–20. <https://doi.org/10.1371/journal.pbio.2000537>
- Kueffer, C., Kinney, K., 2017. What is the importance of islands to environmental conservation? *Environ. Conserv.* 44, 311–322. <https://doi.org/10.1017/S0376892917000479>
- Kuemlangan, B., 2004. Creating legal space for community-based fisheries and customary marine tenure in the Pacific : issues and opportunities, FishCode Review. Rome, Italy.
- Kukkala, A.S., Moilanen, A., 2013. Core concepts of spatial prioritisation in systematic conservation planning. *Biol. Rev.* 88, 443–464. <https://doi.org/10.1111/brv.12008>
- Laffoley, D., Le Gouvello, R., Simard, F., 2017. Aquaculture and marine protected areas: Exploring Potential Opportunities and Synergies.
- Lal, M.M., Bosserelle, C., Kishore, P., Southgate, P.C., 2020. Understanding marine larval dispersal in a broadcast-spawning invertebrate: A dispersal modelling approach for optimising spat collection of the Fijian black-lip pearl oyster *Pinctada margaritifera*. *PLoS One* 15, e0234605. <https://doi.org/10.1371/journal.pone.0234605>
- Lau, J.D., Cinner, J.E., Fabinyi, M., Gurney, G.G., Hicks, C.C., 2020. Access to marine ecosystem services: Examining entanglement and legitimacy in customary institutions. *World Dev.* 126, 104730. <https://doi.org/10.1016/j.worlddev.2019.104730>
- Lauer, M., Aswani, S., 2010. Indigenous knowledge and long-term ecological change: Detection, interpretation, and responses to changing ecological conditions in pacific island communities. *Environ. Manage.* 45, 985–997. <https://doi.org/10.1007/s00267-010-9471-9>
- Laurent, D., Kerbrat, A.S., Darius, H.T., Rossi, F., Yeeting, B., Haddad, M., Golubic, S., Pauillac, S., Chinain, M., 2012. Ciguatera shellfish poisoning (CSP): a new ecotoxicological phenomenon from cyanobacteria to humans via giant clams, in: Jensen, M.A. (Ed.), *Food Chains: New Research*. Nova Science Publishers, Inc., New York, pp. 1–30. <https://doi.org/10.1017/CBO9781107415324.004>
- Le Gendre, R., Andréfouët, S., Dumas, F., 2010. Rapport de mesures sur l'atoll de Takaroa. Caractérisation du fonctionnement hydrodynamique de l'atoll.
- Lehodey, P., Senina, I., Wibawa, T.A., Titau, O., Calmettes, B., Conchon, A., Tranchant, B., Gaspar, P., 2018. Operational modelling of bigeye tuna (*Thunnus obesus*) spatial dynamics in the Indonesian region. *Mar. Pollut. Bull.* 131, 19–32. <https://doi.org/10.1016/j.marpolbul.2017.08.020>
- Le Pennec, M., Anastas, M., Bichet, H., Buestel, D., Cochard, J.-C., Cochennec-Laureau, N., Coeroli, M., Conte, E., Correia, P., Fougerouse-Tsing, A., Langy, S., Le Moullac, G., Lo, C., Peltzer, L., Pham, A., 2009. Huître perlière et perle de Tahiti. Ed. Université de la Polynésie française. 204 pp. ISBN 978-2-9534554-2-7
- Léopold, M., Beckensteiner, J., Kaltavara, J., Raubani, J., Caillon, S., 2013. Community-based management of near-shore fisheries in vanuatu: What works? *Mar. Policy* 42, 167–176. <https://doi.org/10.1016/j.marpol.2013.02.013>
- Léopold, M., Guillemot, N., Rocklin, D., Chen, C., 2014. A framework for mapping small-scale coastal fisheries using fishers' knowledge. *ICES J. Mar. Sci.* 12.
- Levy, J.S., Ban, N.C., 2013. A method for incorporating climate change modelling into marine conservation planning: An Indo-west Pacific example. *Mar. Policy* 38, 16–24.

<https://doi.org/10.1016/j.marpol.2012.05.015>

- Lewis, N., Day, J., Wilhelm, 'Aulani, Wagner, D., Gaymer, C., Parks, J., Friedlander, A., White, S., Sheppard, C., Spalding, M., San Martin, G., Skeat, A., Tai, S., Teroroko, T., Evans, J., 2017. Large-Scale Marine Protected Areas: guidelines for design and management, IUCN. ed, Best Practice Protected Area Guidelines Series, No. 26. IUCN, International Union for Conservation of Nature, Gland, Switzerland. <https://doi.org/10.2305/IUCN.CH.2017.PAG.26.en>
- Link, J.S., Watson, R.A., 2019. Global ecosystem overfishing: Clear delineation within real limits to production. *Sci. Adv.* 5, 1–12. <https://doi.org/10.1126/sciadv.aav0474>
- Lipsett-Moore, G., Hamilton, R., Peterson, N., Game, E., Atu, W., Kereseke, J., Pita, J., Ramohia, P., Siota, C., 2010. Ridges to Reefs Conservation Plan for Choiseul Province, Solomon Islands. Honiara, Solomon Islands.
- Magris, R.A., Costa, M.D.P., Ferreira, C.E.L., Vilar, C.C., Joyeux, J.C., Creed, J.C., Copertino, M.S., Horta, P.A., Sumida, P.Y.G., Francini-Filho, R.B., Floeter, S.R., 2021. A blueprint for securing Brazil's marine biodiversity and supporting the achievement of global conservation goals. *Divers. Distrib.* 27, 198–215. <https://doi.org/10.1111/ddi.13183>
- Magris, R.A., Pressey, R.L., Weeks, R., Ban, N.C., 2014. Integrating connectivity and climate change into marine conservation planning. *Biol. Conserv.* 170, 207–221. <https://doi.org/10.1016/j.biocon.2013.12.032>
- Magris, R.A., Treml, E.A., Pressey, R.L., Weeks, R., 2016. Integrating multiple species connectivity and habitat quality into conservation planning for coral reefs. *Ecography (Cop.)*. 39, 649–664. <https://doi.org/10.1111/ecog.01507>
- Maina, J.M., Jones, K.R., Hicks, C.C., McClanahan, T.R., Watson, J.E.M., Tuda, A.O., Andréfouët, S., 2015. Designing climate-resilient marine protected area networks by combining remotely sensed coral reef habitat with coastal multi-use maps. *Remote Sens.* 7, 16571–16587. <https://doi.org/10.3390/rs71215849>
- Makino, A., Beger, M., Klein, C.J., Jupiter, S.D., Possingham, H.P., 2013. Integrated planning for land-sea ecosystem connectivity to protect coral reefs. *Biol. Conserv.* 165, 35–42. <https://doi.org/10.1016/j.biocon.2013.05.027>
- Makino, A., Yamano, H., Beger, M., Klein, C.J., Yara, Y., Possingham, H.P., 2014. Spatio-temporal marine conservation planning to support high-latitude coral range expansion under climate change. *Divers. Distrib.* 20, 859–871. <https://doi.org/10.1111/ddi.12184>
- Margules, C.R., Pressey, R.L., 2000. Systematic conservation planning. *Nat.* 405, 243–253. <https://doi.org/10.1038/35012251>
- Marre, J., Garcia Imhof, C., 2021. An assessment of socioeconomic impacts due to COVID-19 on coastal fisheries in Tonga. *SPC Fish. Newsl.* #165 24–28.
- Masselink, G., Beetham, E., Kench, P., 2020. Coral reef islands can accrete vertically in response to sea level rise. *Sci. Adv.* 6, 1–11. <https://doi.org/10.1126/sciadv.aay3656>
- McBride, M.M., Dalpadado, P., Drinkwater, K.F., Godø, O.R., Hobday, A.J., Hollowed, A.B., Kristiansen, T., Murphy, E.J., Ressler, P.H., Subbey, S., Hofmann, E.E., Loeng, H., 2014. Krill, climate, and contrasting future scenarios for Arctic and Antarctic fisheries. *ICES J. Mar. Sci.* 71, 1934–1955. <https://doi.org/10.1093/icesjms/fsu002>
- McCluskey, S.M., Lewison, R.L., 2008. Quantifying fishing effort: a synthesis of current methods and their applications. *Fish Fish.* 9, 188–200.
- McCormack, F., 2011. Rāhui: A blunting of teeth. *J. Polyn. Soc.* 120, 43–55.
- McFarlane, R.A., Horwitz, P., Arabena, K., Capon, A., Jenkins, A., Jupiter, S., Negin, J., Parkes, M.W., Saketa, S., 2019. Ecosystem services for human health in Oceania. *Ecosyst. Serv.* 39, 5.

<https://doi.org/10.1016/j.ecoser.2019.100976>

- Metcalfe, K., Vaughan, G., Vaz, S., Smith, R.J., 2015. Spatial , socio-economic , and ecological implications of incorporating minimum size constraints in marine protected area network design 29, 1615–1625. <https://doi.org/10.1111/cobi.12571>
- Mills, M., Adams, V.M., Pressey, R.L., Ban, N.C., Jupiter, S.D., 2012. Where do national and local conservation actions meet? Simulating the expansion of ad hoc and systematic approaches to conservation into the future in Fiji. *Conserv. Lett.* 5, 387–398. <https://doi.org/10.1111/j.1755-263X.2012.00258.x>
- Mills, M., Pressey, R.L., Weeks, R., Foale, S., Ban, N.C., 2010a. A mismatch of scales: challenges in planning for implementation of marine protected areas in the Coral Triangle. *Conserv. Lett.* 3, 291–303. <https://doi.org/10.1111/j.1755-263X.2010.00134.x>
- Mills, M., Pressey, R.L., Weeks, R., Foale, S., Ban, N.C., 2010b. A mismatch of scales: Challenges in planning for implementation of marine protected areas in the Coral Triangle. *Conserv. Lett.* 3, 291–303. <https://doi.org/10.1111/j.1755-263X.2010.00134.x>
- Mills, M., Weeks, R., Pressey, R.L., Gleason, M.G., Eisma-osorio, R., Lombard, A.T., Harris, J.M., Killmer, A.B., White, A., Morrison, T.H., 2015. Real-world progress in overcoming the challenges of adaptive spatial planning in marine protected areas. *Biol. Conserv.* 181, 54–63. <https://doi.org/10.1016/j.biocon.2014.10.028>
- Moilanen, A., Franco, A.M.A., Early, R.I., Fox, R., Wintle, B., Thomas, C.D., 2005. Prioritizing multiple-use landscapes for conservation: Methods for large multi-species planning problems. *Proc. R. Soc. B Biol. Sci.* 272, 1885–1891. <https://doi.org/10.1098/rspb.2005.3164>
- Moilanen, A., Wilson, K., and Possingham, H. 2009. *Spatial Conservation Prioritization: Quantitative Methods and Computational Tools*. Oxford University Press, Oxford; New York.
- Monaco, C.J., Sangare, N., Le Moullac, G., Basset, C., Belliard, C., Mizuno, K., Smith, D.L., Lo-Yat, A., 2021. Dynamic Energy Budget model suggests feeding constraints and physiological stress in black-lip pearl oysters, 5 years post mass-mortality event. *Mar. Pollut. Bull.* 167, 112329. <https://doi.org/10.1016/j.marpolbul.2021.112329>
- Montaggioni, L. 2015. – Naissance et evolution géologique des îles Australes. In: Salvat B., Bambridge T., Tanret D. et Petit J., 2015. *Environnement marin des îles Australes, Polynésie française*. Institut Récifs Coralliens Pacifique, CRIOBE et The Pew Charitable Trusts Polynésie française. ISBN 978-2-905630-08-7, EAN 9782905630087. Polynésie française, Tahiti, p. 29-39
- Morin, E., Gatti, C.M. iti, Bambridge, T., Chinain, M., 2016. Ciguatera fish poisoning: Incidence, health costs and risk perception on Moorea Island (Society archipelago, French Polynesia). *Harmful Algae* 60, 1–10. <https://doi.org/10.1016/j.hal.2016.10.003>
- Naidoo, R., Balmford, A., Ferraro, P.J., Polasky, S., Ricketts, T.H., Rouget, M., 2006. Integrating economic costs into conservation planning. *Trends Ecol. Evol.* 21, 681–687. <https://doi.org/10.1016/j.tree.2006.10.003>
- Newton, K., Côté, I.M., Pilling, G.M., Jennings, S., Dulvy, N.K., 2007. Current and Future Sustainability of Island Coral Reef Fisheries. *Curr. Biol.* 17, 655–658. <https://doi.org/10.1016/j.cub.2007.02.054>
- Nicolle, A., Moitié, R., Ogor, J., Dumas, F., Foveau, A., Foucher, E., Thiébaud, E., 2017. Modelling larval dispersal of *Pecten maximus* in the English Channel: a tool for the spatial management of the stocks. *ICES J. Mar. Sci.* 74, 1812–1825. <https://doi.org/10.1093/icesjms/fsw207>
- Nielsen, E.S., Beger, M., Henriques, R., Selkoe, K.A., von der Heyden, S., 2017. Multispecies genetic objectives in spatial conservation planning. *Conserv. Biol.* 31, 872–882.

<https://doi.org/10.1111/cobi.12875>

- Nikitine, J., Wilson, A.M.W., Dawson, T.P., 2018. Developing a framework for the efficient design and management of large scale marine protected areas. *Mar. Policy* 94, 196–203. <https://doi.org/10.1016/j.marpol.2018.05.012>
- NOAA (2021) Office for coastal management – Digital Coast <<https://coast.noaa.gov/digitalcoast/tools/marxan.html>> last accessed: sept 2021
- Nunn, P.D., Aalbersberg, W., Lata, S., Gwilliam, M., 2014. Beyond the core: Community governance for climate-change adaptation in peripheral parts of Pacific Island Countries. *Reg. Environ. Chang.* 14, 221–235. <https://doi.org/10.1007/s10113-013-0486-7>
- O’Leary, J.K., Goodman, M., Tuda, A., Machumu, M., West, L., 2020. Opportunities and challenges in achieving co-management in marine protected areas in East Africa: a comparative case study. *J. Indian Ocean Reg.* 0, 1–31. <https://doi.org/10.1080/19480881.2020.1825201>
- Okada, E.K., Agostinho, A.A., Gomes, L.C., 2005. Spatial and temporal gradients in artisanal fisheries of a large Neotropical reservoir, the Itaipu Reservoir, Brazil. *Can. J. Fish. Aquat. Sci.* 62, 714–724. <https://doi.org/10.1139/f05-015>
- Oyinlola, M.A., Reygondeau, G., Wabnitz, C.C.C., Troell, M., Cheung, W.W.L., 2018. Global estimation of areas with suitable environmental conditions for mariculture species. *PLoS One* 13, 1–19. <https://doi.org/10.1371/journal.pone.0191086>
- Pauly, D., Zeller, D., 2016. Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nat. Commun.* 7. <https://doi.org/10.1038/ncomms10244>
- Payri, C.E., Vidal, E., 2019. Biodiversity, a pressing need for action in Oceania. Presses Universitaires de la Nouvelle-Calédonie (PUNC), Nouméa, New Caldonia.
- Pinsky, M.L., Palumbi, S.R., Andréfouët, S., Purkis, S.J., 2012. Open and closed seascapes: Where does habitat patchiness create populations with high fractions of self-recruitment? *Ecol. Appl.* 22, 1257–1267. <https://doi.org/10.1890/11-1240.1>
- PIRT - Pacific Islands Roundtable for Nature Conservation, SPREP PROE, Gouvernement de la Nouvelle-Calédonie, 2020. Vemööre Declaration : Commitments to nature conservation action in the Pacific Islands region, 2021-2025, in: SPREP PROE, Gouvernement de la Nouvelle-Calédonie (Eds.), 10th Pacific Islands Conference. Nouméa, New Caldonia, pp. 2021–2025.
- Plagányi, É.E., Skewes, T., Murphy, N., Pascual, R., Fischer, M., 2015. Crop rotations in the sea: Increasing returns and reducing risk of collapse in sea cucumber fisheries. *Proc. Natl. Acad. Sci.* 112, 6760–6765. <https://doi.org/10.1073/pnas.1406689112>
- Poirine, B., 1999. The economy of french polynesia after the nuclear boom. *Pacific Econ. Bull.* 14, 93–109.
- Possingham, H.P., Ball, I.R., Andelman, S., 2000. Mathematical methods for identifying representative reserve networks., in: Ferson, S. and Burgman, M. (Ed.), *Quantitative Methods for Conservation Biology*. New York, pp. 291–305. <https://doi.org/10.1007/0-387-22648-6>
- Pressey, R.L., Bottrill, M.C., 2009. Approaches to landscape- and seascape-scale conservation planning: Convergence, contrasts and challenges. *Oryx* 43, 464–475. <https://doi.org/10.1017/S0030605309990500>
- Pressey, R.L., Mills, M., Weeks, R., Day, J.C., 2013. The plan of the day : Managing the dynamic transition from regional conservation designs to local conservation actions. *Biol. Conserv.* 166, 155–169.
- Pressey, R.L., Watts, M.E., Barrett, T.W., Ridges, M.J., 2009. The C-Plan Conservation Planning System : Origins , Applications , and Possible Futures, in: Moilanen, A., Wilson, K.A., Possingham, H.P. (Eds.), *Spatial Conservation Prioritization*. Oxford Biology, pp. 211–234.

- Purcell, S.W., Mercier, A., Conand, C., Hamel, J.-F., Toral-Granda, M.V., Lovatelli, A., Uthicke, S., 2013. Sea cucumber fisheries: global analysis of stocks, management measures and drivers of overfishing. *Fish Fish.* 14, 34–59. <https://doi.org/10.1111/j.1467-2979.2011.00443.x>
- Purcell, S.W., Uthicke, S., Byrne, M., Eriksson, H., 2015. Rotational harvesting is a risky strategy for vulnerable marine animals. *Proc. Natl. Acad. Sci.* 112, 1. <https://doi.org/10.1073/pnas.1515074112>
- Purkis, S.J., Gleason, A.C.R., Purkis, C.R., Dempsey, A.C., Renaud, P.G., Faisal, M., Saul, S., Kerr, J.M., 2019. High-resolution habitat and bathymetry maps for 65,000 sq. km of Earth's remotest coral reefs. *Coral Reefs.* <https://doi.org/10.1007/s00338-019-01802-y>
- Rees, S.E., Foster, N.L., Langmead, O., Pittman, S., Johnson, D.E., 2017. Defining the qualitative elements of Aichi Biodiversity Target 11 with regard to the marine and coastal environment in order to strengthen global efforts for marine biodiversity conservation outlined in the United Nations Sustainable Development Goal 14. *Mar. Policy* 1–10. <https://doi.org/10.1016/j.marpol.2017.05.016>
- Reimaanlok National Planning Team, 2008. Reimaanlok: National Conservation Area Plan for the Marshall Islands 2007-2012. N. Baker: Melbourne, Australia.
- Reimer, J.M., Devillers, R., Claudet, J., 2020. Benefits and gaps in area-based management tools for the ocean Sustainable Development Goal. *Nat. Sustain.* 20. <https://doi.org/10.1038/s41893-020-00659-2>
- Reisser, C.M.O., Le Gendre, R., Chupeau, C., Lo-Yat, A., Planes, S., Andréfouët, S., 2020. Population Connectivity and Genetic Assessment of Exploited and Natural Populations of Pearl Oysters within a French Polynesian Atoll Lagoon. *Genes (Basel)*. 11, 426. <https://doi.org/10.3390/genes11040426>
- Remoissenet, G., Wabnitz, C., 2012. Postlarval capture and culture of *Tridacna maxima* giant clams in French Polynesia. *SPC Fish. Newsl.* 139, 16–19.
- ReVelle, C.S., Williams, J.C., Boland, J.J., 2002. Counterpart models in facility location science and reserve selection science. *Environ. Model. Assess.* 7, 71–80. <https://doi.org/10.1023/A:1015641514293>
- Roberts, C.M., O'Leary, B.C., McCauley, D.J., Cury, P.M., Duarte, C.M., Lubchenco, J., Pauly, D., Sáenz-Arroyo, A., Sumaila, U.R., Wilson, R.W., Worm, B., Castilla, J.C., 2017. Marine reserves can mitigate and promote adaptation to climate change. *Proc. Natl. Acad. Sci. U. S. A.* 114, 201701262. <https://doi.org/10.1073/pnas.1701262114>
- Rodier, M., Longo, S., Henry, K., Ung, A., Lo-Yat, A., Darius, H., Viallon, J., Beker, B., Delesalle, B., Chinain, M., 2019. Diversity and toxic potential of algal bloom-forming species from Takaroa lagoon (Tuamotu, French Polynesia): a field and mesocosm study. *Aquat. Microb. Ecol.* 83, 15–34. <https://doi.org/10.3354/ame01900>
- Rotjan, R., Jamieson, R., Carr, B., Kaufman, L., Mangubhai, S., Obura, D., Pierce, R., Rimon, B., Ris, B., Sandin, S., Shelley, P., Sumaila, U.R., Taei, S., Tausig, H., Teroroko, T., Thorrold, S., Wikgren, B., Toatu, T., Stone, G., 2014. Establishment, Management, and Maintenance of the Phoenix Islands Protected Area, *Advances in Marine Biology*. <https://doi.org/10.1016/B978-0-12-800214-8.00008-6>
- Ruddle, K., 2008. Publications on Marine Traditional Knowledge and Management 1. October 13–24.
- Salvat, B., Bambridge, T., Tanret, D., Petit, J., 2015. Environnement marin des îles Australes, Polynésie française, CRILOBE Ins. ed. Polynésie française, Tahiti.
- Sangare, N., Lo-Yat, A., Moullac, G. Le, Pecquerie, L., Thomas, Y., Lefebvre, S., Gendre, R. Le, Beliaeff, B., Andréfouët, S., 2020. Impact of environmental variability on *Pinctada margaritifera* life-history traits: A full life cycle deb modeling approach. *Ecol. Modell.* 423, 109006. <https://doi.org/10.1016/j.ecolmodel.2020.109006>



- Sangha, K.K., Maynard, S., Pearson, J., Dobriyal, P., Badola, R., Hussain, S.A., 2019a. Recognising the role of local and Indigenous communities in managing natural resources for the greater public benefit: Case studies from Asia and Oceania region. *Ecosyst. Serv.* 39, 100991. <https://doi.org/10.1016/j.ecoser.2019.100991>
- Sangha, K.K., Maynard, S., Pearson, J., Dobriyal, P., Badola, R., Hussain, S.A., 2019b. Recognising the role of local and Indigenous communities in managing natural resources for the greater public benefit: Case studies from Asia and Oceania region. *Ecosyst. Serv.* 39, 100991. <https://doi.org/10.1016/j.ecoser.2019.100991>
- Saoulé, M.E., 1985. What is Conservation Biology? *Bioscience* 35, 727–734. <https://doi.org/10.11647/OBP.0177.01>
- Savoré, S., 2019. Matrix for the characterization of fishing activities, Fisheries and Aquaculture Department, Food and Agriculture Organization of the UN. Rome, Italy.
- Singh, A., 2015. SPC ACTIVITIES Remarkable growth of seaweed farming in Bougainville. *SPC Fish. Newsl.* #146 2–3.
- Singh, A., Lulu, I., 2021. SPC ACTIVITIES Empowering seaweed farmers to develop new products in Solomon Islands. *SPC Fish. Newsl.* #165 35–36.
- Singleton, R.L., Roberts, C.M., 2014. The contribution of very large marine protected areas to marine conservation: Giant leaps or smoke and mirrors? *Mar. Pollut. Bull.* 87, 7–10. <https://doi.org/10.1016/j.marpolbul.2014.07.067>
- Skinner, M.P., Brewer, T.D., Johnstone, R., Fleming, L.E., Lewis, R.J., 2011. Ciguatera Fish Poisoning in the Pacific Islands (1998 to 2008). *PLoS Negl. Trop. Dis.* 5, e1416. <https://doi.org/10.1371/journal.pntd.0001416>
- Smallhorn-West, P., Sheehan, J., Rodriguez-Troncoso, A.P., Malimali, S., Halafihi, T., Aisea, L., Mailau, S., Le'ota, A., Ceccarelli, D., Stone, K., Pressey, B., Jones, G., 2020. Kingdom of Tonga Special Management Area report 2020.
- Smallhorn-West, P.F., Bridge, T.C.L., Malimali, S., Pressey, R.L., Jones, G.P., 2019. Predicting impact to assess the efficacy of community-based marine reserve design. *Conserv. Lett.* 12, 1–8. <https://doi.org/10.1111/conl.12602>
- Smallhorn-West, P.F., Govan, H., 2018. Towards reducing misrepresentation of national achievements in marine protected area targets. *Mar. Policy* 97, 127–129. <https://doi.org/10.1016/j.marpol.2018.05.031>
- Smallhorn-West, P.F., Stone, K., Ceccarelli, D.M., Malimali, S., Halafihi, T., Bridge, T.C.L., Pressey, R.L., Jones, G.P., 2020a. Community management yields positive impacts for coastal fisheries resources and biodiversity conservation. *Conserv. Lett.* 13, 1–12. <https://doi.org/10.1111/conl.12755>
- Smallhorn-West, P.F., Weeks, R., Gurney, G., Pressey, R.L., 2020b. Ecological and socioeconomic impacts of marine protected areas in the South Pacific: assessing the evidence base. *Biodivers. Conserv.* 29, 349–380. <https://doi.org/10.1007/s10531-019-01918-1>
- Song, A.M., Cohen, P.J., Hanich, Q., Morrison, T.H., Andrew, N., 2019. Multi-scale policy diffusion and translation in Pacific Island coastal fisheries. *Ocean Coast. Manag.* 168, 139–149. <https://doi.org/10.1016/j.ocecoaman.2018.11.005>
- Tedesco, P., 2015. Modélisation bio-physique de lagons d'atolls : application à la perliculture. Plouzané, France.
- Teitelbaum, A., Friedman, K., 2008. Successes and failures in reintroducing giant clams in the Indo-Pacific region. *SPC Trochus Inf. Bull.* 14, 19–26.
- Thiault, L., Collin, A., Chlous, F., Gelcich, S., Claudet, J., 2017. Combining participatory and

- socioeconomic approaches to map fishing effort in smallscale fisheries. *PLoS One* 12, 1–18. <https://doi.org/10.1371/journal.pone.0176862>
- Thomas, Y., Dumas, F., Andréfouët, S., 2016. Larval connectivity of pearl oyster through biophysical modelling; evidence of food limitation and broodstock effect. *Estuar. Coast. Shelf Sci.* 182, 283–293. <https://doi.org/10.1016/j.ecss.2016.03.010>
- Thomas, Y., Dumas, F., Andréfouët, S., 2014. Larval dispersal modeling of pearl oyster *pinctada margaritifera* following realistic environmental and biological forcing in ahe atoll lagoon. *PLoS One* 9. <https://doi.org/10.1371/journal.pone.0095050>
- Thomas, Y., Le Gendre, R., Garen, P., Dumas, F., Andréfouët, S., 2012. Bivalve larvae transport and connectivity within the Ahe atoll lagoon (Tuamotu Archipelago), with application to pearl oyster aquaculture management. *Mar. Pollut. Bull.* 65, 441–452. <https://doi.org/10.1016/j.marpolbul.2011.12.027>
- Torres-Pulliza, D., Wilson, J.R., Darmawanb, A., Campbell, S.J., Andréfouët, S., 2013. Ecoregional scale seagrass mapping: A tool to support resilient MPA network design in the Coral Triangle. *Ocean Coast. Manag.* 55–64. <https://doi.org/10.1016/j.ocecoaman.2011.03.004>
- Treml, E.A., Roberts, J., Halpin, P.N., Possingham, H.P., Riginos, C., 2015. The emergent geography of biophysical dispersal barriers across the Indo-West Pacific. *Divers. Distrib.* 21, 465–476. <https://doi.org/10.1111/ddi.12307>
- Trouillet, B., Bellanger-Husi, L., El Ghaziri, A., Lamberts, C., Plissonneau, E., Rollo, N., 2019. More than maps: Providing an alternative for fisheries and fishers in marine spatial planning. *Ocean Coast. Manag.* 173, 90–103. <https://doi.org/10.1016/j.ocecoaman.2019.02.016>
- Tsang, Y.-P., Tingley, R.W., Hsiao, J., Infante, D.M., 2019. Identifying high value areas for conservation: Accounting for connections among terrestrial, freshwater, and marine habitats in a tropical island system. *J. Nat. Conserv.* 50, 125711. <https://doi.org/10.1016/j.jnc.2019.125711>
- Tuck, M.E., Ford, M.R., Masselink, G., Kench, P.S., 2019. Physical modelling of reef island topographic response to rising sea levels. *Geomorphology* 345, 106833. <https://doi.org/10.1016/j.geomorph.2019.106833>
- Tulloch, V.J., Possingham, H.P., Jupiter, S.D., Roelfsema, C., Tulloch, A.I.T., Klein, C.J., 2013. Incorporating uncertainty associated with habitat data in marine reserve design. *Biol. Conserv.* 160, 41–51.
- Tulloch, V.J.D., Brown, C.J., Possingham, H.P., Jupiter, S.D., Maina, J.M., Klein, C.J., 2016. Improving conservation outcomes for coral reefs affected by future oil palm development in Papua New Guinea. *Biol. Conserv.* 203, 43–54. <https://doi.org/10.1016/j.biocon.2016.08.013>
- UN - United Nations General Assembly, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. <https://doi.org/10.1017/s0251107x00020617>
- United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. New York, USA. <https://doi.org/10.1201/b20466-7>
- Van Wynsberge, S., Andréfouët, S., Gaertner-Mazouni, N., Remoissenet, G., 2015. Conservation and resource management in small tropical islands: Trade-offs between planning unit size, data redundancy and data loss. *Ocean Coast. Manag.* 116, 37–43. <https://doi.org/10.1016/j.ocecoaman.2015.06.031>
- Van Wynsberge, S., Andréfouët, S., Gaertner-Mazouni, N., Wabnitz, C.C.C., Menoud, M., Le Moullac, G., Levy, P., Gilbert, A., Remoissenet, G., 2017. Growth, Survival and Reproduction of the Giant Clam *Tridacna maxima* (Röding 1798, Bivalvia) in Two Contrasting Lagoons in French Polynesia. *PLoS One* 1–20. <https://doi.org/10.1371/journal.pone.0170565>
- Van Wynsberge, S., Andréfouët, S., Gilbert, A., Stein, A., Remoissenet, G., 2013. Best Management Strategies for Sustainable Giant Clam Fishery in French Polynesia Islands: Answers from a

- Spatial Modeling Approach. *PLoS One* 8, 15. <https://doi.org/10.1371/journal.pone.0064641>
- Van Wynsberge, S., Andréfouët, S., Hamel, M.A., Kulbicki, M., 2012. Habitats as surrogates of taxonomic and functional fish assemblages in coral reef ecosystems: A critical analysis of factors driving effectiveness. *PLoS One* 7, 1–11. <https://doi.org/10.1371/journal.pone.0040997>
- Venier, C., Menegon, S., Possingham, H.P., Gissi, E., Zanella, A., Depellegrin, D., Sarretta, A., Barbanti, A., McGowan, J., 2021. Multi-objective zoning for aquaculture and biodiversity. *Sci. Total Environ.* 785, 146997. <https://doi.org/10.1016/j.scitotenv.2021.146997>
- Visalli, M.E., Best, B.D., Cabral, R.B., Cheung, W.W.L., Clark, N.A., Garilao, C., Kaschner, K., Kesner-Reyes, K., Lam, V.W.Y., Maxwell, S.M., Mayorga, J., Moeller, H. V., Morgan, L., Crespo, G.O., Pinsky, M.L., White, T.D., McCauley, D.J., 2020. Data-driven approach for highlighting priority areas for protection in marine areas beyond national jurisdiction. *Mar. Policy* 122, 1–14. <https://doi.org/10.1016/j.marpol.2020.103927>
- von der Heyden, S., Beger, M., Toonen, R.J., van Herwerden, L., Juinio-Meñez, M.A., Ravago-Gotanco, R., Fauvelot, C., Bernardi, G., 2014. The application of genetics to marine management and conservation: examples from the Indo-Pacific. *Bull. Mar. Sci.* 90, 123–158. <https://doi.org/10.5343/bms.2012.1079>
- Wabnitz, C.C.C., 2015a. SPC ACTIVITIES Pacific Islands flame angelfish probably all belong to the same stock. *SPC Fish. Newsl.* #146 9–10. <https://doi.org/10.1007/s00227-006-0471-5>. Thresher
- Wabnitz, C.C.C., 2015b. SPC ACTIVITIES Commercial marine aquarium surveys in Samoa. *SPC Fish. Newsl.* #146 11–13.
- Walters, C., 2003. Folly and fantasy in the analysis of spatial catch rate data. *Can. J. Fish. Aquat. Sci.* 60, 1433–1436. <https://doi.org/10.1139/f03-152>
- Warren, C., Steenbergen, D.J., 2021. Fisheries decline, local livelihoods and conflicted governance: An Indonesian case. *Ocean Coast. Manag.* 202, 105498. <https://doi.org/10.1016/j.ocecoaman.2020.105498>
- Watson, M.S., Jackson, A.-M., Lloyd-Smith, G., Hepburn, C.D., 2021. Comparing the Marine Protected Area Network Planning Process in British Columbia, Canada and New Zealand – Planning for cooperative partnerships with Indigenous communities. *Mar. Policy* 125, 104386. <https://doi.org/10.1016/j.marpol.2020.104386>
- Watts, M.E., Ball, I.R., Stewart, R.S., Klein, C.J., Wilson, K., Steinback, C., Lourival, R., Kircher, L., Possingham, H.P., 2009. Marxan with Zones: Software for optimal conservation based land- and sea-use zoning. *Environ. Model. Softw.* 24, 1513–1521. <https://doi.org/10.1016/j.envsoft.2009.06.005>
- Webb, J., 2020. Kiribati economic survey: Oceans of opportunity. *Asia Pacific Policy Stud.* 7, 5–26. <https://doi.org/10.1002/app5.297>
- Weeks, R., 2017. Incorporating seascape connectivity in conservation prioritisation. *PLoS One* 12, 1–16. <https://doi.org/10.1371/journal.pone.0182396>
- Weeks, R., Adams, V.M., 2018. Research priorities for conservation and natural resource management in Oceania's small-island developing states. *Conserv. Biol.* 32, 72–83. <https://doi.org/10.1111/cobi.12964>
- Weeks, R., Green, A.L., Joseph, E., Peterson, N., Terk, E., 2016. Using reef fish movement to inform marine reserve design. *J. Appl. Ecol.* 8. <https://doi.org/10.1111/1365-2664.12736>
- Weeks, R., Jupiter, S.D., 2013. Adaptive Comanagement of a Marine Protected Area Network in Fiji. *Conserv. Biol.* 27, 1234–1244. <https://doi.org/10.1111/cobi.12153>
- Weeks, R., Pressey, R.L., Wilson, J.R., Knight, M., Horigue, V., Abesamis, R.A., Acosta, R., Jompa, J.,

2014. Ten things to get right for marine conservation planning in the Coral Triangle. *F1000Research* 1–20. <https://doi.org/10.12688/f1000research.3886.1>
- Weeks, R., Russ, G.R., Bucol, A.A., Alcala, A.C., 2010a. Shortcuts for marine conservation planning: The effectiveness of socioeconomic data surrogates. *Biol. Conserv.* 143, 1236–1244. <https://doi.org/10.1016/j.biocon.2010.02.031>
- Weeks, R., Russ, G.R., Bucol, A.A., Alcala, A.C., 2010b. Incorporating local tenure in the systematic design of marine protected area networks. *Conserv. Lett.* 3, 445–453. <https://doi.org/10.1111/j.1755-263X.2010.00131.x>
- Weir, T., Dovey, L., Orcherton, D., 2017. Social and cultural issues raised by climate change in Pacific Island countries: an overview. *Reg. Environ. Chang.* 17, 1017–1028. <https://doi.org/10.1007/s10113-016-1012-5>
- Wendt, H.K., Weeks, R., Comley, J., Aalbersberg, W., 2016. Systematic conservation planning within a Fijian customary governance context. *Pacific Conserv. Biol.* 22, 10. <https://doi.org/10.1071/pc16001>
- Wenger, A.S., Atkinson, S., Santini, T., Falinski, K., Hutley, N., Albert, S., Horning, N., Watson, J.E.M., Mumby, P.J., Jupiter, S.D., 2018. Predicting the impact of logging activities on soil erosion and water quality in steep, forested tropical islands. *Environ. Res. Lett.* 13, 1–12. <https://doi.org/10.1088/1748-9326/aab9eb>
- Winter, K.B., Rii, Y.M., Reppun, F.A.W.L., Delaforgue Hintzen, K., Alegado, R.A., Bowen, B.W., Bremer, L.L., Coffman, M., Deenik, J.L., Donahue, M.J., Falinski, K.A., Frank, K., Franklin, E.C., Kurashima, N., Kekuewa Lincoln, N., Madin, E.M.P., McManus, M.A., Nelson, C.E., Okano, R., Olegario, A., Pascua, P., Oleson, K.L.L., Price, M.R., Rivera, M.A.J., Rodgers, K.S., Ticktin, T., Sabine, C.L., Smith, C.M., Hewett, A., Kaluhiwa, R., Cypher, M., Thomas, B., Leong, J.A., Kekuewa, K., Tanimoto, J., Kukea-Shultz, K., Kawelo, A.H., Kotubetey, K., Neilson, B.J., Lee, T.S., Toonen, R.J., 2020. Collaborative research to inform adaptive comanagement: A framework for the he'eia national estuarine research reserve. *Ecol. Soc.* 25, 1–17. <https://doi.org/10.5751/ES-11895-250415>
- Yamano, H., Kayanne, H., Yamaguchi, T., Kuwahara, Y., Yokoki, H., Shimazaki, H., Chikamori, M., 2007. Atoll island vulnerability to flooding and inundation revealed by historical reconstruction: Fongafale Islet, Funafuti Atoll, Tuvalu. *Glob. Planet. Change* 57, 407–416. <https://doi.org/10.1016/j.gloplacha.2007.02.007>
- Yasumoto T, Inoue A, Bagnis R, Adaci R. (1977). Finding of a dinoflagellate as a likely culprit of ciguatera. *Bull Jap Soc Scient Fish*, 43 : 1021-1026
- Zeller, D.S., Booth, S., Pauly, D., 2007. Fisheries Contributions to the Gross Domestic Product: Underestimating Small-scale Fisheries in the Pacific. *Mar. Resour. Econ.* 21, 355–374. <https://doi.org/10.1086/mre.21.4.42629521>

## Appendices

**Appendix 1.** Review of the technical features of 34 SCP case studies on POTIs. PU= Planning units, DDPU= data driven planning units, BLM= Boundary Length Modifier, CSM= Connectivity strength modifier, CPUE= catch per unit effort, PNG= Papua New Guinea. FSM= Federated States of Micronesia, NGO=non-governmental organization. MCRMP= Millennium Coral Reef Mapping Project, LMMA= locally managed marine areas, MPA= marine protected area, nb= number, min.= minimum, max.=maximum, obj=objective(s), cons.= conservation, hab.= habitats, ecosyst.= ecosystem, comm= community/ies, sp.= species, gov.= government, spag= spawning aggregation sites. For Success rate of objectives, only the quantitative results clearly presented are provided

Date	Authors	Country or Territory	Methodological/ Applied paper (M/A)	Institutional context	Marine conservation objectives (nb)	Origin of the map	Conservation targets (%)	Costs: Proxies? Validation?	Other constraints	SCP software + version	Spatial domain (km <sup>2</sup> )	PU size (m <sup>2</sup> ) (shape), BLM (y/n)	Success rate of objectives
2003	TNC	FSM	A	NGO	Ecological systems, comm. & species (53)	-	20-30%	-	-	-	29,175	-	38% sites are protected
2007	Hinchley et al.	Palau	A	Academic with NGO & gov.	Ecosystems, hab., species & special areas (39)	1:25,000 USGS, Landsat7	30-100%	28 socio-economic factors	Existing reserves	SPOT + Marxan	3114	15,000 m <sup>2</sup> BLM	NA
2008	Reimaanlok Nat'l Planning Team	Marshall Isl.	A	Academic & gov.	Coarse scale (hab./ ecosyst.) (10), fine scale (sp./ rare comm./ cultural point) (6), sp. (21)	IKONOS, Quickbird, LandSat & ASTER; Landsat7 for coral reefs	30-100%	Socio-economic costs, distributed among comm.	Existing reserves	-	14,067	-	30-100%
2009	Andréfouët et al.	Wallis	M, A	Academic & gov.	Geomorphic hab. (MCRMP, level 5) + benthic map (56). 9 biological inventories	MCRMP	20%	Management costs (minimal size of the MPA; cost = BML)	-	R	269	250,000 1,000,000 & 4,000,000 m <sup>2</sup> BLM	NA
2009	Green et al.	PNG	A	Academic with NGO		-	-	15 data layers combined to derive a total cost layer (detailed socio-economic surveys)	-	Marxan	13,000	100,000 m <sup>2</sup> (hexagon). BLM Min. size of MPA ; Max spacing dist.	NA

2010	Lipsett-Moore et al.	Solomon Isl.	A	Academic & NGO with Tribal Communities	Marine cons. features (114) (47 coral reefs derived by 4 bioregions)	MCRMP (coral reef types); experts (bioregions)	10-95%	PU area minus PU proportion of rapid inclusion in the protected area network.	Existing, proposed, protected or managed areas	Marxan & Zonae cogito	7 894	500,000 m <sup>2</sup> BLM	NA
2010	Jupiter et al.	Fiji	M, A	Academic & NGO	Hab. (11) & sp.	Workshop participants	25-100%	-	LMMAs	-	-	-	NA
2010	Kool et al.	Solomon Isl.	A	Academic, NGO + gov.	Functional hab. types (8)	MCRMP	10-50%	No costs for the marine part	Reserves	Marxan	60,638	2,500,000 m <sup>2</sup> BLM	NA
2011	Adams, et al.	Fiji	M, A	Academic	Hab. (7)	Aerial photographs (Fiji dept. of Lands & topographic map sheets)	30%	Modelled opportunity cost, modelled profit, CPUE with multiple gear types (surveys)	Existing Tapu areas (partly open for fishing) & no take MPA	Marxan	262	2500 & 62,500 m <sup>2</sup>	NA
2012	Klein et al.	Fiji	M, A	Academic	Coral reef attributes (4)	Landsat 5 Thematic Mapper (30m.) (for land)	Maximize coral reef condition	Fishing pressure (proxy: inhab. density)	-	-	7759	1,000,000 m <sup>2</sup>	NA
2012	Mills et al.	Fiji	M	Academic & local authorities	Ecosystem types (8)	"all available data" (see Mills et al., 2011)	30%	Socio-economic cost (proxy: distance to road / village)	Reserves: locked in or not.	Maxent Marxan with Zone	30	500,000 m <sup>2</sup>	Ecological effectiveness scores varied from 0.10 to 1.
2013	Tulloch et al.	Fiji	M, A	Academic	Benthic habitats (33)	QuickBird 2006, Ikonos 2007, transects (Knudby et al., 2011)	10-99%. Certainty target: 50-99%	Equal cost	-	Marxan v.2.43 , Marxan with Prob.	114	5000 m <sup>2</sup> (hexagon)	NA
2013	Hamel et al.	Wallis, Alofi & Futuna	A	Academic & local gov.	Geomorphic map (Wallis: 16, Alofi: 4, Futuna: 3) Geomorphic + benthic map (W: 55, A: 6, F: 3)	Landsat 7 ETM+ (30m.), MCRMP, benthic map from aerial photos (2m.)	20%	Fishing grounds (objective: keep all subsistence fishing grounds open for extraction)	3 small informal customary MPAs in Wallis	ESRI R ArcMapTM 10.0 & R, Marxan	300	250,000 & 40,000 m <sup>2</sup> (square)	Only 60% of the cons. obj. achieved when all fishing grounds open for W&F, 20% for Alofi.
2013	Weeks & Jupiter.	Fiji	A	Academic, collaboration with local chiefs, & NGO	Fish, invertebrate abundance & coral cover.	-	30% of 10 coral reef classes	uniform socio-economic costs, (validated then with workshop)	Reserves	Marxan	273	-	NA

2013	Makino et al. (a)	Fiji	M, A	Academic	Reefs (2) & forest (1); with adjacent-reef symmetric land-sea connectivity	-	30% (reefs) 20% (forests)	Cost of land; foregone fishing revenue (model)	-	Marxan, with connectivity value matrix	2971	1,000,000 m <sup>2</sup> (hexagon); CSM	NA
2013	Makino et al. (b)	Fiji	M	Academic	Marine hab. (5)	-	30%	Opportunity cost (fishing pressure surrogate, coastal pop. model)	LMMA, permanent, semi/open access areas.	Marxan with Zones	10,044	1,000,000 m <sup>2</sup>	NA
2014	Deas et al.	New Caledonia	A	Academic	Geomorphic (26) & geomorphic + benthic (106)	Quickbird (2.4m.) MCRMP	20%	Opportunity cost (19 layers, fisheries atlas)	customary exclusive fishing area	Marxan	211	216,000 m <sup>2</sup> (hexagon) BLM	NA
2014	Klein et al.	Fiji	M, A	Academic & gov.	Vegetation types (7)	-	40%	Clan cost (tenure negotiations) & equal cost	Protected Areas: locked in	Marxan	Approx. 16,400	1,000,000 m <sup>2</sup> BLM	Up to 2.8x better for reefs, with land-sea connection.
2015	Gurnay et al.	Fiji	M, A	Academic	Geomorphic reef classes (9); or CPUE	MCRMP	10-90% hab. or: 90% min. of CPUE	Conservation objectives or CPUE	-	Marxan, Marxan with Zones	260	60,000 m <sup>2</sup>	60% (cons. obj.) & 90% (CPUE obj.)
2015	Government of PNG	PNG	M, A	NGO & gov.	Hab. &/or special features, spag	-	10-50%	Proxy of port landing & distance to ports	Lock-out/in reserves & mining leases	Marxan	2,510,750	50,000,000 m <sup>2</sup> BLM	NA
2015	Van Wynsberge et al.	French Polynesia	M, A	Academic & gov.	Hab. map (no detail on level)	Quickbird satellite image (2.4m.)	Giant clam density	Vulnerability of giant clam (in situ measures) & fishing effort (interviews)	-	GIS Esri@ ArcMap 10.1	Approx. 28	25; 2500; 10,000; 40,000; 160,000 m <sup>2</sup> ; DDPU	NA
2016	Cheok et al.	Fiji & FSM	M	Academic	Reef classes (5 different levels)	Landsat 7 ETM + (30m.) MCRMP	30%	Uniform or variable	-	Marxan	24,439 (Fiji) 32,168 (FSM)	1,000,000 & 25,000,000 m <sup>2</sup>	NA
2016	Tulloch et al.	PNG	A	Academic	Coastal ecosyst. types (9) (coral reef+geomorphic distrib.)	Landsat 7i ETM+ (90m.) MCRMP	30%	Opp. costs (global artisanal fishing data & survey) & land runoff (model)	Constraints from oil palm agriculture, & indirect pollution	Marxan 2.4 modified to take into account uncertainty	-	-	NA BLM
2016	Weeks et al.	FSM	A	Academic	Coral reefs (9) sea grass (8), fishes' home ranges (12).	MCRMP seagrass surveys	30%	-	Assessment of efficiency of reserves	-	-	-	NA

2016	Wendt et al.	Fiji	M, A	Academic & local communities	Geomorphic, benthic, hab., spag, turtle nesting & cultural sites	Field surveys & satellite imagery	30-80%	Opportunity cost, disputed areas, & enforceability	LMMA	Marxan with zones	446	15,000 m <sup>2</sup> BLM	LMMA: 12% reef protected, vs 19% for SCP discussed with comm.
2017	Hamel et al.	PNG	M, A	Academic	Geomorphic hab. (28)	Worldview satellite image (2m.)	20%	Fishing activity (7 proxies either validated by interviews or derived from the perceived fishing importance)	-	Marxan	40	90,000 m <sup>2</sup>	Perceived fishing value: larger costs (4.5-14.4%) vs fishing activity (0.1-0.2%).
2017	Tulloch et al.	Fiji	M	Academic	Geomorphic (9) Benthic (33)	Quickbird (2.4m.), field surveys (Knudby et al, 2011)	30%	Equal cost or fishing opportunity cost (model)	Ignored existing MPA	Marxan or Marxan with Probability	262	5000 m <sup>2</sup>	NA
2017	Weeks	FSM	M, A	Academic	Nearshore marine hab. & mangroves	-	30%	Equal cost or combined seascape connectivity	-	Marxan	-	25,000 m <sup>2</sup> ; BLM	NA
2018	Kabbadj et al.	French Polynesia	M, A	Academic & gov.	Overall biomass of clams, leagally exploited clams, abundance of recruits, area of hab. with highest density (4).	Combination of satellite imagery for habitat maps, & field work	10-30-50%	homogenous cost, fishing frequentation surrogate, distance to the closest <i>hoa</i>	Reserve & mass mortality events	QMarxanZ plugin in QGIS Wien 2.8.6.	-	250,000 m <sup>2</sup> (hexagon)	NA
2019	Oyafuzo et al.	Hawaii	M, A	Academic	Habitat-base distribution map for 7 bottom fish species (no precision).	-	Max. cons. value, reserve aggreg.; min. opp. cost, total area.	Opportunity cost (gross revenue for 7 bottomfish)	Existing reserves	Marxan	1188	250,000 m <sup>2</sup> BLM	NA
2018	Delevaux et al.	Fiji	M, A	Academic	Hab., bathymetry, benthic group of corals (4) & fish group biomass (4)	Quickbird, Ikonos & Landsat Thematic Mapper +local coral reef survey	-	-	-	R with dismo & raster packages	-	3600 m <sup>2</sup>	NA



**Appendix 2.** For each paper analyzed in the introduction (SCP in the POTIs and further, if their themes were relevant to the POTIs), the main questions, themes or take-home messages are developed here.

<b>Date</b>	<b>Authors</b>	<b>Region or country</b>	<b>Main questions, themes or take-home message</b>
2003	The Nature Conservancy	FSM	- Ecoregional assessment, as a foundation for conservation planning - Expert-driven identification of conservation targets and goals (terrestrial and marine)
2005	Stewart and Possingham	General	- The success of reserve proposals is often weighed against socio-economic criteria
2007	Hinchey et al.	Palau	- Ecoregional assessment, as a foundation for conservation planning - Expert-driven identification of conservation targets and goals (terrestrial and marine) - Iterative proposition of protected area networks using existing data, gap analysis, systematic conservation planning (SCP) concept, ridge-to-reef approach, and Marxan software as a tool
2008	Reimaanlok Nat'l Planning Team	Marshall Isl.	- Development of a national framework for the planning and establishment of community-based conservation areas - Expert-driven identification of conservation targets and goals (terrestrial and marine), and conservation gap analysis - Planning steps for implementation of action and community based fishery management
2009	Andréfouët et al.	Wallis	- MPA selection based on habitat representation (30%) and taking into account habitat map errors - Sensitivity to planning unit (PU) sizes - Surrogacy analysis between habitat and biological species, based on multi-taxa inventory
2009	Ban et al.	Philippines	- Explore simple SCP scenarios that can be run with limited data (habitat or socio-economy), according to (or not) existing MPAs - Most sites worldwide, especially developing countries will be data limited - Socio-economic data are more critical than biophysical data to move forward with local communities in a data poor context
2009	Green et al.	PNG	- Application of SCP under a resilient framework to identify MPAs - Based on biodiversity and socio-economic proxies
2010	Barlett et al.	Vanuatu	- Call for more integration of local custom and culture to manage resources
2010	Jupiter et al.	Fiji	- First stages of conservation gap analysis to identify targets and goals
2010	Klein et al.	Coral Triangle	- Emphasize the value of integrated land-reef planning to mitigate threats to coral reefs - Model at ecoregional scale management and opportunity costs associated with land and marine protected areas - Model the return of investment in terms of coral reef protection, which set priorities for managers
2010	Kool et al.	Solomon Isl.	- Gap analysis within a ridge to reef framework
2010	Lipsett-Moore et al.	Solomon Isl.	- Ridge to reef approach where conservation plans are proposed principally based on representation of habitats - Discuss the outcomes with a variety of stakeholders and traditional managers
2010	Mills et al.	Coral Triangle	- Provide a comprehensive review of decisions about spatial scale that influence conservation planning outcomes - Understanding decisions about scale and related trade-offs can improve local conservation from regional plans & implementation of ecologically functional networks

2010	Weeks et al. (a)	Philippines	<ul style="list-style-type: none"> <li>- How to define opportunity cost where no socio-economic data is available in a small-scale fishery context?</li> <li>- How well socioeconomic surrogates reflect the true cost of conservation action to stakeholders and communities?</li> <li>- Assess the effectiveness of various socio-economic surrogates (area, population, coastal density, fishers, boats)</li> <li>- Conclude that surrogates based on the number of fishers or boats outperformed those based on overall population census data</li> <li>- Conclude that quality of socioeconomic data can be improved faster than biodiversity data, and can significantly impact conservation plans</li> </ul>
2010	Weeks et al. (b)	Philippines	<ul style="list-style-type: none"> <li>- Describe how to consider local marine tenure explicitly in SCP designs, in order to consider local objectives within a larger design</li> <li>- Use Marxan with Zones software with biodiversity/habitat and local fishing targets (minimize loss of fishing grounds)</li> <li>- Conclude that including local tenures boundaries, instead of considering all communities as one group, lead to larger costs but likely better socio-economic equity and acceptability</li> <li>- Suggest that there may be a tradeoff between the socioeconomic acceptability of shared costs and ecological viability of many small no-take areas</li> </ul>
2011	Adams et al.	Fiji	<ul style="list-style-type: none"> <li>- Model opportunity costs and profits to fishers from their displacement due to conservation measures</li> <li>- Modelled opportunity costs and profits as a function of food fish abundance and probability of catch, based on gear type and market value of species</li> <li>- Fisher surveys provided catch per unit effort (CPUE) metrics and current fishing efforts</li> <li>- Compare various SCP scenarios with constraint on opportunity costs, profit or CPUE</li> </ul>
2011	Baker et al.	Marshall Isl.	<ul style="list-style-type: none"> <li>- Formalize the development of a national framework for the planning and establishment of community-based conservation areas (cf. Reimaanlok National planning team, 2008)</li> <li>- Use SCP concepts, combined with indigenous knowledge, in a so-called hybrid plan</li> </ul>
2011	Ban et al.	General	<ul style="list-style-type: none"> <li>- Review how to design, implement and manage MPAs for coral reefs</li> <li>- In terms of SCP designs, identify emerging trends: more mixed bottom-up &amp; top-down approaches; more use of socio-economic data; call for adaptive planning</li> </ul>
2011	Game et al.	Solomon Isl.	<ul style="list-style-type: none"> <li>- Develop a planning process using community-driven conservation opportunities, with a SCP approach to prioritization</li> <li>- The software Zonae Cogito, representing Marxan outputs, is used to facilitate exchanges with local communities</li> </ul>
2011	Mills et al.	Fiji	<ul style="list-style-type: none"> <li>- Conservation gap analysis with different scenario of effectiveness of existing protected areas</li> <li>- Assess how existing conservation areas meet the 2020 ecosystem representation objectives</li> </ul>
2012	Allnut et al.	Madagascar	<ul style="list-style-type: none"> <li>- Critical assessment of prioritization methods at regional scale, including SCP methods</li> <li>- Use a variety of habitat, biodiversity, climate stress, and socio-economic proxies</li> <li>- Conclude that categorical methods can match the SCP optimization methods results</li> <li>- Conclude on the necessity to compare different method outputs</li> </ul>
2012	Fernandes et al.	Coral Triangle	<ul style="list-style-type: none"> <li>- Principles for trans-boundary designs with 3 objectives: fishery sustainability, biodiversity conservation, resilience to climate change</li> <li>- Focus on and enumerate biophysical principles; provide rationales</li> </ul>
2012	Bottrill and Pressey	General	<ul style="list-style-type: none"> <li>- Importance of effectiveness and evaluation for effective, adaptive, and informative conservation planning</li> </ul>
2012	Hamel and Andréfouët	Maldives	<ul style="list-style-type: none"> <li>- MPA selection based on biological species (multi-taxa) representation</li> <li>- Species distribution are generalized using habitat distribution, from different types of habitat maps</li> <li>- Solutions appear compatible with other approaches based on mega-fauna hot-spot and tourism activities</li> </ul>

2012	Keppel et al.	Pacific Isl.	<ul style="list-style-type: none"> <li>- Terrestrial focus but applicable to marine conservation</li> <li>- State that conservation is far from reaching its objectives for Pacific Islands Countries (PICS)</li> <li>- Highlight the problem of strong differences of approaches between governments and local NGOs, and international often well-funded big international nongovernment organizations (BINGOs) and donors</li> <li>- Suggest that current theory and practice for conservation is not entirely applicable to PICS considering social practice and values, in particular local customary resource management</li> <li>- Highlight that landowners should be key stakeholders in all conservation activities</li> <li>- Provide guidelines to improve efficiency and productivity of conservation programs in PICS</li> </ul>
2012	Klein et al.	Fiji	<ul style="list-style-type: none"> <li>- Built on Klein et al. 2010. re-emphasize the importance of integrated land-reef planning for protection and prioritization</li> <li>- Assess how to maximize coral reef condition by minimizing land-based run-offs (itself a consequence of non-protection)</li> <li>- Reef condition is defined by an index of exposure to run-offs and fishing</li> <li>- Assess cost-effectiveness of protecting coral reefs when all forest is protected</li> </ul>
2012	Mills et al.	Fiji	<ul style="list-style-type: none"> <li>- Compare systematic vs adhoc extension of MPA network in a 10 year period, in order to meet 2020 ecosystem representation targets</li> <li>- Ad hoc scheme emulated the Locally Managed Marine Area (LMMA) Fiji network expansion rates</li> <li>- Model the suitability of PU to become new MPA with Maxent software and various indicators</li> <li>- Suitability used as cost in the systematic approach</li> </ul>
2013	Hamel et al.	Wallis and Futuna	<ul style="list-style-type: none"> <li>- How do fishery opportunity cost modulate habitat-based marine reserve plan?</li> <li>- How does the thematic richness of habitat maps influence these results?</li> <li>- Conclude on difficulty to use international guidelines for local implementation of marine reserves</li> </ul>
2013	Levy and Ban.	Coral Triangle	<ul style="list-style-type: none"> <li>- How to integrate Climate Change projections into SCP designs?</li> <li>- Use spatial and temporal historical pattern of Sea Surface Temperature (SST) vs SST projection given by only one climate model</li> <li>- Targets projected areas less affected by climatic stress, within a temporal scheme, stratified by ecoregion</li> <li>- Study driven by coral bleaching information</li> </ul>
2013	Makino et al. (a)	Fiji	<ul style="list-style-type: none"> <li>- Test how zones (no-take, partially open, open), their effectiveness, and their costs, influence SCP solutions</li> <li>- Effectiveness is an <i>a priori</i> relative contribution to conservation objectives</li> <li>- Use Marxan with Zones software</li> </ul>
2013	Makino et al. (b)	Fiji	<ul style="list-style-type: none"> <li>- Target coral reef conservation with the objective of prioritizing marine reserves close to catchments with high forest cover</li> <li>- Aim to maximize intact land-sea protected area connections and minimize land-based run-offs on coral reefs.</li> <li>- Compare designs that allow for no connectivity, adjacent connectivity in the sea, symmetric and asymmetric land-sea connectivity</li> <li>- Conclude that connectivity has a huge influence on the solutions computed for habitat representation objectives</li> </ul>
2013	Torres-Pulliza et al.	Indonesia	<ul style="list-style-type: none"> <li>- Identify reserve areas based on seagrass maps at ecoregion scale using a resilience framework</li> <li>- Demonstrate the value of updated habitat maps</li> </ul>
2013	Tulloch et al.	Fiji	<ul style="list-style-type: none"> <li>- Assess of influence of habitat mapping errors in SCP outputs, using Marxan vs Marxan with Probability</li> <li>- The conservation objectives were defined by habitat representation levels (10-90%)</li> </ul>
2013	Weeks and Jupiter	Fiji	<ul style="list-style-type: none"> <li>- Propose one framework for adaptive management and conservation in time</li> <li>- Adaptive management required to enhance effectiveness of existing MPAs and improve resilience to climate change</li> <li>- Build on historical LMMA and their actions: customary, periodically harvested closures or permanent no-take areas</li> <li>- Use SCP tools under resilience framework</li> <li>- Identify factors affecting successful adaptive comanagement</li> </ul>
2014	Andréfouët and Hamel	Solomon Isl.	<ul style="list-style-type: none"> <li>- Using habitat maps at regional scale to systematically guide data gap analysis</li> <li>- Use inventory of meta-data</li> </ul>
2014	Deas et al.	New Caledonia	<ul style="list-style-type: none"> <li>- How do fishery opportunity costs modulate habitat-based marine reserve plan?</li> <li>- How does the thematic richness of habitat maps influence these results?</li> </ul>

			<ul style="list-style-type: none"> <li>- How does the type of opportunity cost influence these results?</li> <li>- What is the value of socio-economic proxies?</li> <li>- Provide practical guidelines for managers</li> </ul>
2014	Klein et al.	Fiji	<ul style="list-style-type: none"> <li>- In a terrestrial island context, recommend decision makers to use prioritization approach and avoid additive scoring systems</li> <li>- Point out scoring systems main weaknesses: (i) could not achieve representation goals, (ii) use arbitrary weights for the selection criteria</li> </ul>
2014	Klein et al.	Fiji	<ul style="list-style-type: none"> <li>- Expand Klein et al. 2012</li> <li>- Determine the incidental benefit of different terrestrial reserve networks to the condition of adjacent coral reefs</li> <li>- Assess how to maximize coral reef condition through investment in terrestrial protected areas</li> <li>- Compare results from the different prioritization approaches for land conservation</li> <li>- Recommend SCP, based on quantitative criteria (representation, adequacy, efficiency, complementarity)</li> <li>- Provide practical guidelines for managers</li> </ul>
2014	Makino et al.	Japan	<ul style="list-style-type: none"> <li>- SCP motivated by temporal shift of coral species distribution due to global warming</li> <li>- Conservation objectives are temperature zones, not coral distribution zones</li> <li>- PU are defined by both a spatial and temporal index</li> <li>- Spatial and temporal connections between PU are modeled and taken into account by Marxan</li> <li>- Consider areas consistently important through time, and those temporary important</li> <li>- Planning according to future conditions was marginally more costly than planning for present conditions</li> </ul>
2015	Gurney et al.	Fiji	<ul style="list-style-type: none"> <li>- Influence of socio-economic factors on SCP outputs</li> <li>- Socioeconomic factors are treated as costs or objectives, stakeholders are treated as a single group or multiple groups</li> <li>- Equity is enhanced when multiple stakeholders are taken into account</li> </ul>
2015	Government of PNG	PNG	<ul style="list-style-type: none"> <li>- Identification of marine high conservation interest based on comprehensiveness, adequacy, representation and resilience (CARR) principles</li> <li>- Include definition of conservation objectives and goals, and gap analysis</li> <li>- Cost socio-economic proxy based on port landing data and distance from port</li> <li>- Use Marxan to identify high priority areas</li> <li>- Lead to proposals for regional analyses</li> </ul>
2015	Horigue et al.	Philippines	<ul style="list-style-type: none"> <li>- Comparing the efficiency of coordinated vs non-coordinated, and systematic vs non-systematic MPA designs across spatial scales and level of governance</li> <li>- Simulate the expansion of an existing network through different scenarios</li> <li>- Confirm the value of systematic planning when scaling-up MPA designs</li> </ul>
2015	Maina et al.	Kenya	<ul style="list-style-type: none"> <li>- Update coral reef habitat maps at national scales before computing various systematic conservation (SC) plans</li> <li>- Include a factor to minimize or maximize exposure to climate stressors</li> <li>- Compare the effects of different socio-economic proxies and costs</li> <li>- Conclude on the value of updating habitat maps and highlight the portfolio of possible solutions</li> </ul>
2015	Makino et al.	Japan	<ul style="list-style-type: none"> <li>- Follow-up of Makino et al. 2014 using different climate scenarios</li> </ul>
2015	Mills et al.	Fiji and others	<ul style="list-style-type: none"> <li>- Review on adaptive planning</li> <li>- Relevant case studies suggest that challenges are far from being all overcome</li> <li>- Challenges includes identification of triggers for change, several institutional limits, data gaps, and methods</li> </ul>
2015	Van Wynsberge et al.	French Polynesia	<ul style="list-style-type: none"> <li>- How to trade-off between PU size, data redundancy and data loss to design MPAs?</li> <li>- Provide practical guidelines for managers</li> </ul>
2016	Cheok et al.	Fiji	<ul style="list-style-type: none"> <li>- Assess the combined effects of size of PUs, habitat resolution and description on regional SC plans</li> <li>- Use simple (uniform and distance-based) proxies as socio-economic costs</li> <li>- Assess the incidental representation of conservation objectives between scenarios at different resolutions</li> <li>- Provide practical guidelines for managers</li> </ul>

2016	Tulloch et al.	PNG	<ul style="list-style-type: none"> <li>- Integrated land-marine planning exercise, in anticipation of development of oil palm plantations next to coral reefs</li> <li>- Assess the impact on coral reefs of various land-use development scenarios using a variety of biophysical models</li> <li>- SCP scenario targets habitat representation (30%), minimize fishers opportunity costs and maximize reefs in good condition (low sediment run-off impacts)</li> </ul>
2016	Weeks et al.	FSM	<ul style="list-style-type: none"> <li>- Discuss how to include fish movement knowledge in conservation prioritization</li> <li>- Discuss value of the consultation of stakeholders</li> <li>- Highlight the importance of understanding how MPAs are connected by larval dispersal, juvenile and adult movement (species dependency)</li> </ul>
2016	Wendt et al.	Fiji	<ul style="list-style-type: none"> <li>- Critically assess the value of SCP for management in a customary marine tenure context</li> <li>- Redesign with SCP principles a MPA network from an existing network</li> <li>- Conclude that benefits are indirect, through identifying and conceptualizing management issues, and in engaging communities for data collection and decision-making</li> <li>- SCP analytical solutions are of secondary importance</li> </ul>
2017	Cheok et al.	Fiji	<ul style="list-style-type: none"> <li>- Focus on how regional scale designs translate into local actions, and after their implementation, discuss the adequate frequency of revisiting the designs</li> <li>- At each iteration, the network is expanded based on complementarity habitat (geomorphology) and rarity representation criteria</li> <li>- Evaluate time to reach final objectives, costs, and overlap between initial and final solutions</li> </ul>
2017	Geange et al.	New Zealand	<ul style="list-style-type: none"> <li>- Conservation gap analysis using Zonation SCP software</li> <li>- Compare existing MPA networks with SC plans designed to meet international representation guidelines</li> </ul>
2017	Magris et al.	Brazil	<ul style="list-style-type: none"> <li>- Compare existing set of MPAs and new clean-slate designs to assess cost-effectiveness for multiple coral reef conservation objectives</li> <li>- Consider objectives for biodiversity, connectivity, and resilience to global warming</li> </ul>
2017	Pressey et al.	General	<ul style="list-style-type: none"> <li>- Criticize on-going conservation actions based more on beliefs than on facts, and promote instead evidenced-based actions</li> </ul>
2017	Tulloch et al.	Fiji	<ul style="list-style-type: none"> <li>- Evaluate the relative influence on SCP solutions and their costs when using habitat map with different resolution, accuracy and creation costs</li> <li>- Use Marxan with Probability to account for habitat map accuracy</li> <li>- Use fisher opportunity costs modeled in Adams et al. 2011</li> </ul>
2017	Weeks	FSM	<ul style="list-style-type: none"> <li>- Aim to include fish post-settlement connectivity in SCP prioritization algorithms</li> <li>- Target the inclusion of functionalities between habitat patches and not just their representation</li> <li>- In practice, a distance-based algorithm leads to connectivity metrics between adult and juvenile habitat patches</li> <li>- Connectivity metric is used as a cost function in Marxan</li> </ul>
2017	Jupiter et al.	Fiji, PNG, Solomon Isl., Hawaii	<ul style="list-style-type: none"> <li>- Framework for Integrated Land-Sea Management (ILSM)</li> </ul>
2018	Álvarez-Romero et al.	General	<ul style="list-style-type: none"> <li>- Global review on SCP, with 155 studies</li> <li>- Create a database on SCP studies worldwide</li> </ul>
2018	Jones et al.	Western Indian Ocean	<ul style="list-style-type: none"> <li>- Identify priority fishery management area at regional scale, with different objectives and SCP prioritizing scenarios</li> <li>- Objectives are to minimize lost fishing opportunity, minimize recovery time of fish biomass, avoid areas of weak management and incorporate international collaboration</li> <li>- Solutions differ substantially between scenarios</li> <li>- Several objectives biased priority zones towards developed, wealthy and sparsely populated areas</li> </ul>
2018	Hamel et al.	PNG	<ul style="list-style-type: none"> <li>- What is the influence of proxies of fishing data in minimizing lost fishing opportunities?</li> <li>- Cross-compare the incidental costs induced by the use of different proxies</li> <li>- Focus on the perceived values of fishing grounds by local communities</li> <li>- Conclude that perceived value can be negatively impacted by proxies traditionally used in SCP</li> </ul>

2018	Kabbadj et al.	French Polynesia	<ul style="list-style-type: none"> <li>- Compare locally and regionally designed SC plans for giant clam population conservation</li> <li>- The threat is principally climate-driven, not fishery-driven</li> <li>- Use different objectives derived from stock assessment data</li> <li>- Highlight the incidental effect of regional plans, in particular the resulting poor equity between sites</li> <li>- Provide practical guidelines for managers</li> </ul>
2018	Sinclair et al.	General	<ul style="list-style-type: none"> <li>- Survey of how practitioners, mostly academics, have used SCP</li> <li>- Responses biased towards developed countries</li> <li>- Clearly identify i) research studies and ii) studies aiming for real-word implementation</li> <li>- Conclude that collaboration will bridge gaps and that transfer from research to implementation is effective</li> </ul>
2018	Weeks and Adams	Pacific Isl.	<ul style="list-style-type: none"> <li>- List scientific questions that, if resolved, could help better management and conservation in small-island developing states (SIDS)</li> <li>- Sort priorities for academics, NGOs and government agencies</li> <li>- Emphasize the importance of involving a variety of practitioners and stakeholders to identify conservation and research priorities</li> <li>- Discuss the perception on the amount of already established knowledge useful for conservation, resource management in Oceania's SIDS, and local capacity to implement management actions</li> </ul>
2018	Delevaux et al.	Hawai'i	<ul style="list-style-type: none"> <li>- Modeling framework to inform ridge-to-reef management in Hawai'i</li> <li>- Includes customary ridge-to-reef conservation practices</li> </ul>
2018	Delevaux et al.	Fiji	<ul style="list-style-type: none"> <li>- Modeling framework to inform ridge to reef management</li> </ul>
2019	Kininmonth et al.	Philippines	<ul style="list-style-type: none"> <li>- Aim to evaluate the best strategy for the progressive implementation of a MPA network in time</li> <li>- Algorithms for extension are compared regarding their capacity to maximise a metapopulation mean life-time</li> <li>- Algorithms use larval dispersal connectivity models and graph theory metrics</li> </ul>
2019	Oyafuzo et al.	Hawai'i	<ul style="list-style-type: none"> <li>- Assess with SCP tools the effectiveness of existing MPAs using opportunity cost metrics</li> <li>- Compare 3 opportunity cost scenarios and show that existing MPAs actually maximized opportunity costs</li> <li>- Recommend multiple-criteria decision making (MCDM) framework to assist reserve design</li> </ul>

Pangéa : Enquête Pêche & Ciguatera - Takaroa

Numéro d'identification de l'enquête : \_\_\_\_\_ /!\ à reporter sur la carte /!\

**A. Caractérisation de l'enquêté(e) et pratiques de pêche**

1. Es-tu un **habitant** de Takaroa // viens-tu régulièrement à Takaroa ? \_\_\_\_\_
2. Depuis combien d'années ? \_\_\_\_\_ ou quel âge ? \_\_\_\_\_
3. Es-tu le **chef** de famille ? oui // non.
4. Combien de **personnes** vivent avec toi en permanence ? : \_\_\_\_\_
5. Quel est ton **métier** actuellement ? \_\_\_\_\_
6. Pratiques-tu la **pêche** dans le lagon et ou sur le récif ? oui // non
7. Depuis combien de **temps** pêches-tu ? \_\_\_\_\_ ou quel âge ? \_\_\_\_\_
8. Pour quelles **raisons** pêches-tu ?
  - seulement pour la famille ou les amis
  - profession principale : je suis mon propre chef // je suis employé ?
  - parfois pour la vente -> à quelle fréquence ? (*par mois ou par an*) :

**B. La dernière sortie pêche**

9. De quand **date** ta dernière sortie pêche ? (*remplir tableau de pêche*)
10. Qu'as-tu pêché ? (*remplir tableau de pêche et éventuellement donner ces suggestions pour qu'il n'y ait pas d'oubli*)
  - quelles **espèces** de poissons, rori, poulpes, bénitiers, trochas... ;
  - en quelle **quantité**,
  - avec quelle **technique** : collecte à la main, patia, fusil, filet, épervier, nasse, parc, canne, traîne...
  - dans quelle zone (carte : code P1)
  - comment t'es-tu **déplacé** sur le lieu de pêche : à pied dans l'eau, palmes masque tuba, embarcation : à moteur/à rame ?
11. Sur la carte, si tu reconnais des **repères**, peux-tu noter leur nom ? (karena, hoa, motu...)

**C. La pêche précédente...**

12. A **quand** remonte la pêche précédente ? (*remplir tableau de pêche*)
13. Peux-tu **décrire** également cette précédente pêche ? (*tableau de pêche*)

14. Est-ce que cette pêche était : **comme d'habitude** // inhabituelle  
-> préciser **en quoi** : pour les espèces // quantités // zones de de pêche

et pour quelles **raisons** :

#### D. Les mois précédents...

15. En **juillet**, combien de fois es-tu allé pêcher ? (*par semaine ou dans le mois*) \_\_\_\_\_

16. Et au mois de **juin** ? \_\_\_\_\_

17. Peux-tu décrire ce que tu avais pêché, tu te souviens ? (*tableau de pêche*)

#### E. Tout au long de l'année...

18. Est-ce que ta pêche est **régulière** tout au long de l'année comme celle de ces derniers mois ?

- oui // non -> qu'est-ce qui change le plus ?

- les **espèces** : quelles esp. quand ?

- la **fréquence** : avec les fêtes Noël, *tiurai*, autre ? // la saison // la météo -> Préciser :

- la **quantité** : d'habitude je pêche Plus // Moins. Pourquoi ?

19. **Globalement** dans l'année, peux-tu décrire ta pêche (*tableau « en général »*).

20. Si tu utilises un **bateau**, t'appartient-il ? oui // non

Est-il tout le temps disponible ? oui // non

(Carte : code B pour **zone d'amarrage** du bateau)

21. En général tu pêches : tout seul // en famille // avec des amis ou collègues // autre :

22. De manière générale, **quand** choisis-tu de partir à la pêche ?

- en fonction des **commandes** // du passage d'une **goélette** // d'un **avion**

- en fonction des **fêtes**/événements

- ça dépend des **saisons** pour pêcher pour telles espèces, préciser :

- ça dépend des **autorisations** (trochas, langoustes...), préciser :

- quand j'ai **besoin** de subvenir à la **famille** // besoin **d'argent**

- en fonction de la saison // lune // marée - autre :

23. Quand tu pars pêcher, comment perçois-tu une concession ou **ferme** perlière ?



- tu évites // tu pêches parfois // souvent autour ? desquelles ? (carte : code F) Pourquoi ? \_\_\_\_\_

24. Est-ce que tu **exportes** les produits de ta pêche vers d'autres îles ? oui // non

- si oui, vers quelle(s) **île(s)** : \_\_\_\_\_

- quelles sont les **espèces** que tu exportes ? \_\_\_\_\_

A qui sont destinés les produits que tu exportes :

- Famille ou amis pour leur consommation personnelle // pour revendre en bord de route

- A un marché // grande surface // hôtel -> préciser :

- autre :

25. Si tu pêches pour la vente, quels **revenus** cela t'apporte ?

(par pêche, par mois, par an... obtenir estimation annuelle)

#### F. Pêche et ciguatéra...

26. Est-ce qu'il y a de la ciguatéra à **Takaroa** ? oui // non

27. As-tu eu personnellement ou parmi tes proches, une expérience d'**intoxication** ? oui // non

28. Si oui, peux-tu donner pour chaque cas : l'espèce en cause, sa taille, et où elle avait été pêchée

*Tableau ciguatera :*

<b>Intoxication</b>	Cas 1	Cas 2	Cas 3
<b>Espèce</b>			
<b>Taille</b>			
<b>Inscrire zone sur carte</b>	PC1	PC2	PC3

29. Y a-t-il dans le lagon des **zones connues** où il faut éviter de pêcher à cause de la ciguatéra ?

Indiquer ces zones sur la carte (code : C1, C2, C3...) oui // non

30. En général, y a-t-il des zones où tu ne vas **pas pêcher** ? (carte code : PN1, PN2...) oui // non

31. De manière générale pour **les habitants** de Takaroa, y a-t-il des zones où **personne** ne va pêcher ? (carte code : PNT1, PNT2..) oui // non -> préciser :

#### G. Facultatif...

32. De manière générale, **comment choisis-tu** ton site de pêche ? Indiquer les zones sur la carte.
- site **proche** de la **maison** (code SPM) // ou du **bateau** (code SPB)
  - site près d'une concession ou **ferme** perli (code SPF) // près d'autre chose : quoi ? (code SP\_)
  - site choisi selon le type d'espèce visée (code SE) : quel site pour quelles espèces ?
  - site à abondance de poissons etc (code SA)
  - site choisi si météo : calme // vent // pluie // courant - autre :
33. Y a-t-il de la pêche dans le lagon vert // mare à kopara // hoa // autre :
34. Dans le lagon de Takaroa, as-tu remarqué des **zones importantes** (fonctionnelles) pour :
- la reproduction-frai (carte code FR1 pour Fonction Repro)
  - enfouissement des œufs (code FO1) // alevinage-présence de juvéniles (code FJ1)
  - autre (préciser codes) :
35. De manière générale pour les habitants de Takaroa, y a-t-il des **zones particulières** pour
- leur valeur culturelle (code VC1,...). Préciser :
  - leur valeur spirituelle (code VS1,...). Préciser : - autre :
36. Penses-tu à d'autres informations importantes à partager, sur la pêche, qu'on aurait oubliées ?  
D'autres noms de lieux - repères à placer sur la carte ?

### Exemples d'enquêtes menées à Raivavae







**Appendix 4.** Complete legend of the geomorphological and benthic habitat map of Gambier lagoon.

CodeH	Level1	Code_L1	Level2	Code_L2	Level3	Code_L3	Benthos	Code_Benth	Stock
0	Lagon Profond	0	Lagon Profond	0	Lagon Profond	0		0	0
1	Seuil	1	Terrasse	26			Sable	5	1
2	Seuil	1	Terrasse	26			Dalle	3	1
3	Seuil	1	Platier	22			Corail	1	1
4	Seuil	1	Platier	22			Mixte	6	1
5	Seuil	1	Pente	17			Corail	1	1
6	Seuil	1	Bassin avec constructions	2			Mixte	6	1
10	Frangeant	2	Terrasse	26			Sable	5	0
11	Frangeant	2	Terrasse avec constructions	27			Corail	1	0
12	Frangeant	2	Terrasse avec constructions	27			Mixte	6	0
13	Frangeant	2	Terrasse reticulée	31			Corail	1	0
14	Frangeant	2	Platier protégé	24			Corail	1	0
15	Frangeant	2	Platier exposé	23			Corail	1	0
16	Frangeant	2	Platier	22			Dalle	3	0
17	Frangeant	2	Pente	17			Sable	5	0
18	Frangeant	2	Pente	17			Corail	1	0
19	Frangeant	2	Pente	17			Mixte	6	0
20	Frangeant	2	Pente reticulee	21			Mixte	6	0
21	Frangeant	2	Pente	17	Communaute Fungia	26	Corail	1	1
22	Frangeant	2	Bassin	1			Sable	5	0
23	Frangeant	2	Bassin avec constructions	2			Mixte	6	0
24	Frangeant	2	Bassin reticule	3			Mixte	6	0
25	Frangeant	2	Lagon enclave	8			Sable	5	0
26	Frangeant	2	Lagon enclave avec constructions	9			Mixte	6	0
27	Frangeant	2	Lagon semi-ouvert	12			Sable	5	0

28	Frangeant	2	Terrasse profonde	28			Sable	5	0
40	Massif de frangeant	3	Platier	22			Corail	1	0
50	Barrière	4	Terrasse	26			Sable	5	0
51	Barrière	4	Terrasse avec constructions	27			Mixte	6	0
52	Barrière	4	Platier	22			Corail	1	0
53	Barrière	4	Platier	22			Corail-Algues	2	0
54	Barrière	4	Platier	22			Mixte	6	0
55	Barrière	4	Platier	22			Détritique	4	0
56	Barrière	4	Platier	22			Détritique-dalle	5	0
57	Barrière	4	Platier	22			Dalle	3	0
58	Barrière	4	Eperons intertidaux	4	Eperons	1	Corail	1	0
59	Barrière	4	Eperons subtidaux	5	Sillons	2	Sable	5	0
60	Barrière	4	Eperons subtidaux	5	Eperons	1	Corail	1	0
61	Barrière	4	Eperons subtidaux	5	Eperons-sillons courts	4	Corail	1	0
62	Barrière	4	Eperons subtidaux	5	Eperons compacts	1	Corail	1	0
63	Barrière	4	Eperons subtidaux	5	Eperons-sillons high energy	5	Corail	1	0
64	Barrière	4	Eperons subtidaux	5	Eperons-sillons high energy de motu	5	Corail	1	0
65	Barrière	4	Eperons subtidaux	5	Eperons-sillons low energy	6	Corail	1	0
66	Barrière	4	Pente externe	19	Contrefort	8	Corail	1	0
67	Barrière	4	Pente externe	19	Vallons	9	Sable	5	0
68	Barrière	4	Pente externe	19	Platte-forme rainurée	10	Corail	1	0
69	Barrière	4	Massif subtidal	14			Corail	1	0
70	Barrière	4	Passé peu profonde	15			Corail	1	0
71	Barrière	4	Terrasse profonde avec constructions	29			Mixte	6	0

72	Barrière	4	Terrasse profonde avec eperons	30			Corail	1	0
80	Lagon	4	Lagon profond	9	Fond sédimentaire	11	Sable	5	0
81	Lagon	4	Lagon profond	9	Texture homogène	12	Corail	1	0
82	Lagon	4	Lagon profond	9	Texture rainurée	13	Corail	1	0
83	Lagon	4	Lagon profond	9	Communauté mixte	14	Mixte	6	0
84	Lagon	4	Lagon profond réticulé	10	Communauté mixte Est alvéolaire	15	Mixte	6	0
85	Lagon	4	Lagon profond réticulé	10	Communauté mixte NW patés	16	Mixte	6	0
86	Lagon	4	Lagon profond réticulé	10	Communauté mixte SW pates très dense	17	Mixte	6	0
87	Lagon	4	Lagon réticulé	7	Communauté mixte W pates très dense	18	Mixte	6	0
88	Lagon	4	Lagon réticulé	11	Communauté mixte Centre-Est pates et alvéole	19	Mixte	6	0
89	Lagon	4	Lagon réticulé	11	Communaute NC	20	Mixte	6	0
90	Lagon	4	Lagon réticulé	11	Communaute NCE	21	Mixte	6	0
91	Lagon	4	Lagon réticulé	11	Communaute CW	22	Mixte	6	0
92	Lagon	4	Lagon réticulé	11	Fond sédimentaire	11	Sable	5	0
93	Lagon	4	Lagon	6	dune sableuses	23	Sable	5	0
94	Lagon	4	Pente interne avec constructions	20	Pates disperses densité moyenne	24	Mixte	6	0
95	Lagon	4	Pente interne avec constructions	20	Pates disperses densité faible	25	Sable	5	0
96	Lagon	4	Passe profonde avec constructions	16			Mixte	6	0
97	Lagon	4	Lagon réticulé	11	Communaute Fungia	26	Corail	1	1

110	Massif	5	Massif profond	13	Domes coralliens	27	Corail	1	0
111	Massif	5	Massif profond	13			Inconnu	100	0
112	Massif	5	Platier subtidal	25			Mixte	6	1
113	Massif	5	Platier subtidal	25			Corail	1	0
114	Massif	5	Terrasse avec constructions	27			Mixte	6	0
115	Massif	5	Platier	22			Corail	1	0
116	Massif	5	Pente et massif reticulé isolé	18			Mixte-corallien	11	0
117	Massif	5	Pente	17			Sable	5	0
118	Massif	5	Terrasse profonde	28			Sable, dalle, corail	12	0
1000	Land	1000	Land	1000	Land	1000	Land	1000	0



## Sensitivity of marine spatial planning solutions to Marxan parameterization when ciguatera poisoning modulates fishing opportunity costs

*This contribution is “in preparation” and intended to be submitted to a newspaper in letter format.*

**Key-words:** systematic conservation planning; boundary length modifier; penalty factor; conservation objectives; sensitivity analysis.

### Introduction

Conservation plans often have to balance biodiversity protection objectives with local human activities that, ideally, should be impacted as little as possible to warrant compliance. Technically, systematic conservation planning (SCP) scientists have proposed optimization approaches and tools that compute from spatially-explicit data a portfolio of solutions that would maximize the fulfilment of preselected quantitative conservation objectives while minimizing the socio-economic costs to local stakeholders and communities. There are now a number of toolboxes that can accomplish these trade-offs. The most popular software is Marxan and its derivatives. Marxan has been used worldwide in terrestrial, riverine, coastal and oceanic environments, from the high latitudes to the tropics. It has been instrumental in designing reserve networks, some that could reach implementation stages, such as in the UK, Scotland or Australia (Peckett, 2015). Once a territory has been segmented in spatial planning units (PUs) and each PU has values of objective feature and cost, Marxan identifies through a simulated annealing procedure a best solution in term of objective *vs* cost optimization. This best solution is a binary view that shows for each PU if it is part or not of the solution. Marxan also provides quantitative selection-frequency maps that shows how frequently the PUs have been selected for a number of executions of the same optimization problem.

In Pacific Ocean tropical island coastal environment, Marxan has often been used to provide conservation solutions that would protect marine species and habitats, while minimizing the cost of conservation to local fishers (André et al., 2021a). In other words, the basic scheme is that Marxan selected preferentially reserves where fishers would fish the less, hence minimizing fishing opportunity costs (Naidoo et al. 2004). In practice, both objectives and opportunity costs have been instantiated in a myriad of different forms using a variety of scenarios that could also include complex objectives, (incl. for instance ecological processes), and cost functions. The simplest scenario would be to use habitat maps and an objective of representation for all habitats (e.g. 20% of the surface area of each habitats) in the conservation network, while the costs to minimize would be the loss of high yield fishing grounds. Then, from this simple scheme, one can imagine and develop much more complex scenarios. Complexity can be added for the objectives, for the costs, and for both. For instance, it is often necessary to take into account other activities and values than just those related to fishing,



penalty factor). They can also largely influence the results spatially speaking. Exploring how these options influence the results are part of the process of running a Marxan analysis, although this is not necessarily trivial. It was noted in a recent review of SCP in the Pacific Ocean islands that sensitivity analysis, and discussion on the effects of parameterization should be much more systematic in SCP literature (André et al. 2021a) as they tend to disappear from more recently published papers that focus on presenting increasingly complex scenarios. However these analysis should be transparent as they are necessary to fully grasp how robust the results are.

Among the Marxan parameters, boundary costs and species (or conservation) penalties are important factors that can drastically change solutions by putting higher constraints, or relaxing them, relative to the compacity of network and reaching the targets of representation of features. The boundary cost constraint or boundary length modifier (BLM) forces a reserve to be as compact as possible, selecting in priority PUs that are connected so that the total boundary length of the network decreases. When BLM is set at 0, it does not constrains the site-selection process so the solution found minimises the cost, whereas when BLM is positive, it constrains the site-selection process so the solution cost increases as a result, to allow a trade-off between cost and compacity. BLM is used for a scenario to weight the boundary cost *versus* the user defined cost (here, costPU) and the scale of both must have the same range. Here, we explored scenarios for BLM=0, and for an optimal BLM that is searched and defined following the procedure described by Ardron et al. (2010) and Stewart and Possingham (2005).

When running Marxan, one will frequently face the situation that not all the biodiversity quantitative conservation targets can be met for a given cost function. Indeed, due to high costs (such as when using a BLM different from zero), solutions may be more difficult to find, more costly, or may even not exist. Results are reported in the form of 'missing values' that can be detailed per objective for each run, or just a mention that for a number of runs, not all targets could be met. In the case of missing values, a practitioner can face two options. First, he is not too concerned if not all targets are precisely met, and he may relax the constraint on the initial targets or require that targets be met at least at a certain percentage (target reached at 90%, 95% of other). Second, he absolutely needs the target to be respected although in this case, the cost of the solutions will necessarily rise. The species penalty factor, or SPF, is one way to address the situation, in the first case, by lowering it, and in the second case, by increasing it. The SPF should be set at a higher value the more important the conservation feature is. SPF can be set differently for each conservation objective.

Because conservation solutions can be significantly affected by small parameter modifications, and in agreement with the recommendations made by André et al. (2021a) who encouraged sensitivity analysis, we aim at providing here additional results on the sensitivity of marine spatial planning solutions to Marxan parameterization when ciguatera poisoning is used to modulate fishing opportunity costs. Specifically, we investigate the effects that can be attributed to Marxan and its users, namely through the use of two key parameters: the boundary cost and the species penalty factors. We also extend the number of scenarios with more variations of the ciguatera weighting factor  $a$ , and with two different habitat maps used to set conservation targets (here fixed at 20% of each habitat). Our objective is therefore to reinforce, in particular for managers, the demonstration of the interest of using ciguatera data

to limit opportunity costs to fishers by showing a portfolio of different conservation plan results, and their different effectiveness compared to plans without ciguatera.

## Material and methods

The study site is Raivavae Island, in French Polynesia. The lagoon surface area was divided into 83 PUs of hexagonal shape.

Data collection is described in detail in André et al. (2021b). In short, fishers map-based interviews performed in November 2019 allowed to map fishing grounds and level of catches. Using GIS software, these data were spatially refined by fishing gears, by the limitations of the types of habitats where they can be used, and aggregated by PUs. The results produce an index of catch per fishing area (CaPUs in Equation 1). Further, the same fishers also described their knowledge on ciguatera risk, due to actual poisoning or suspicion of risk of poisoning. Ciguatera was mapped as an index of risk per PU (CiPUs in equation 1). The cost function was implemented as in the Equation 1 to account for both fishing and ciguatera according to the weight factor  $a$ . Here,  $a$  ranged from 0 to 1, by increment of 0.25.

Two different pre-existing maps were used here to define conservation objectives and quantitative targets. Habitat types were mapped using satellite imagery and inform on respectively the geomorphology of the coral reef formations. Map H1, follows the classification scheme described in Andréfouët et al. (2006), while Map H2 follows the distributions of habitats where giant clam densities vary, following Andréfouët et al. (2009). Here, we stated that 20% of the area covered by each habitat should be protected. The two maps, H1 and H2 included respectively 14 and 20 habitat classes.

One constraint when using Marxan is that the tuning of the different parameters have to be done each time a major component of the analysis is changed, would it be by locking-in or locking-out some PU in the solution, change the opportunity (or other) costs, modify the conservation feature maps, conservation targets or apply a BLM factor that itself influence the costs. Practically, when using a BLM, it is therefore a good practice to calibrate SPF values to reach an acceptable number of non-missing values (Fischer et al. 2013). Here, for 1000 runs, we set this limit at 900 when applying the same SPF to all objectives. Hence, a missing value flag highlighting one, or more, missed target for un given run would be tolerated at the level of 10% of the runs. This means that among the portfolio of solutions explored by the 1000 runs, at least 900 runs should find solutions that achieve all targets and a maximum of 100 runs had missing values among the targeted objectives. In practice, this percentage is fairly high and we did not consider that the conservation target had to be strictly met.

We set the limit of 1000 runs due to computation time (about 6 minutes on a PC laptop Core i5; 16,384 MB RAM). Although we acknowledge that more runs could explore more solutions beyond the local minimum found via simulated annealing, and enhance the missing value criteria, the solutions were already stable (spatially) after 1000 runs in all cases due also to the low complexity of our problem.

In André et al. (2021b), Marxan was used with BLM=0 and SPF was identical for all features and set the same for all scenarios according to the most demanding scenario after an empirical

tuning phase (Fischer et al., 2013). Here, we aim to fully explore the influence of these two parameters. Sixteen scenarios were computed by using 2 habitats maps, 4 increments of parameter  $a$ , and 2 options for BLM (set to zero or optimal) with their respective ranges of tuned SPF (Table 1).

Considering that the raw cost values incurred by each scenario cannot be meaningfully directly compared due to their different nature and range, to measure the benefits of using ciguatera, we applied a similar process as in André et al. (2021b), by computing a ratio of effectiveness:

$$Eff_a = \sum_{i=1}^{\#bestPU(a)} Cost_{a=1}(PU_i) / \sum_{j=1}^{\#bestPU(a=1)} Cost_{a=1}(PU_j) \quad (\text{Equation } 2)$$

With  $Cost_{a=1}(PU_i)$  is the cost of a PU when the combined fishing and ciguatera cost function is computed with  $a=1$  in Equation 1.  $i$  the number of PU selected for the best solution achieved with weight  $a$ , and  $j$  the number of PU in the best solution achieved with  $a=1$ . With this formulation,  $Eff_a$  is the relative increase of costs between scenario with and without ciguatera, taking cost with  $a = 1$  as “true cost” of PUs. If computed for  $a=1$ ,  $Eff_a=1$  (or 100% if expressed in percent).

In theory, Equation 2 could be computed for all combinations of scenarios, but meaningful comparisons are for scenarios with similar habitat maps and BLM options.

## Results and Discussion

Parameters and results from all 16 scenarios are synthesized in Table 1.

The effectiveness  $Eff_a$  between comparable scenarios are presented in Table 2.

Table 1: Summary of the main results for the 16 scenarios. Raw cost is the best solution cost as defined from Equation 1; #PU is the number of PU in the best solution; BL (in meters) is the summed boundary length of the network solution; 0MV is the number of runs that had zero missing value (more than 900 out of the 1000 runs). The last column (#PU/0MV) can be seen an indicator of effectiveness of the network. The lower the value, the better, suggesting a lower number of PUs for a higher 0MV number.

Scenario	Map	$a$	BLM	SPF	Raw cost	#PU	BL (m.)	0MV	#PU/0MV
1	H1	1	0	20	6.22	15	29543	906	0.0166
2	H1	1	0.003	5	10.28	23	11003	1000	0.0230
3	H1	0.5	0	20	5.45	15	29802	917	0.0164
4	H1	0.5	0.001	5	8.79	23	10699	998	0.0230
5	H1	0.25	0	20	4.53	15	33338	962	0.0156
6	H1	0.25	0.001	5	7.71	23	10699	999	0.0230
7	H1	0	0	200	2.91	17	33852	994	0.0171
8	H1	0	0.001	5	6.10	23	11500	964	0.0239

9	H2	1	0	20	5.88	15	27162	937	0.0160
10	H2	1	0.001	5	7.21	20	12844	978	0.0204
11	H2	0.5	0	20	5.04	15	29319	979	0.0153
12	H2	0.5	0.001	5	6.99	20	13104	909	0.0220
13	H2	0.25	0	20	4.27	15	28610	963	0.0156
14	H2	0.25	0.001	10	6.23	21	14325	960	0.0219
15	H2	0	0	20	2.64	17	37313	926	0.0184
16	H2	0	0.001	10	5.21	22	13235	999	0.0220

Table 2: Sensitivity analysis results with  $Eff_i$  as a measure of effectiveness expressing (in percent) the relative increase of costs between scenario with ( $a>0$ ) and without ciguatera ( $a=0$ ). For instance, it is 48% more expensive to not use ciguatera data ( $a=0$ ) comparing to use ciguatera and fishing data at the same level ( $a=1$ )

Scenario	$Eff_a=1$	$Eff_a=0.5$	$Eff_a=0.25$	$Eff_a=0$
H1, BLM=0	100%	101%	112%	148%
H1, BLM=optimal	100%	99%	99%	99%
H2, BLM=0	100%	102%	110%	150%
H2, BLM=optimal	100%	112%	109%	134%

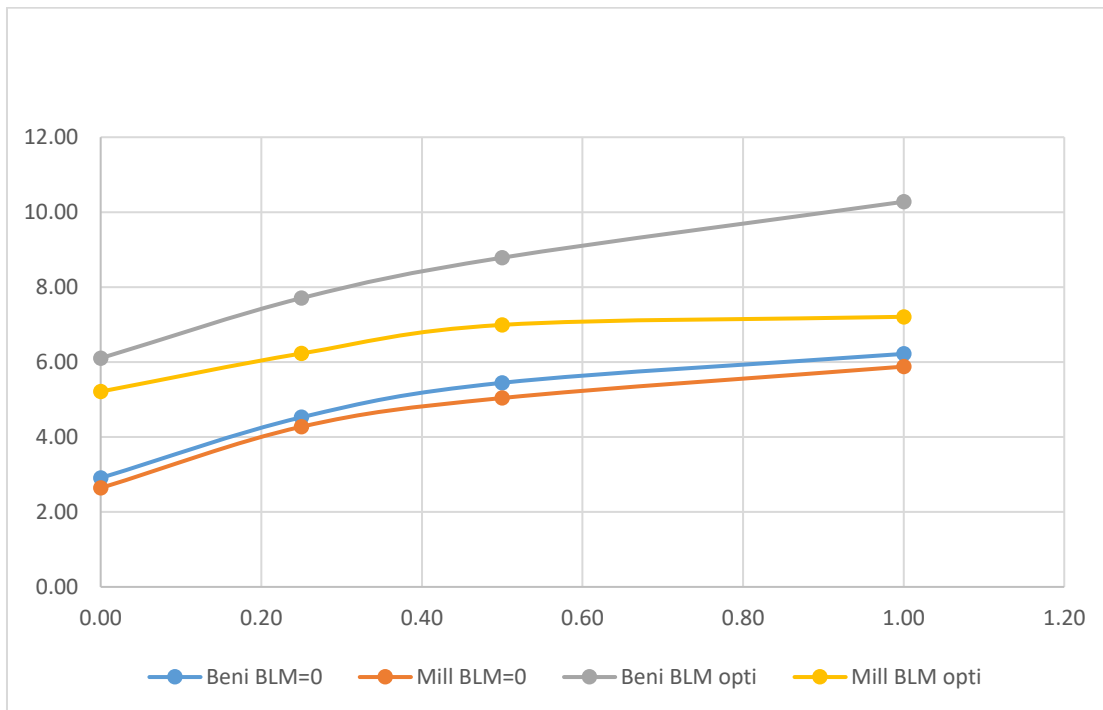


Figure 1: Curves of the raw cost for each habitat map, and level of BLM.

[ Figure 2: Frequency solutions for 16 scenarios ]

The sensitivity analyses performed here, with additional scenarios aiming at evaluating first the effects in Marxan parameterization confirms the benefits of using ciguatera to decrease the fisher opportunity costs in potential conservation plans (Table 2). The initial conclusions from André et al. (2021) remain valid. However some options have stronger influences than other. For instance, when BLM is used with map H1, there is little benefit of using ciguatera. This behaviour is not apparent with map H2 because the spatial distribution of some habitats that need to be included at 20% prevent the identification of very compact solution (Fig. 2). As expected the ratio #PU/MV (Table 1) is the highest when using a BLM factor, which reflects the fact that a higher number of PUs is required to reach the same target. In conjunction, scenarios with no ciguatera ( $a=0$ ) shows the highest #PU/MV of all BLM=0 scenario for both H1 and H2. In other cases ( $a>0$ ) this ratio does not change much for a given habitat map. The use of two different maps however shows an effect with lower #PU/MV for H2 than H1 when an optimal BLM is used. This can be explained by the fact that both maps reflect the distribution of geomorphological entities, albeit with slightly different representation and levels of details that prevent the BLM option to be as effective when dealing with different habitat maps and habitat spatial structures. Different habitat maps, focusing on relevant benthic features or bathymetry could also bring more variations, as shown in other Pacific Island conservation planning studies (Hamel et al., 2013; and see Gairin & Andréfouët, 2020).

Generally, a large range of options and solutions may not make easy the appropriation of the results and further decision process for managers. It is easy to be overwhelmed by too many options on the menu. Complexity and high number of solutions can make SCP results more difficult to include in a decision process, because managers will have to decide on the reference scenario. Nevertheless, we believe this transparency and a representative suite of results is better than presenting an arbitrary narrow number of options. Here, the range of results presented in Table 2 should convince managers and stakeholders that, in the case of islands or locations where ciguatera is a significant problem, it can be ultimately used to the benefits of fishers. It is a valuable input, certainly worth investing into in terms of data collection in many sites. Besides the obvious benefits of updating knowledge on the ciguatera status itself which can have implications for human population health management, the fishers knowledge collected and integrated in spatial format as in André et al. (2021b) or following a different protocol, can serve coastal management as well.

Additional tests and scenarios could be obviously included in an extended sensitivity analysis. Additional tests could take into account the size and types of PUs (Van Wynsberge et al., 2015) including irregularly shaped PUs. Finally, while Marxan was used here, other planning software could be used with the same input data set, such as ConsNET (Ciarleglio et al., 2009), C-Plan (Pressey et al., 2009) or Zonation (Moilanen et al., 2009), and with their own sensitivity analyses to their input parameters. It also could be possible, for Raivavae, to run scenario only for specific fishing activities (giant clam *vs* finfish fishing). In the future, we will focus more on testing different management scenarios for other French Polynesia islands, still with fishing modulated by ciguatera cost functions, in different French Polynesia islands.

Finally, besides the confirmation of the benefit of using a ciguatera data layer, this study re-emphasizes the need and value of providing thorough documentation of SCP scenarios, which tends to disappear from published papers. Sensitivity analyses are not luxury, they are actually

a significant part of any SCP work and the foundation of robust conclusions, yet, they may be missing, and this prevents for users to fully grasp the relevance and representativity of the results, and therefore their generalization.

## References

- André L. V., Van Wynsberge, S., Chinain, M., Gatti, C. M.i, Dempsey, Al., Andréfouët, S., 2021a. A framework for mapping local knowledge on ciguatera and artisanal fisheries to inform systematic conservation planning. *ICES Journal of Marine Science*. <https://doi.org/10.1093/icesjms/fsab016>.
- André, L.V., Van Wynsberge, S., Chinain, M., Andréfouët, S., 2021b. An appraisal of systematic conservation planning for Pacific Ocean Tropical Islands coastal environments. *Marine Pollution bulletin*, 165: 20p. DOI 10.1016/j.marpolbul.2021.112131
- Andréfouët, S., Muller-Karger, F. E., Robinson, J. A., Kranenburg, C., Torres-Pulliza, D., Spraggins, S. A., and Murch, B. 2006. Global assessment of modern coral reef extent and diversity for regional science and management applications: a view from space. *In Proceedings of 10th International Coral Reef Symposium*, pp. 1732–1745.
- Chinain, M., Darius, H. T., Ung, A., Fouc, M. T., Revel, T., Cruchet, P., Pauillac, S., *et al.* 2010. Ciguatera risk management in French Polynesia: The case study of Raivavae Island (Australes Archipelago). *Toxicon*, 56: 674–690.
- Hamel, M.A., Andréfouët, S., Pressey, R.L., 2013. Compromises between international habitat conservation guidelines and small-scale fisheries in Pacific island countries. *Conserv. Lett.* 6, 46–57. <https://doi.org/10.1111/j.1755-263X.2012.00285.x>
- Ciarleglio M. J., Wesley Barnes Sahotra Sarkar, 2009. ConsNet: new software for the selection of conservation area networks with spatial and multi- criteria analyses. *Ecography*. <https://doi.org/10.1111/j.1600-0587.2008.05721.x>
- Moilanen, A., Kujala, H., Leathwick, J.R. 2009. The zonation framework and software for conservation prioritization. *In* A. Moilanen, K. Wilson, H.P. Possingham (Eds.), *Spatial Conservation Prioritization: Quantitative Methods & Computational Tools*, Oxford University Press, pp. 196-210
- Pressey R.L., Watts, M.E., Barrett, T.W. and Ridges, M.J. 2009. The C-Plan Conservation Planning System: Origins, Applications, and Possible Futures (Chapter 16) *In* A. Moilanen, K. Wilson, H.P. Possingham (Eds.), *Spatial Conservation Prioritization: Quantitative Methods & Computational Tools*, Oxford University Press.



PHOTO CREDIT:

All photos are from Serge Andréfouët apart from General introduction cover, which is from Vetea Liao, and the Chapter 3 cover, from Laure André.

**Cover:** A pearl oyster farm and its concessions (lines of buoys) in Mangareva lagoon.

**Title page:** A pearl oyster farm near remarkable coral assemblage, Mangareva lagoon

**General introduction cover:** A selection of black pearls from Mangareva

**Chapter 1 cover:** Aerial view of an atoll rim in the Tuamotu Archipelago (Raroia)

**Chapter 2 cover:** Back from fishing in Raivavae lagoon

**Chapter 3 cover:** In search of suitable habitats for oyster restocking in Takaroa Atoll

**Chapter 4 cover:** Fishing at dusk

**Chapter 5 cover:** Occupation of the lagoon space by pearl oyster farms in Gatavake bay, Mangareva.

**General Discussion cover:** A fisher using a *poti marara* vessel for FAD fishing, in Takaroa



## Abstract

Implementing conservation and sustainable resource management actions is crucial in the context of the current environmental crisis. In the field of conservation science, **Systematic Conservation Planning** (SCP) identifies areas that optimally meet the trade-off between conservation objectives and socio-economic costs to be minimized (i.e. opportunity cost: what could have been gained but become foregone opportunities when a reserve is implemented). Guided by spatialized and quantified data, SCP provides decision support to managers in a transparent manner. However, our state-of-the-art assessment of the marine SCP use in the Pacific Ocean Tropical Islands (POTIs) indicates a general tendency to SCP exercises disconnected from the concrete needs of managers. We have thus identified several orphaned themes that seem crucial for management of POTIs coastal spaces.

We therefore look at how to better integrate these identified gaps into spatial planning of island lagoons, particularly in French Polynesia. We break this down into four lines of research: 1) how to integrate **ciguatera** into SCP (a poisoning due to the consumption of certain seafood products, highly prevalent in the Pacific) and what is the impact of ciguatera risk areas for reef fisheries management? 2) How to respond to the spatial management needs of the **black pearl farming** at its various stages? 3) How could SCP make useful contributions to or help optimize **traditional marine resource management** (*rāhu*)? 4) How to plan for activity **diversification** in a given lagoon and measure the impacts associated to the different spatial configurations? Through four studies conducted on three islands in French Polynesia (Takaroa, Raivavae, Mangareva), this work demonstrates the SCP contributions made in response to local problems and stakeholder needs for optimal management of the coastal space.

This study produces original data adapted to the studied contexts and provides a new methodology for integrating, for the first time, ciguatera into spatial analysis to reduce the opportunity cost for fishers. In addition, this study illustrates how SCP can be mobilized to optimize a traditional scheme of fisheries spatial management integrating opportunity cost and ciguatera. Lastly, this method allows identifying suitable areas for restocking oysters and evaluates how to reallocate lagoon space in case of diversification activities. Although these applications are guided by site-specific needs and data, the topics addressed can be generalized to many POTIs. Finally, this thesis demonstrates that, in an international and regional context where commitments for conservation and sustainable management are multiplying, SCP constitutes a valuable tool in bridging the research-implementation gap by translating, in conjunction with managers, international ambitions into adapted local responses.