Coral reefs ecosystem services under global environmental change; Interdisciplinary approaches to guide science and action

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UNIVERSITE BRETAGNE LOIRE / SCIENCES DE LA MER ET DU LITTORAL

Thèse préparée à l'Université de Bretagne Occidentale

pour obtenir le diplôme de DOCTEUR délivré de façon partagée par L'Université de Bretagne Occidentale et l'Université de Bretagne Loire

Spécialité : Sciences Économiques

École Doctorale Sciences de la Mer et du Littoral

présentée par

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Préparée à l'UMR 6308 AMURE

Coral reefs ecosystem services under global environmental change

Interdisciplinary approaches to guide science and action

Thèse soutenue le 11 janvier 2018
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A ma famille

« Parfois je lève la tête et regarde mon frère l'Océan avec amitié: il feint l'infini, mais je sais que lui aussi se heurte partout à ses limites, et voilà pourquoi, sans doute, tout ce tumulte, tout ce fracas. »

- Romain Gary, La Promesse de l’aube

"If we need to, we can lower the temperature dramatically just by switching from Fahrenheit to Celsius."

- Jimmy Kimmel

Abstract

Global environmental change (GEC), including ocean acidification, climate change, and other environmental stressors driven by human activities threaten coastal and marine systems and the people who depend upon them. The scientific community, including the IPCC, has undertaken global level assessments to understand the vulnerability of coastal areas to climate change to inform investment and to prioritize action against its effects. Often these studies are highly complicated and include hidden feedbacks and endogeneity. This research seeks to improve and harmonize global level assessments, by focusing on the role of underlying factors and assumptions, to better identify and address the impact of drivers associated with GEC, especially climate change and ocean acidification. This global-level approach can help target locations where in-depth local level analyses need to be conducted.

Looking specifically at coral reefs, a critical review of the literature reveals that ocean acidification and warming interact and may affect a multitude of physiological and ecological processes in complex ways. These complex interactions may mean that the negative effects on coral reef ecosystems will happen sooner and be more severe than previously thought. Yet, most research on the effects of global change on coral reefs focus on one or few stressors, pathways or outcomes. Our findings show that a regionally targeted strategy of research should addresses this complexity and provides more realistic projections about coral reef impacts in the face of global environmental change.

Designing policies to offset potential harm to coral reef ecosystems and people requires a better understanding of where GEC could cause the most severe impacts to reef ecosystems and people. To identify where people are at risk and where more science is needed, we map global-scale indicators of physical, ecological and human factors to understand how human dependence on coral reef ecosystems will be affected by globally-driven threats to corals that are expected in a high-CO_2 world.

To understand the extent of potential actions to manage coral reefs under GEC, we revise a typology of management strategies, first developed by Gattuso et al. (2015) that could serve managers and decision makers prioritizing strategies to deal with the impacts of GEC on reefs and people. A systematic literature review reveals how science is currently responding to the challenge posed by GEC on coral reefs. The review also identifies gaps in research. The management strategies we examine tend focus on the different components of vulnerability: ecological vulnerability or social vulnerability.

Finally, we attempt to operationalize an overlooked component of vulnerability assessments, ecological adaptive capacity, to serve as a tool for prioritizing action. Building on the frameworks of socio-ecological vulnerability assessments, resilience-based management, and ecological limits, we design a conceptual framework of ecological adaptive capacity, list potential indicators and create a decision framework to operationalize this concept. By measuring the capacity of coral reefs to maintain their functions and services under GEC, ecological adaptive capacity can help managers and decision-makers prioritize local action.

Building on the existing literature and datasets, this manuscript seeks to improve theories and methodologies to evaluate impacts, vulnerability and adaptation to global environmental change. Interdisciplinary approaches are used to analyze and map the effects of GEC on coral reefs social-ecological systems. This thesis analyses the emergence of a scientific field on solutions to global environmental change for coral reef socio-ecological systems and develops frameworks and tools to guide action in the context of global environmental change.

Keywords: global environmental change, climate change, ocean acidification, coral reefs, ecosystem services, multiple stressors, vulnerability, resilience, adaptive management, global assessments, adaptation

Table of Content

Foreword

Most of this manuscript is written in English. The introduction and discussion are written in French. The foreword, acknowledgments, abbreviations and short abstract are both written in French and English. This manuscript is based on research articles published or produced for publication in international peer reviewed journals. The chapters that correspond to journal articles are listed below and are available online. The last chapter, chapter 5, is work in progress that will continue in a project starting after the PhD. Some supplementary materials to the research articles were included in the different chapters to ease the reading of the manuscript. Materials developed in the PhD to complement the different chapters can be found in annexes. All the references are found in a separate section at the end of the manuscript.

-Chapter 2 has been published in the journal *Frontiers in Marine Science* as:
Pendleton, L., Hoegh-Guldberg, O., Langdon, C., Comte, A. (2016). Multiple Stressors and Ecological Complexity Require A New Approach to Coral Reef Research. Frontiers in Marine Science. doi: 10.3389/fmars.2016.00036
-Chapter 3 has been published in the journal *Plos One* as:
Pendleton, L.H., Comte, A., Langdon, C., Ekstrom, J.A., Cooley, S.R., Suatoni, L. Beck, M.W., Brander, L.M, Burke, L., Cinner, J.E., Doherty, C., Edwards, P.E.T, Gledhill, D., Jiang, L., van Hooidonk, R.J., Teh, L., Waldbusser, G.G., Ritter, J. (2016). Coral Reefs and People in a High-CO_2 World: Where Can Science Make a Difference to People? *Plos One*. doi:10.1371/journal.pone.0164699
-Chapter 4 has been submitted for publication in the *Journal of Environmental Management* under the title:
Comte, A., Pendleton, L.H. Management strategies for coral reefs and people under global environmental change: 25 years of scientific research

Avant-Propos

Ce manuscrit est principalement écrit en langue anglaise. L'introduction et la discussion sont écrites en français. L'avant-propos, les remerciements, les abréviations et le résumé court sont écrité en anglais et en français. Ce manuscrit est basé sur des articles scientifiques publiés ou soumis, ou en préparation pour être soumis dans des journaux internationaux à comité de lecture. Les chapitres correspondants à des articles sont listés ci-dessous et sont disponibles en ligne. Le dernier chapitre, Chapitre 5, est un travail en cours qui se poursuivra dans un projet qui débutera après la thèse. Plusieurs matériaux supplémentaires aux articles de recherche ont été inclus directement dans les différents chapitres pour faciliter la lecture. Les travaux ayant servis à développer les chapitres de ce manuscrit sont présentés en annexes. Toutes les références se trouvent dans une section distincte à la fin du manuscrit.

-Le Chapitre 2 est publié dans le journal *Frontiers in Marine Science* sous la référence :
Pendleton, L., Hoegh-Guldberg, O., Langdon, C., Comte, A. (2016). Multiple Stressors and Ecological Complexity Require A New Approach to Coral Reef Research. *Frontiers in Marine Science*. doi: 10.3389/fmars.2016.00036
-Le Chapitre 3 est publié dans le journal *Plos One* sous la référence :
Pendleton, L.H., Comte, A., Langdon, C., Ekstrom, J.A., Cooley, S.R., Suatoni, L. Beck, M.W., Brander, L.M, Burke, L., Cinner, J.E., Doherty, C., Edwards, P.E.T, Gledhill, D., Jiang, L., van Hooidonk, R.J., Teh, L., Waldbusser, G.G., Ritter, J. (2016). Coral Reefs and People in a High-CO_2 World: Where Can Science Make a Difference to People? *Plos One*. doi:10.1371/journal.pone.0164699
-Le Chapitre 4 est en révision dans le journal *Journal of Environmental Management* sous le titre :
Comte, A., Pendleton, L.H. Management strategies for coral reefs and people under global environmental change: 25 years of scientific research

Acknowledgements

First, I would like to thank my director, Linwood Pendleton, and my co-adviser Denis Bailly. You allowed me to work on this thesis in the best possible conditions. You were always available for me and your patience and your trust were very precious during these three years. Linwood, I learned tremendously working with you, and your mentorship means more than an “academic fatherhood”. Denis, your vision and your support matters a lot to me.

I thank the members of my jury, Joachim Claudet, Gilbert David, Julie Ekstrom, Gaël Giraud, Harold Levrel, and Aurélie Thomassin. I am deeply honored that you accepted to evaluate my work. It is not possible to find more prestigious jury.

I thank the members of my committee, Jean-Pierre Gattuso, Patrice Guillotreau, and Alexandre Magnan. You greatly contributed to this work and I am thankful that you took the time to follow the progress of this thesis.

This work was supported by the "Laboratoire d'Excellence" LabexMER (ANR-10-LABX-19) and co-funded by a grant from the French government under the program "Investissements d'Avenir", and by a grant from the Regional Council of Brittany.

I thank the co-authors of my articles; their work has greatly improved the quality and the interdisciplinary reach of my manuscripts. I also thank all the people who took part in this work. I was always very well surrounded during these three years.

To all the PhD students from the laboratoire AMURE, from the basement to the ground floor, and in particular to Manuel, Julien, Adeline, Charlène, Michel, Océane, Anne-Charlotte, Marie, Soazig et Maxime, I thank you very much for first bearing with my jokes during all these years and also for all the warm moments we shared together.

This thesis could not have happened without the help of Séverine Julien, Sophie Monge, Nicolas Roncin, Juliette Kermarec and Elisabeth Bondu and I thank you for your administrative mollycoddling. I would also like to thank the whole AMURE research unit for the warm welcome and the kindness that every PhD student experiences here. A special thanks to the dream team that is the international chair. A huge thank you to Antoine, the all-inclusive man. Thanks also to the coffee breaks colleagues, Pierre, Eva, Brice, Camille, Céline, and all the interns for making this essential moment even more enjoyable. Thank you to Claire, office mate and tropical destinations buddy.

I have to thank my family, you are amazing and I owe you everything. I thank my friends from Brest. You give a warm vibe to this city and fill it with adventure. I also thank my non-Brest friends, les loulous in particular for whom no amount of work or academic grade would change their perception of my lack of intellectual capacity. Thank you Germain for your immense contribution to science (I put you here like you asked).

Finally, I thank you Juliette. You gave me a little of your determination and a lot of your love.

Remerciements

Je tiens tout d'abord à remercier mon directeur de thèse, Linwood Pendleton, et mon co-encadrant, Denis Bailly. Vous m'avez permis de réaliser ce travail de thèse dans les meilleures conditions possibles. Votre disponibilité, votre patience et votre confiance ont été très précieuses durant ces trois années. Linwood, j'ai appris énormément à tes côtés et ta supervision représente plus qu'une « paternité académique ». Denis, ta vision et ton soutien comptent beaucoup pour moi.

Je remercie les membres de mon jury de thèse, Joachim Claudet, Gilbert David, Julie Ekstrom, Gaël Giraud, Harold Levrel, et Aurélie Thomassin. Je suis honoré que vous ayez accepté d'évaluer mon travail. Il n'aurait pas été possible de trouver jury plus prestigieux.

Je remercie également les membres de mon comité de thèse, Jean-Pierre Gattuso, Patrice Guillotreau, et Alexandre Magnan dont les idées ont largement contribué à enrichir ce travail. Je vous suis reconnaissant d'avoir pris le temps de suivre la progression de ma thèse.

Ce travail a bénéficié d'une aide de l'Etat gérée par l'Agence Nationale de la Recherche au titre du programme « Investissements d'avenir » portant la référence ANR-10-LABX-19, ainsi que d'une aide de la Région Bretagne (allocation de recherche doctorale).

Je remercie les co-auteurs de mes articles, leur collaboration a enrichi la qualité et la portée interdisciplinaire de mes manuscrits. Je remercie ensuite tous ceux qui ont participé de près ou de loin à ces travaux, j'ai toujours été très bien entouré durant ces trois années.

A tous les doctorants du laboratoire AMURE, de la cave au rez-de-chaussée, et en particulier à Manuel, Julien, Adeline, Charlène, Michel, Océane, Anne-Charlotte, Marie, Soazig et Maxime, je vous dis un grand merci, d'abord pour avoir supporté mes blagues pas toujours de qualité durant toutes ces années et aussi pour tous les échanges qu'on a pu avoir dans le labo et en dehors.

Cette thèse n'aurait pas pu voir le jour sans l'aide précieuse de Séverine Julien, Sophie Monge, Nicolas Roncin, Juliette Kermarec et Elisabeth Bondu qui ont toujours répondu avec le sourire à ma tendance à l'assistanat. Je tiens également à remercier tout le laboratoire AMURE pour l'accueil et la bienveillance qui est ressenti par tous les doctorants qui y séjournent. Merci à la dream team de la chaire. Un énorme merci à Antoine, l'homme qui sait tout faire. Merci également aux collègues de la pause-café, Pierre, Eva, Brice, Camille, Céline, et tous les stagiaires pour avoir rendu ce moment indispensable encore plus agréable. Merci à Claire, collègue de bureau et de destination tropicales.

Je remercie bien-sûr ma famille, vous êtes géniaux et je vous dois tout. Je remercie mes amis de Brest, vous donnez à cette ville une atmosphère chaleureuse et la remplissez d'aventures. Je remercie également mes amis non-brestois, les loulous en particulier, pour qui aucune quantité de travail académique ni distinction ne changera leur vue sur mes capacités intellectuelles limitées. Merci Germain pour ton immense contribution à la science (c'est bon je t'ai mis ici comme tu me l'as demandé).

Enfin, je te remercie Juliette, tu m'as donné un peu de ta détermination et beaucoup de ton amour.

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List of Abbreviations / *correspondance en français*

Ωar – Aragonite Saturation State / *Etat de saturation en aragonite*

AC – Adaptive Capacity / *CA – Capacité d'Adaptation*

AR – Assessment Report / *RE – Rapport d'Evaluation*

CBD – Convention on Biological Diversity / *CDB – Convention sur la Diversité Biologique*

CC – Climate change / *CC – Changements Climatiques*

CO_2 – Carbon dioxide / *dioxyde de carbone*

CoTS – Crown-of-Thorns Starfish / *Acanthaster pourpre* / *Acanthaster planci*

CR – Coral reefs / RC – Récifs Coralliens

DHW – Degree Heating Weeks / *Quantité d'anomalie thermique semaines*

EAC – Ecological Adaptive Capacity / *CAE – Capacité d'Adaptation Ecologique*

EEZ – Exclusive Economic Zone / *ZEE – Zone Economique Exclusive*

ES – Ecosystem services / *SE – Services Ecosystémiques*

GBC – Great Barrier Reef / *Grande Barrière de Corail*

GCF – Green Climate Fund / *FVC – Fonds Vert pour le Climat*

GCRMN – Global Coral Reefs Monitoring Network

GDP – Gross Domestic Product / *PIB – Produit Intérieur Brut*

GEC – Global Environmental Change / *CEG – Changements Environnementaux Globaux*

GHG – Green House Gases / *GES – Gaz à Effets de Serre*

GOA-ON – Global Ocean Acidification Observing Network

HDI – Human Development Index / *IDH – Indice de Développement Humain*

ICRI – International Coral Reef Initiative / *Initiative internationale pour les récifs coralliens*

IFRECOR – *Initiative Française pour les Récifs Coralliens* / French Initiative for Coral Reefs

IPCC – Intergovernmental Panel on Climate Change / *GIEC – Groupement International d'Experts sur le Climat*

LDC – Least-Developed Countries / *PMA – Pays les Moins Avancés*

MPA – Marine Protected Area / *AMP – Aire Marine Protégée*

NAP – National Adaptation Plan / *PNA – Plan National d'Adaptation*

NDC – Nationally Determined Contributions / *CDN – Contribution Déterminée au niveau National*

NGO – Non-Governmental Organization / *ONG – Organisation Non Gouvernementale*

OA – Ocean Acidification / *AO – Acidification de l'Océan*

OP – Ocean Province / *Province Océanique*

PCA – Principal Component Analysis / *ACP – Analyse de Composantes Principales*

RBM – Resilience Based Management / *Gestion Basée sur la Résilience*

RCP – Representative Concentration Pathway / *Profils représentatifs d'évolution de concentration*

SES – Social-ecological systems / *SSE – Systèmes socio-écologiques*

SDG – Sustainable Development Goals / *ODD – Objectifs du Développement Durable*

SIDS – Small Islands Developing States / *PEID – Petits États Insulaires en Développement*

SRM – Solar Radiation Management / *Gestion du rayonnement solaire*

SST – Sea Surface Temperature / *Température de surface de la mer*

TEEB – The Economics of Ecosystems and Biodiversity

TEV – Total Economic Valuation / *VET – Valeur Economique Totale*

UNFCCC – United Framework Convention on Climate Change / *CCNUCC – Convention Cadre des Nations Unis sur les Changements Climatiques*

USD – Dollars US

Scientific Production

1. Peer-reviewed articles

Comte, A. and Pendleton, L. (under review). Management strategies for coral reefs and people under global environmental change: 25 years of scientific research. *Journal of Environmental Management*

Morandi*, B., Marin* F., Urbina-Barreto*, I., **Comte, A.**, Galuppi, S., Behivoke, F., Mirhani, N., Bandeira, B., Chabi, R., Delvaux, E., Lahitsiresy, M., Manahirana, J-J., Moma, L., Mroimana, N., Nassuf, A., Pereira, J., Rakotojanahary, F., Randrianandrasana, J., Rasolontiavina, N., Remisy, S., Uger, M. (2018). L'interdisciplinarité en pratique : retour d'expérience de la « Deuxième École d'Été Australe sur la Vulnérabilité du Patrimoine Récifal (EEA VulPaRe, 2016) ». *Natures Sciences Sociétés*.

Drakou, E., Kermagoret, C., **Comte, A.**, Trapman, B., Rice, J. (2017). Reflections on Marine Socio-Ecological Systems Research: when young researchers meet the seniors. *ICES Journal of Marine Science*.

Pendleton☯, L.H., **Comte☯, A.**, Langdon, C., Ekstrom, J.A., Cooley, S.R., Suatoni, L. Beck, M.W., Brander, L.M, Burke, L., Cinner, J.E., Doherty, C., Edwards, P.E.T, Gledhill, D., Jiang, L., van Hooidonk, R.J., Teh, L., Waldbusser, G.G., Ritter, J. (2016). Coral Reefs and People in a High-CO_2 World: Where Can Science Make a Difference to People? *Plos One*.

Pendleton, L.H., Hoegh-Guldberg, O., Langdon, C., **Comte, A**. (2016). Multiple Stressors and Ecological Complexity Require A New Approach to Coral Reef Research. *Frontiers in Marine Science*.

2. Other articles

Grillet, C., Bertin, C., Le, J.T., **Comte, A**. (2016) Marine Ecosystem Services in Europe. In OCEAN AND CLIMATE, 2016 – Scientific Notes, Second edition, Tome 2. www.ocean-climate.org, 92 pages.

Comte, A., Pendleton, L.H., Quillérou, E., Bailly, D. (2015). Informing Climate Investment Priorities for Coastal Populations. In OCEAN AND CLIMATE, 2015 – Scientific Notes.www.ocean-climate.org, 116 pages.

Quilcaille, Y., Chavaillaz, Y., Giguet, S., Jézéquel, A., Rajaud, A., Ferron, C., Amat, A., Dépoues, V., Revelard, A., Lugen, M., Tourneville, L., **Comte, A.**, Mouroux, X., Ranche, M., Hovsepian, M., Sansilvestri, R. (2015). (In)certitudes et adaptation au climat futur : le regard des «acteurs de demain», Studies N°04/15, Iddri, Paris, France, 34 p.

3. Communications in international conferences

Comte, A. and Pendleton, L.H. (2017). Operationalizing Ecological Adaptive Capacity to assess Impacts, Resilience, and Action for Coral Reefs in the Face of Global Environmental Change. Oral Presentation, *IPFC 2017*. Papeete, Tahiti.

Comte, A., Pendleton, L.H., et al. (2016) Coral Reefs and People In A High CO_2 World: Where Can Science Make A Difference To People? Oral Presentation. *13th International Coral Reef Symposium*. Honolulu, Hawaii, USA.

Comte, A., Pendleton, L.H., et al. (2015). Indicator-based assessment of climate change impacts on populations that depend on the goods and services provided by coral reefs. Poster Session, *EURASC Symposium "Impacts on Climate Change"*. Brest, France.

4. Workshops organization

Comte, A. Hasson, A. 2017. Ocean Science and Youth Forum. FADEX-O. UPMC Jussieu, Paris, France.

Drakou, E., Kermagoret, C., **Comte, A.**, Trapman, B. Young Researchers Workshop. MSEAS 2016. Brest, France.

Introduction générale

Les récifs coralliens concentrent la plus importante biodiversité marine dans le monde (Roberts et al., 2002). Les sociétés humaines en dépendent fortement, les récifs étant au cœur du mode de vie d'environ 500 millions de personnes à travers le monde pour la pêche, le tourisme, la protection des côtes, l'attachement culturel aux récifs, et la découverte de molécules pour la médecine (Moberg and Folke, 1999). Les changements climatiques qui entrainent des modifications des paramètres physico-chimiques et écologiques de l'océan, couplés à l'augmentation des pressions anthropiques locales qui se généralisent sur les côtes de la planète, menacent les récifs coralliens (Burke et al., 2011) qui sont par ailleurs déjà dégradés. Ce constat pose donc le problème en termes de changements environnementaux globaux (CEG). Etant donné l'importance des écosystèmes pour les sociétés, répondre aux défis des CEG est un enjeu majeur. L'inertie du système climatique et les leviers d'actions pour atténuer les émissions de gaz à effet de serre étant relativement limités pour la plupart des décideurs et des gestionnaires, il est essentiel de réfléchir à des stratégies d'adaptation aux effets des CEG pour les écosystèmes et les sociétés. Se pose donc la question de comment mobiliser la connaissance scientifique sur l'adaptation des écosystèmes et des sociétés face aux effets des CEG pour guider l'action publique. Cette thèse interdisciplinaire a pour objectif de questionner les avancées scientifiques sur ce thème et d'utiliser de nouveaux cadres analytiques, méthodes, et indicateurs pour guider la science et l'action.

Cette introduction est structurée en cinq sections. Les objectifs généraux et les thèmes développés dans la thèse sont présentés dans un premier temps. Ensuite, les différentes facettes de la problématique sont abordées dans une revue de la littérature récente autours des CEG, des politiques publiques, et des approches d'évaluation des impacts des CEG. Le cadre théorique de la vulnérabilité utilisé dans la thèse est présenté dans une troisième section, suivi d'une description brève du contexte dans lequel s'est déroulée cette thèse pour finir par le plan de la thèse.

1. Objectifs généraux de la thèse

Les pouvoirs publics au niveau international, national, et local, doivent agir pour répondre aux menaces liées aux changements environnementaux globaux qui pèsent sur les écosystèmes et les sociétés. Dans le milieu marin, la priorisation et le développement des politiques publiques doit tenir compte du manque de connaissance des réponses des écosystèmes aux CEG du fait de la complexité des processus et de la forte dépendance de certaines populations côtières aux services écosystémiques rendus par ces écosystèmes.

Cette thèse se concentre plus particulièrement sur l'étude de la vulnérabilité et de l'adaptation aux CEG des systèmes socio-écologiques associés aux récifs coralliens. Ceux-ci sont caractérisés par une importante biodiversité, support de multiples services écosystémiques pour les populations humaines et sont particulièrement affectés par les CEG. Les cadres analytiques, méthodes, et données mobilisés s'inspirent de plusieurs champs disciplinaires. Les cadres analytiques de la vulnérabilité et de l'adaptation des systèmes socio-écologiques mobilisent des dimensions physiques, océanographiques, écologiques, sociales et économiques. Il est également important d'ancrer spatialement la distribution des impacts, de la vulnérabilité et de l'adaptation aux CEG pour prioriser l'action et la recherche (Preston et al., 2011; Tulloch et al., 2015). La notion de systèmes socio-écologiques et le développement d'indicateurs nous sont apparus comme deux pistes particulièrement intéressantes pour répondre à ces enjeux. Par ailleurs, le développement d'une science du changement, mais également d'une science « pour le changement » (Fazey et al., 2015) doit permettre de comprendre l'étendue des stratégies disponibles face aux effets des CEG. Ce champ de recherche doit être analysé pour améliorer sa portée en dehors du monde académique et prioriser l'investissement dans la recherche et l'action.

Les chapitres proposés dans cette thèse visent à contribuer à trois grands thèmes de recherche dans le domaine de l'étude des impacts des CEG sur les systèmes socio-écologiques marins. Premièrement, ils s'inscrivent dans le développement de recherches interdisciplinaires sur les systèmes socio-écologiques, mobilisant la notion de services écosystémiques, appliqués ici au cas des récifs coralliens. Deuxièmement, ils proposent des avancées théoriques et méthodologiques pour évaluer les impacts, la vulnérabilité, et l'adaptation afin de guider les politiques publiques visant à répondre aux effets des CEG. Troisièmement, ils se veulent une contribution à l'émergence d'un nouveau champ de recherche dédié à l'information des gestionnaires et décideurs politiques confrontés aux impacts des CEG.

2. Revue de la littérature récente

Une revue synthétique de la littérature récente est présentée ici à titre d'introduction de la problématique générale de la thèse et des thèmes auxquels elle se rapporte. Cette revue se penche d'abord sur la notion de changements environnementaux globaux et les enjeux sociétaux qui en découlent, puis sur les réponses des politiques publiques face à ces changements environnementaux globaux à plusieurs échelles, et enfin sur les approches scientifiques existantes pour l'évaluation des impacts des CEG.

a. Les changements environnementaux globaux, un enjeu pour la recherche et l'action

Depuis la révolution industrielle, les activités humaines modifient le climat par l'émission de gaz à effet de serre (GES) et par le changement d'affectation des sols (IPCC, 2013). Les activités humaines modifient également d'autres paramètres physico-chimiques et écologiques de l'environnement global. Ces changements sont particulièrement importants dans l'océan. L'océan a absorbé 95% du réchauffement du système terrestre (IPCC, 2013) et 25% des émissions de dioxyde de carbone (CO_2) (Le Quéré et al., 2012), entrainant son acidification. Les changements climatiques entraînent également une diminution du niveau d'oxygène contenu dans l'océan, altèrent la circulation thermo-haline et font augmenter le niveau de la mer. Ces modifications de l'environnement induisent des changements écologiques à l'échelle globale. Ces changements sont par ailleurs intensifiés, voir dominés dans certains endroits, par d'autres activités humaines locales qui ont pris une ampleur globale comme la déforestation, la pollution de l'eau et des sols, l'accumulation de déchets plastiques dans les océans, et la surexploitation des ressources naturelles (Maxwell et al., 2016). Pratiquement la totalité de l'océan est affecté par les activités humaines (Halpern et al., 2015). Cette combinaison de facteurs entraine une perte de biodiversité de plus en plus rapide et problématique à l'échelle globale, certains chercheurs n'hésitant pas à parler de sixième extinction de masse (Barnosky et al., 2011). L'ampleur des modifications dues aux activités humaines ont amené les scientifiques à définir une nouvelle aire géologique où l'espèce humaine est devenue une force géologique importante : l'anthropocène (Crutzen, 2002). Ces enjeux de modification global des processus physico-chimiques et écologiques ont été théorisés sous le terme de changements environnementaux globaux (CEG) (Clark and Holling, 1985; Turner et al., 1990). Ces CEG ont des conséquences sur les sociétés et sur les écosystèmes de notre planète et appellent une recherche interdisciplinaire pour traiter de ces enjeux à une échelle appropriée (Price, 1990).

Les CEG vont affecter directement de nombreux secteurs de l'économie. Le secteur primaire lié à l'exploitation des ressources naturelles est le plus dépendant d'un climat stable. Les CEG vont affecter les pêcheries du globe et donc les populations humaines qui dépendent de la pêche comme source d'alimentation, d'économie, et de culture (Allison et al., 2009; Barange et al., 2014; Cheung et al., 2010). Le secteur industriel, ainsi que le secteur tertiaire comme les assurances et le tourisme, seront également impactés par les effets des CEG (Allison and Bassett, 2015). La combinaison des modifications de la fréquence, de l'intensité et de la distribution géographique des cyclones et l'augmentation du niveau de la mer pourraient entraîner des dommages pour les habitations et les infrastructures côtières, 350 millions de personnes vivant sur les côtes pourraient être exposées à des inondations en 2050 (Wong et al., 2014).

Les CEG décrivent des modifications globales des écosystèmes et de la biodiversité. Ces impacts sont étudiés depuis de nombreuses années (voir par exemple Dobson et al., 1989). Tous les écosystèmes vont être affectés, de l'arctique jusqu'aux forêts tropicales en passant par les fonds marins. L'aire de répartition de nombreuses espèces va être modifiée dû aux changements environnementaux. Ceci est particulièrement problématique pour les espèces isolées (montagne, îles) qui ne pourront pas migrer pour suivre les changements de leur aire de répartition (Burrows et al., 2014). Ces changements de répartition des espèces peuvent également modifier la stabilité des écosystèmes quand les espèces affectées ont des fonctions uniques, et modifier l'exploitation des ressources naturelles telles que les ressources halieutiques (Barange et al., 2014).

L'augmentation de la température de l'océan va entraîner une modification de la répartition des espèces marines (Burrows et al., 2011), et impacter la physiologie des coraux, dans les cas extrêmes en provoquant des phénomènes de blanchissement (Hoegh-Guldberg et al., 2007). L'acidification de l'océan va affecter les écosystèmes marins, et particulièrement les organismes calcificateurs comme les récifs coralliens, les coquillages et les copépodes (Gattuso et al., 2012). Les interactions entre ces menaces et leurs effets cumulés sur les écosystèmes marins et les populations humaines qui en dépendent sont encore mal comprises (Nagelkerken and Connell, 2015; Riebesell and Gattuso, 2015). Ces changements posent la question de la gestion des écosystèmes sous contraintes climatiques (Heller and

Zavaleta, 2009). Etant donné l'importance d'un environnement stable qui produit des biens et des services pour les sociétés humaines (Costanza et al., 1997), il est nécessaire de comprendre et d'anticiper ces modifications pour pouvoir y répondre.

Les modifications des écosystèmes auront de nombreux impacts sur les populations humaines et l'économie. En effet, les écosystèmes et les systèmes sociétaux sont en interactions et doivent être étudiés de façon holistique. Pour intégrer ces deux systèmes et étudier leurs relations, nous parlerons de systèmes socio-écologiques (SSE) (Longépée, 2014). Les écosystèmes produisent de nombreux biens et services, dénommés services écosystémiques (TEEB, 2009). On distingue quatre types de services fournis par la nature : les services d'approvisionnement, de régulation, culturels et de support (Millenium Ecosystem Assessment, 2005). Les services d'approvisionnement sont obtenus en exploitant les ressources naturelles comme dans le cas de la pêche. Les services de régulation comme la séquestration du carbone et la purification de l'eau et de l'air proviennent des cycles biogéochimiques dans les écosystèmes. Les services culturels viennent des activités de récréation comme le tourisme et le développement culturel, mais également au développement spirituel et à l'attachement à des pratiques coutumières et ancestrales. Les services de supports sont liés aux fonctions des écosystèmes comme la pollinisation, les zones favorables à la reproduction ou les zones de nurserie qui permettent la production des autres types de services écosystémiques.

Les changements environnementaux globaux affectent la production de ces services par les milieux naturels (Worm et al., 2006). Les services d'approvisionnement sont d'ores et déjà affectés par les changements de répartition des espèces et l'introduction d'espèces invasives. Dans certaines régions, il sera de plus en plus difficile de cultiver la vigne qui a besoin de conditions climatiques spécifiques (Jones et al., 2005). Le secteur primaire de l'économie est donc particulièrement impacté. Les services de régulation sont également affectés. Par exemple, le stockage du carbone dans les écosystèmes pourrait diminuer dans les forêts, les mangroves, et surtout dans les toundras qui relâchent du carbone avec la fonte du permafrost (Lenton et al., 2009). Ces effets entrainent des boucles de rétroaction positives qui renforcent les CEG. Prendre en compte la perte de services écosystémiques liés aux effets des CEG est donc bénéfique pour améliorer les politiques publiques environnementales et climatiques (Arkema et al., 2015).

L'évaluation des impact des CEG sur le milieu marin, les écosystèmes qui s'y trouvent et les économies qui en dépendent, constituent une frontière de la recherche (Allison and Bassett, 2015; Gattuso et al., 2015; Weatherdon et al., 2016). Le milieu marin possède en effet des spécificités qui compliquent son étude. Les écosystèmes sont peu étudiés car peu accessibles, et les activités humaines y sont limitées, bien qu'en expansion. Les études disponibles se focalisent le plus souvent sur un effet unique ou une menace unique liés aux CEG, et limitent donc notre compréhension des interactions entre de multiples menaces (Nagelkerken and Connell, 2015). Néanmoins, de nombreux changements environnementaux s'opèrent dans le milieu marin et les conséquences sur les écosystèmes et les sociétés méritent d'être étudiées.

Il est nécessaire mieux comprendre les impacts des CEG sur l'économie et sur l'environnement afin d'agir et d'apporter des réponses dans le but d'en éviter les effets les plus négatifs. Cette thèse traite plus particulièrement de la manière d'aborder la question des menaces cumulées sur les écosystèmes coralliens et les sociétés qui en dépendent à travers l'évaluation des services écosystémiques qui y sont associés.

b. Les politiques publiques face aux enjeux des CEG

Les CEG sont un problème global par nature. C'est donc dans un premier temps à l'échelle globale que les Etats ont pris conscience de ces enjeux et tentent d'y répondre de manière multilatérale. La première pierre de cette collaboration globale a été posée au Sommet de la Terre à Rio en 1992. S'en est suivi la création de 3 conventions-cadre internationales sous l'égide de l'Organisation des Nations Unies (ONU) : la Convention Cadre des Nations Unies sur les Changements Climatiques (CCNUCC), la Convention sur la Diversité Biologique (CDB), et la Convention sur la Désertification. Les CEG sont progressivement pris en compte dans d'autres forums internationaux, notamment avec les objectifs d'Aichi pour la biodiversité et les Objectifs du Développement Durable (ODD) de l'ONU.

La CCNUCC est le forum international privilégié pour tenter de répondre aux changements climatiques. Les négociations climatiques ont abouti à un premier traité, le Protocole de Kyoto en 1997. Ce traité ne concernait que les pays industrialisés et a largement échoué à limiter l'émission de GES. C'est finalement en 2015 qu'un nouveau traité, l'Accord de Paris, a vu le jour. Contrairement au Protocole de Kyoto qui imposait un quota d'émissions à chaque partie prenante, l'Accord de Paris utilise un mécanisme volontaire, les « Contributions Déterminées au niveau National » (CDN) pour réduire les émissions de GES, qui s'appliquent aux pays industrialisés mais également à tous les pays en capacité de le faire.

Des groupements scientifiques ont vu le jour pour appuyer les conventions onusiennes. La CCNUCC est appuyée par le Groupement Inter-Gouvernemental d'Experts sur le Climat (GIEC). Le GIEC est le plus gros groupement d'experts scientifiques pluridisciplinaires et de décideurs politiques de l'histoire. Il produit notamment des rapports, appelés Rapports d'Evaluation (RE) pour faire une synthèse des travaux scientifiques sur les changements climatiques (CC). Ces rapports possèdent trois groupes de travail : (i) les causes physiques, (ii) les impacts, la vulnérabilité et l'adaptation, et (iii) l'atténuation.

Le GIEC propose donc deux types de réponses face aux changements climatiques : l'atténuation traitée dans le groupe de travail (iii) des RE et l'adaptation traitée dans le groupe de travail (ii) des RE. Les mesures d'atténuation visent à réduire les causes des CC, les émissions de gaz à effet de serre et les GES déjà présents dans l'atmosphère et l'océan, notamment pour limiter l'augmentation de la température. Le deuxième type de réponse pour lutter contre les CEG est de s'adapter à ses effets négatifs et d'exploiter les opportunités créées en s'adaptant aux nouvelles conditions environnementales. Un objectif global d'atténuation a en effet été validé avec l'accord de Paris: significativement moins de 2°C de réchauffement en 2100 par rapport au début de l'ère industrielle et si possible 1,5°C. Il n'y pas d'objectif chiffré dans le cas de l'adaptation, ce qui rend sa mise en œuvre plus complexe. Le but de l'adaptation est de réduire la vulnérabilité aux CEG (article 4.4 de la CCNUCC), de limiter la redistribution des effets négatifs et d'éviter la « maladaptation » (Adger, 2006). Les politiques à mettre en œuvre et les recommandations qui découlent de ces objectifs généraux sont donc multiples, les incertitudes sont décuplées (Smit and Wandel, 2006), et les barrières et limites à l'adaptation sont nombreuses (Moser and Ekstrom, 2010).

Si on prend pour exemple la montée du niveau de la mer, les politiques d'atténuation visent à réduire les gaz à effet de serre pour limiter l'augmentation de la température qui induit cette montée du niveau de la mer. Les politiques d'adaptation visent à diminuer les impacts sur les sociétés et/ou les écosystèmes, par exemple en construisant une digue autour des habitations côtières. Dans ce cas, une maladaptation pourrait venir de la construction d'une digue trop basse qui procurerait un faux sentiment de sécurité et qui ne diminuerait pas l'exposition des populations côtières à la montée future du niveau de la mer.

Certains pensent que l'adaptation ne fait que légitimer une faible réponse d'atténuation en choisissant d'optimiser les coûts et les bénéfices de différentes politiques à différentes échelles de temps (Godard, 2010). En effet, de par l'utilisation d'un taux d'actualisation dans les modèles économiques, une préférence est donnée pour les actions qui se trouvent éloignées dans le temps, au détriment des politiques d'atténuation qui ont un coût immédiat pour des bénéfices futurs. Quoi qu'il en soit, l'inertie du système climatique est telle que certains impacts des CEG sont inévitables, il est donc indispensable de s'y adapter. Les négociations internationales au sein de la CCNUCC se focalisent en partie sur les politiques d'adaptation. D'abord, c'est à travers les mécanismes financiers que l'adaptation est prise en compte. Les fonds multilatéraux comme le Fonds Vert pour le Climat (FVC) doivent financer des projets d'atténuation et d'adaptation de manière équilibrée. Dans les faits, la répartition du financement est largement en faveur de l'atténuation. Ensuite, la CCNUCC encourage les Etats à évaluer leur vulnérabilité et à formuler des mesures d'adaptation dans leur CDN, ainsi qu'à développer des plans nationaux d'adaptations (PNA).

Les milieux marins et côtiers sont de plus en plus abordés dans les travaux du groupe de travail (ii) des RE du GIEC. Un chapitre sur 7 était dédié à l'océan dans le RE1, 3 chapitres sur 18 dans le RE2, 2 chapitres sur 19 dans le RE3, 2 chapitres sur 20 dans le RE4, et enfin 4 chapitres sur 30 lui sont consacrés dans le RE5. L'importance de l'océan est désormais l'objet de plus en plus de travaux de recherche, et la production d'un rapport spécial sur l'océan et la cryosphère a été validée par le GIEC. Un des 17 ODD (objectif 14) est également dédié spécifiquement à l'océan. Ces objectifs internationaux influencent une nouvelle direction de recherche en appui aux politiques publiques qui pose la question de la coordination des travaux de recherche sur les effets et solutions aux GEC dans l'océan, un thème largement abordé dans cette thèse. Dans le milieu marin, une typologie de l'ensemble des réponses possibles aux effets des CEG sur les écosystèmes et les services écosystémiques associés a été développée par Gattuso et al. (2015). Nous nous baserons dans cette thèse sur ces travaux pour créer une typologie des solutions spécifiques aux récifs coralliens dans le quatrième chapitre.

Les impacts des CEG requièrent des actions à tous les niveaux de prise de décisions. La gouvernance globale est évidemment essentielle puisque le problème est de nature globale et que la possibilité de passager clandestin est très grande. La réduction des émissions de GES a des bénéfices globaux tandis que les coûts sont individuels. Par ailleurs, le problème éthique de la répartition de l'effort et de la répartition des impacts entre les pays dit « pollueurs » et les pays qui ont peu contribué au problème mais qui vont subir les effets des CEG (particulièrement les petits états insulaires et les pays les moins développés) doit également être traité à l'échelle globale.

Différentes échelles d'action doivent être prises en compte dans l'évaluation des impacts et des réponses à apporter aux CEG. La vulnérabilité des écosystèmes et des populations humaines dépend du contexte local qu'il est difficile d'évaluer à l'échelle globale (Hinkel, 2011; Rhiney, 2015). D'un autre côté, les concepts qui servent à évaluer les impacts des CEG sont généraux et il peut être difficile de les appliquer à l'échelle locale. La gouvernance de ces systèmes doit donc être influencée par des approches « *top-down* » et des approches « *bottom-up* » pour être efficace (Berkes, 2010; Charles, 2012). Des systèmes de gouvernance se sont mis en place à l'échelle globale et aux échelles régionales, nationales, et locales pour répondre à ces enjeux. Les politiques publiques mises en œuvre sont pour l'instant inadaptées et trop faibles pour comprendre pleinement les menaces liées aux CEG et pour y répondre efficacement. De nombreux pays ont commencé à planifier leur adaptation aux CEG, notamment en élaborant des plans nationaux d'adaptation aux changements climatiques (PNA). Il existe cependant un manque de financement énorme pour que les pays en développement s'adaptent aux effets des CEG (UNEP, 2014).

Des outils intégrant une approche par les systèmes socio-écologiques sont peu développés dans les politiques climatiques globales, bien que les écosystèmes commencent à être l'objet de politiques publiques. En termes d'atténuation, les écosystèmes ont un grand pouvoir de séquestration du carbone. Des mécanismes tentent de voir le jour pour pouvoir favoriser cette séquestration dans les écosystèmes. Le programme REDD+ et les payements pour services écosystémiques se développent pour financer la protection des écosystèmes comme les forêts qui séquestrent du carbone. Du côté de l'adaptation, des solutions basées sur la nature, aussi appelée adaptation basée sur les écosystèmes, se développe dans les plans climatiques nationaux (Pramova et al., 2011). Là encore, la prise en compte des systèmes marins et côtiers n'est que récente et parcellaire. De nouvelles études tentent d'estimer la contribution des systèmes marins et côtiers (carbone bleu) pour contribuer aux politiques d'atténuation des CEG et de proposer des outils pour la séquestration du carbone dans le but d'être intégrés aux mécanismes de financement comme REDD+ (Howard et al., 2017).

Des outils pour prioriser et dimensionner les réponses publiques face aux effets des CEG doivent être développés à toutes les échelles de décision, du global au local. Etant donné les contraintes budgétaires et le besoin d'optimiser l'allocation de ressources, il est nécessaire de développer des outils pour prioriser les stratégies à entreprendre et les lieux où les implémenter à toutes ces échelles. Les différents chapitres de la thèse abordent cette question principalement du point de vue global.

c. L'évaluation des impacts des CEG

De nombreuses disciplines scientifiques tentent d'apporter leur contribution pour améliorer le niveau de connaissance sur les CEG et pour appuyer la mise en œuvre de politiques publiques. L'étude des impacts et de la vulnérabilité aux CEG s'est énormément développée depuis les années 2000 dans diverses disciplines, en écologie, en biologie, en géographie, en économie et en sciences sociales notamment (Füssel and Klein, 2006) et un nouveau champs d'étude sur les solutions et l'action émerge (Fazey et al., 2015; Hinkel and Bisaro, 2015; Tollefson, 2015). Les économistes se sont emparés des volets atténuation et des volets impacts, vulnérabilité, adaptation pour construire des analyses dites « positives » pour examiner les impacts des CEG sur l'économie et des analyses dites « normatives » pour évaluer l'efficacité des solutions disponibles et guider la décision des politiques climatiques et environnementales. Le postulat économique classique étant que la dégradation de l'environnement résulte d'externalités négatives qui ne sont pas prises en compte dans le calcul économique des acteurs privés car elles n'ont pas de prix, les économistes de l'environnement proposent d'évaluer le coût des changements climatiques (coût de l'inaction) pour pouvoir les intégrer au système économique (internaliser les externalités) de manière optimale (Holtz-Eakin & Selden, 1995). Alors que l'économie de l'environnement tente d'intégrer la dégradation de l'environnement dans le système économique, un deuxième champ, l'économie écologique, part du postulat que le système économique fait partie de la nature et en dépend donc plus fondamentalement. Cette perspective amène à penser les interactions entre environnement et économie différemment, notamment en mobilisant l'évaluation des services écosystémiques et de leur dégradation (Costanza et al., 1997; TEEB, 2009). Ces deux champs d'étude sont brièvement décrits ci-dessous. L'approche retenue dans cette thèse se place sur le champ théorique de l'économie écologique et mobilise le cadre de la vulnérabilité des systèmes socio-écologiques, décrite dans la troisième section de cette introduction.

L'étude des impacts des changements climatiques est un axe important de recherche, qui a pour objectifs d'évaluer les impacts des CC, pour dimensionner les politiques d'atténuation d'une part, et pour aider à la production de politiques d'adaptation d'autre part (Burton et al., 2002). En macro-économie, des modèles d'équilibre général (*Integrated Assessment Models* IAM en anglais) ont été construits pour simuler les effets des CC sur l'économie globale et estimer son impact négatif, le plus souvent en termes de pourcentage de Produit Intérieur Brut (PIB). Ces modèles ont été popularisés par la *Stern Review* (Stern, 2006), et d'autres modèles ont été développés (DICE, FUND, PAGE). Ces modèles couplent la production économique et le forçage dû aux émissions de GES de sorte à optimiser la création de richesse (« utilité » en termes de théorie économique) tout en minimisant la fonction d'impact des GES. Ils estiment ainsi un coût social du carbone en $/t$CO_2$ qui peut être utilisé pour les politiques d'atténuation climatiques. Dans le RE5 du GIEC, il est estimé qu'une augmentation de la température de 2°C en 2100 aurait un coût entre 0,2% et 2% du PIB mondial et que le coût social du carbone se situe entre ~1 et ~100$/t$CO_2$ (Field et al., 2014).

Les outils de politiques publiques développés par les économistes pour répondre aux menaces des changements climatiques mettent en avant deux mécanismes basés sur le marché qui visent à réduire les émissions de GES jusqu'au niveau socialement optimal: la taxe carbone et le marché carbone (Pizer, 2002). La taxe carbone permet de réduire les émissions polluantes en taxant les biens et services qui produisent du CO_2. Le niveau de la taxe peut être fixé grâce aux calculs du coût social du carbone. Le marché carbone fonctionne en fixant un quota maximum d'émission de CO_2 puis en répartissant des permis d'émission entre les acteurs du marché. Ensuite, un système d'achat et de vente de permis d'émissions est mis en place, le prix étant fixé par l'offre et la demande. Ces outils économiques sont souvent couplés à des outils réglementaires comme par exemple les normes d'émissions des moteurs thermiques ou incitatifs comme les subventions à l'isolation des logements. Il semble aujourd'hui difficile d'atteindre l'objectif d'atténuation des émissions des GES. Il ne resterait que 3 ans pour infléchir les émissions pour avoir une chance de rester sous les 2°C (Figueres et al., 2017), et seulement 5% de chance que nous atteignons cet objectif (Raftery et al., 2017).

Ce n'est que plus récemment que la recherche sur le climat s'est intéressée à l'étude de la vulnérabilité et de l'adaptation (Burton et al., 2002; Füssel and Klein, 2006), notions mobilisées par ailleurs par de nombreuses disciplines telles la gestion des risques ou la psychologie. Les définitions des termes de vulnérabilité et d'adaptation utilisées ici proviennent de la littérature sur les changements climatiques. La vulnérabilité aux CEG se définit par « la propension ou la prédisposition à être affecté défavorablement. La vulnérabilité englobe une variété de concepts et d'éléments qui incluent la sensibilité ou susceptibilité au dommage et le manque de capacité à faire face et à s'adapter » * (IPCC AR5 WGII SPM, p.5). On peut également définir la vulnérabilité comme « le degré avec lequel un système, sous-système, ou composant d'un système peut être endommagé à cause d'une exposition à un aléa, définit comme une perturbation ou un facteur de stress » * (Turner et al., 2003).

La vulnérabilité est caractérisée par trois attributs : l'exposition, la sensibilité, et la capacité d'adaptation (Adger, 2006). L'exposition est définie comme « la présence de gens, de modes de vies, d'espèces ou d'écosystèmes, de fonctions environnementales, de services, de ressources, d'infrastructures, ou de capital économique, social, et culturel dans des endroits et des conditions susceptibles de subir des dommages » * (IPCC AR5 WGII SPM, p.5). En matière de gestion des risques on utilise souvent le terme enjeux pour désigner l'exposition. La sensibilité, parfois appelée dépendance ou susceptibilité au dommage, est le degré avec lequel le système exposé peut être affecté par les CEG. La capacité d'adaptation est définie comme « la capacité d'un système à évoluer pour s'accommoder à des aléas de l'environnement ou des changements de politiques et à faire face à une variabilité accrue » * (IPCC AR5 WGII SPM, p.5). Ces concepts sont proches de celui du risque, défini comme une potentialité ou probabilité de dommage qui combine aléa et enjeux.

Plusieurs champs disciplinaires se sont emparés du cadre analytique de la vulnérabilité pour évaluer les effets des changements climatiques et des CEG en économie (Narita et al., 2012; Tol and Yohe, 2007; Yohe and Tol, 2002), en géographie (Adger, 2006; Brooks et al., 2005; Magnan et al., 2012; Moser, 2010; Vogel et al., 2007) en sciences de l'environnement (Füssel and Klein, 2006; Mcfadden, 2007; Preston et al., 2011; Turner et al., 2003) et en écologie (Foden et al., 2013; Graham et al., 2011).

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* Traductions de l'auteur
* Traductions de l'auteur

Les études d'évaluation de la vulnérabilité servent plusieurs objectifs. Ces évaluations servent à identifier les populations humaines ou les écosystèmes vulnérables aux impacts des CEG. D'autres utilisent les évaluations de la vulnérabilité comme outil pour la planification d'actions adaptatives et de la résilience (Adger, 2006), pour le suivi de l'efficacité des stratégies de gestions mises en place face aux effets des CEG, pour l'identification de stratégies d'adaptation (Smit and Wandel, 2006), ou pour prioriser l'allocation de fonds climats, pour guider la recherche future (Ekstrom et al., 2015), ou communiquer les enjeux liés aux CEG à différentes parties prenantes (décideurs, populations identifiées comme vulnérables).

L'adaptation est définie comme « le processus d'ajustement aux climats et à ces effets actuels ou prévus dans le futur. Pour les systèmes humains, l'adaptation cherche à modérer ou éviter des dommages ou exploiter des opportunités. Dans certains systèmes naturels, l'intervention humaine peut aider l'ajustement au climat futur et à ces effets » * (IPCC AR5 WGII SPM, p.5). Ce n'est que récemment que les économistes se sont penchés sur des outils pour informer les politiques d'adaptation aux changements climatiques (Hallegatte, 2009; Hinkel and Bisaro, 2015). Des études récentes ont tenté de chiffrer le coût des politiques d'adaptation. L'initiative de la Banque mondiale appelée « *Economics of Adaptation to Climate Change* » chiffre les besoins d'adaptation des pays développés entre 70 et 100 milliards US$ par an entre 2010 et 2050 avec un scénario de réchauffement à 2°C en 2100 (Narain et al., 2011).

Dans les plans d'adaptations, par exemple les PNA (plan national d'adaptation), l'évaluation des impacts, de la vulnérabilité et de l'adaptation rentre dans une démarche de gestion adaptative. La gestion adaptative a été développée comme un cycle itératif pour pallier les incertitudes concernant les effets des CEG et celles liées aux effets des mesures de gestion sur des systèmes dynamiques et complexes. Cette gestion adaptative se décompose en six phases, (i) la définition d'objectifs à atteindre, (ii) l'évaluation de la vulnérabilité du système, (iii) l'identification des mesures d'adaptation, (iv) la priorisation des mesures à implémenter, (v) l'implémentation du plan, (vi) le suivi, l'évaluation et la révision du plan, qui peut conduire à une modification des objectifs, à une réévaluation de la vulnérabilité, etc. La majorité des études scientifiques sont concentrées sur l'étude de phases spécifiques comme l'évaluation de la vulnérabilité ou le développement d'outils pour prioriser les mesures d'adaptation. Un plus petit nombre d'études se penche sur l'intégration de ces phases. Dans tous les cas, l'évaluation de la vulnérabilité est une étape clé dans la mise en œuvre de politiques d'adaptation aux CEG.

Ces définitions venant de l'étude des changements climatiques nous permettent d'aborder théoriquement les impacts des CEG. Il semble aujourd'hui essentiel et inévitable de s'adapter aux effets des CEG sur l'économie et les écosystèmes. Des études de vulnérabilité sont développées dans le milieu marin pour guider les politiques d'adaptation et de réduction des impacts potentiels (Allison et al., 2009; Ekstrom et al., 2015; Hughes et al., 2012a).

Une intégration interdisciplinaire est nécessaire pour améliorer la prise en compte de la biodiversité et des services écosystémiques dans les études des impacts des CEG, le design et la priorisation de solutions pour l'atténuation et l'adaptation. Les modèles IAM utilisés dans le cadre d'analyses coût bénéfices sous-estiment les impacts potentiels sur l'économie et l'environnement, la modélisation de la fonction d'impact ne prenant pas en compte les impacts sur la disponibilité de services écosystémiques. Les bénéfices des politiques d'atténuation et d'adaptation (c'est à dire le coût de l'inaction) sur les écosystèmes est difficilement mesurable et encore plus difficilement chiffrable (OECD, 2015). Dans l'étude « *Economics of Adaptation to Climate Change* » par exemple, seules les mesures d'adaptation pour la pêche et l'agriculture sont prises en compte, mais pas pour le maintien de la biodiversité et des autres services associés à ces écosystèmes. L'OCDE montre que la biodiversité est un des secteurs les moins bien étudiés par la recherche sur l'adaptation, parlant de faible évidences, d'un manque de connaissance sur l'estimation des bénéfices liés au maintien de la biodiversité et de nombre limité d'études sur les coûts de maintien, notamment les coûts de restauration et de gestion des aires protégées (OECD, 2015). De nouveaux types de modèles se développent pour améliorer la modélisation de l'économie des changements climatiques, mais ces nouveaux modèles n'ont pas pour but d'incorporer les effets des CEG sur les écosystèmes et leurs répercussions sur les sociétés humaines (Farmer, Hepburn, Mealy, & Teytelboym, 2015).

Le champ disciplinaire de l'économie écologique a émergé pour répondre aux enjeux de la place de la biodiversité dans l'économie et pour évaluer les impacts sociétaux de son érosion (Spash & Ryan, 2012). Plusieurs courants de pensées se distinguent au sein de l'économie écologique. Un premier courant a pour objectif d'optimiser l'exploitation des ressources naturelles, incorporant les avancées en écologie dans un paradigme d'économie de l'environnement visant à maximiser le bien-être. Un deuxième courant, pragmatique, regroupe des chercheurs venant souvent des sciences naturelles utilisent la science économique comme moyen pour modifier les politiques publiques en faveur de la protection de l'environnement. Le troisième courant, l'économie socio-écologique, tente de s'extraire des postulats économiques classiques pour étudier la complexité des relations entre écologie et société, le rôle des institutions, de l'histoire, les inégalités et les relations de pouvoir (Spash 2011).

Cette thèse s'inscrit principalement dans le courant pragmatique, bien que des réserves existent sur les méthodologies existantes. Ce courant a notamment développé des méthodologies pour conduire des évaluations de la biodiversité, et particulièrement l'évaluation du coût de l'inaction qui utilise la valeur économique totale (VET) (Braat & ten Brink, 2008). Cette approche a notamment été utilisée dans le programme international TEEB. Ces études, popularisées par une première estimation de la valeur totale des écosystèmes (Costanza et al., 1997) ont pour but de révéler la « valeur » de la nature pour pouvoir mieux l'intégrer aux décisions politiques et économiques, notamment aux analyses coûts bénéfices climatiques décrites précédemment. Cependant, la démarche visant à mesurer en unité monétaire les services produits par les écosystèmes et le coût de leur dégradation pose problème. D'un point de vue théorique, elle suppose une soutenabilité faible, une fongibilité entre les différents capitaux (naturel, économique, humain), et une difficulté méthodologique à estimer les autres services que les services d'usages (Levrel, Hay, Bas, Gastineau, & Pioch, 2012). Les méthodes utilisées pour estimer ces valeurs monétaires reposent en partie sur des études de choix révélés qui sont incomplètes en termes du nombre et de la qualité des services évalués et en partie sur des méthodes de choix déclarés qui sont partielles (Pendleton, Thébaud, Mongruel, & Levrel, 2016). Les utilisations des évaluations basées sur la VET pour chiffrer les impacts des CEG, comme par exemple pour évaluer les impacts des changements climatiques sur les services associés aux récifs coralliens (Chen, Chen, Chu, & Mccarl, 2015), conduisent à n'estimer que des coûts marginaux qui ne reflètent pas les effets de seuils et les changements de phases induits par les CEG qui vont modifier les fonctions des écosystèmes et donc la disponibilité des services écosystémiques. D'autres approches à l'évaluation de l'érosion des services écosystémiques ont émergé récemment comme l'approche par les coûts de maintien et les impacts résiduels (Levrel et al., 2012). Ce diagnostic nous conduit à réfléchir sur de nouvelles manières d'intégrer les impacts des CEG sur les écosystèmes, les services écosystémiques, et les réponses à formuler pour s'y adapter.

Plutôt que de tenter d'estimer des pertes de valeurs de services écosystémiques dues aux CEG en termes monétaires, cette thèse mobilise le cadre analytique de la vulnérabilité des systèmes socio-écologiques. Ce choix est d'abord motivé par l'utilisation du cadre de la vulnérabilité qui prévaut désormais dans les rapports scientifiques produits par le GIEC. Ce choix est également motivé par l'objectif des études d'évaluation de la vulnérabilité qui servent à informer les politiques d'adaptation aux effets des CEG. Le cadre analytique de la vulnérabilité permet également d'intégrer des composantes de nature différente qui caractérisent les socio-écosystèmes : les aspects écologiques comme la résilience et les aspects sociétaux comme l'équité et la capacité d'adaptation. Nous nous positionnons donc ici entre le courant pragmatique, notre premier but étant de guider les politiques publiques, et le courant de l'économie socio-écologique, tentant de comprendre la complexité du système écologique et économique et questionnant le rôle des institutions, ici celui de la science (Spash & Ryan, 2012). Etant donné les effets en partie inévitables des CEG sur les écosystèmes marins et les sociétés qui en dépendent, il est nécessaire de développer des études pour évaluer la vulnérabilité de ces systèmes, appréhender la distribution spatiale des impacts des CEG, la susceptibilité de ces systèmes à ces impacts et de leur capacité d'adaptation pour guider les stratégies de gestion visant à répondre à ces enjeux.

3. L'étude des impacts, de la vulnérabilité et de l'adaptation des systèmes socio-écologiques face aux CEG

Cette troisième section d'introduction générale présente le cadre analytique de la vulnérabilité des systèmes socio-écologiques retenu dans cette thèse. La prise en compte des CEG dans un contexte d'interrelations entre écosystèmes et sociétés, la prise en compte de la résilience et de la gestion adaptative, ainsi que la considération de facteurs de stress et d'échelles multiples nous placent dans un discours sur la vulnérabilité aux CEG qualifié de discours environnement-humain (O'Brien et al., 2007). Les systèmes socio-écologiques sont d'abord définis de manière théorique. Nous présentons ensuite les cadres analytiques qui permettent d'évaluer les impacts, la vulnérabilité et l'adaptation des systèmes socio-écologiques face aux CEG. L'application de ce cadre aux récifs coralliens est ensuite détaillée.

a. L'étude des systèmes socio-écologiques

Afin de comprendre quelles populations humaines ou quels écosystèmes sont les plus à risque face aux CEG, des évaluations cartographiant la vulnérabilité ont été développées. L'intégration des systèmes sociaux et des systèmes écologiques dans une approche commune est en plein essor (Adger, 2000; Collins et al., 2011; Ostrom, 2009; Young et al., 2006). Des modèles théoriques et des cadres analytiques ont été développés pour appréhender l'étude des systèmes socio-écologiques, qui se caractérisent comme des systèmes complexes, intégrés et adaptatifs où l'homme fait partie intégrante de la nature (Folke, 2006; Folke et al., 2003; Levin et al., 2012; Walker et al., 2004). Cette intégration est nécessairement interdisciplinaire, voit la distinction entre sociétés et écosystèmes comme arbitraire et s'intéresse à des propriétés complexes telles que les dynamiques non-linéaires, les croisements d'échelles, les propriétés émergentes et les incertitudes des systèmes socio-écologiques (Díaz et al., 2011; Folke, 2006; Folke et al., 2004, 2002; Gallopín, 2006). L'étude des systèmes socio-écologiques est donc enrichie par l'apport de différentes disciplines, notamment entre sciences naturelles et sciences économiques et sociales (Christie, 2011; Drakou et al., 2017). Collins et al. (2011) proposent un cadre de recherche représenté dans la Figure I.1. Les facteurs extérieurs comme les CEG sont étudiés par les sciences biophysiques et les sciences sociales, le plus souvent de manière indépendante. Le sous-système biophysique (en vert) est étudié par la physique, la biochimie, la biologie, et l'écologie. Le sous-système social (en bleu) est étudié par les sciences humaines et sociales. L'étude des interactions entre ces sous-systèmes (en jaune et en rouge) doit intégrer ces différentes disciplines dans des cadres pluridisciplinaires ou interdisciplinaires.

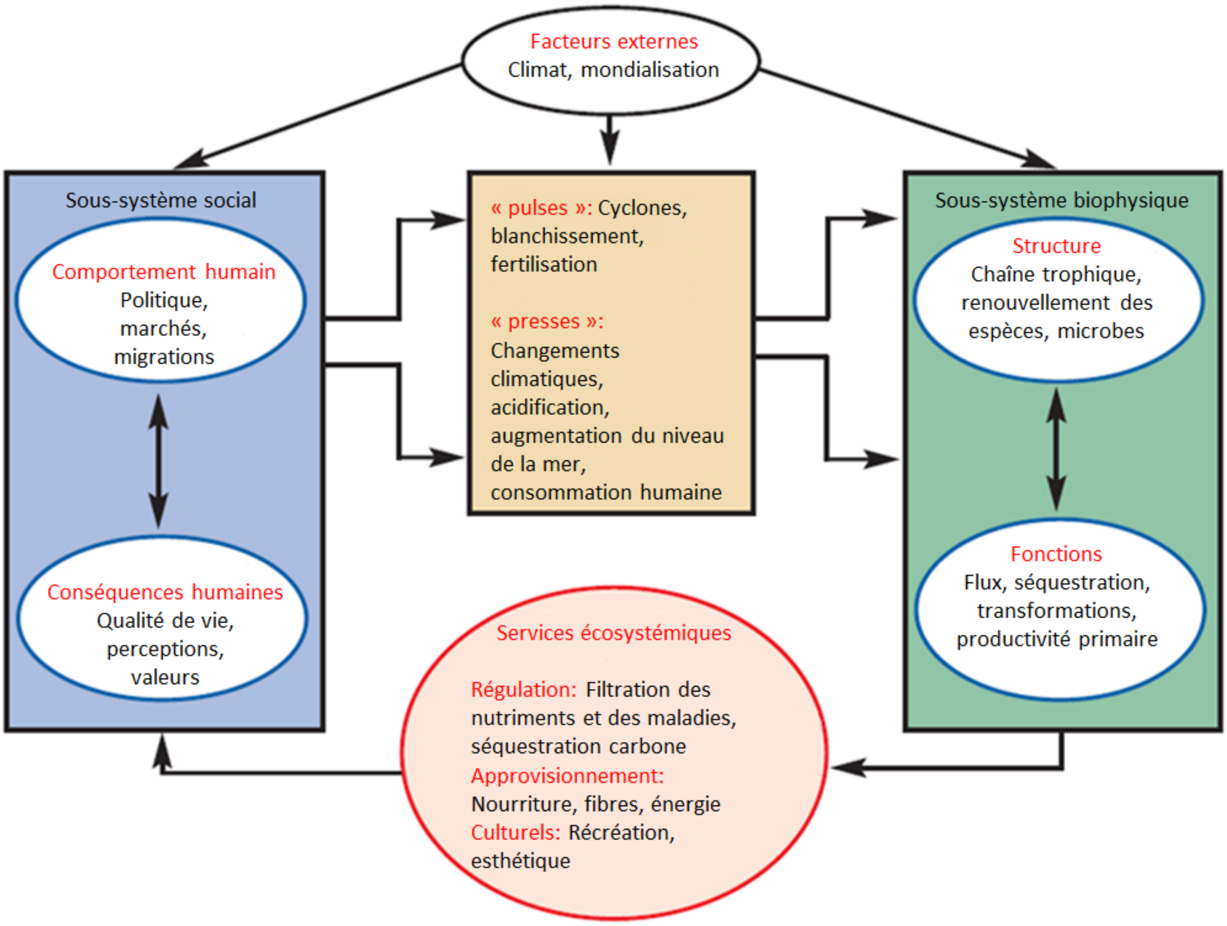

Figure I.1. Cadre de recherche pour l'étude intégrée des systèmes socio-écologiques. Adaptée et traduite de Collins et al. (2011)

b. Les cadres d'évaluation

Les approches utilisées jusqu'à présent pour l'évaluation des impacts des CEG et des réponses à y apporter ne prennent pas suffisamment en compte les liens entre écosystèmes et sociétés humaines. D'une part, les études focalisées sur les impacts économiques ne prennent pas en compte la complexité des écosystèmes et de leurs relations avec les sociétés. La plupart des évaluations de la vulnérabilité prennent par exemple l'environnement comme un intrant, mais ne développent pas les aspects d'adaptation dans les écosystèmes comme elles tentent de le faire avec la capacité d'adaptation des sociétés humaines. Ceci est dû en partie à la difficulté de chiffrer ces impacts en termes comparables aux impacts sur les sociétés. D'autre part, les études sur les impacts et la vulnérabilité des espèces et des écosystèmes marins prennent en compte les activités anthropiques comme des pressions, sans intégrer les changements des activités et des modes de gouvernance des sociétés humaines. La CDB, par exemple, fait le constat que sur les impacts de l'acidification de l'océan, « aucune des questions ne mentionne explicitement les services écosystémiques, les impacts sociétaux ou les réponses politiques possibles » * (CBD, 2014, p.18). Dans cette thèse, nous tentons donc de prendre en compte les aspects physiques et écologiques mais également les aspects socio-économiques liés aux services écosystémiques et à la prise de décision.

Des exemples d'une intégration commencent à émerger dans l'étude de la vulnérabilité et de la résilience des systèmes socio-écologiques (Angeon and Bates, 2015; Bennett et al., 2015; Cinner et al., 2013; Hughes et al., 2012a; Timmerman, 1981; Vogel et al., 2007). L'étude des effets des CEG sur les systèmes socio-écologiques et les réponses à y apporter sont aujourd'hui des enjeux majeurs de recherche qui tendent à se développer (Eakin and Luers, 2006; Tompkins and Adger, 2004). Certaines études d'évaluation de la vulnérabilité tentent d'opérationnaliser le concept de système socio-écologique en intégrant des concepts écologiques dans leur cadre analytique. C'est notamment le cas de la notion de résilience (Folke, 2006; Xu and Marinova, 2013). Cette notion, développée par Holling (1973), est importante pour expliquer les réponses des écosystèmes face à des chocs et des aléas. Holling l'a d'abord définie comme "une mesure de persistance de systèmes et leur capacité à absorber un changement et une perturbation tout en maintenant les mêmes relations entre des variables d'état et les populations" * (Holling, 1973). Cette définition a ensuite été précisée comme "la capacité d'un système à absorber une perturbation et à se réorganiser tout en changeant pour garder essentiellement les même fonction, structure, identité, et interactions" * (Walker et al., 2004).
Il existe deux conceptualisations de la résilience : la résilience d'ingénierie se focalise sur le niveau de choc ou de perturbations qu'un système peut subir avant de basculer dans un autre état fonctionnel. La résilience écologique se focalise sur le temps nécessaire à un système pour revenir à son état initial après un choc ou une perturbation. Le concept de résilience amène donc à penser les effets de seuil (Scheffer et al., 2012) qui peuvent être

* Traduction de l'auteur

opérationnalisés pour guider les politiques, comme les « *planetary boundaries* » à l'échelle globale par exemple (Rockström et al., 2009). La notion de résilience est appliquée à l'étude des sociétés notamment dans les évaluations de vulnérabilité (Adger, 2006; Turner et al., 2003) où elle est liée à la capacité d'adaptation (Engle, 2011).

D'autres études intègrent des composantes écologiques par le prisme des services écosystémiques (Locatelli et al., 2008; Metzger et al., 2006). Elles tentent par exemple d'évaluer la perte de services écosystémiques ou les réponses des sociétés humaines face à ces pertes (Breshears et al., 2010; Rogers et al., 2015) ou de construire un cadre de gestion adaptative basée sur la prise en compte des relations entre changements globaux, fonctions des écosystèmes, et services écosystémiques (Figure I.2.) (Armitage et al., 2009; Birgé et al., 2016). Les gestionnaires et décideurs du milieu marin n'ont pas encore intégré la dimension socio-écosystémique et le développement d'indicateurs liés à la dépendance aux services écosystémiques reste à faire (Cornu et al., 2014). Les travaux développés dans cette thèse, qui intègrent des données socio-économiques et des données environnementales, participent de cette réflexion sur des approches intégrées de la gestion du milieu marin.

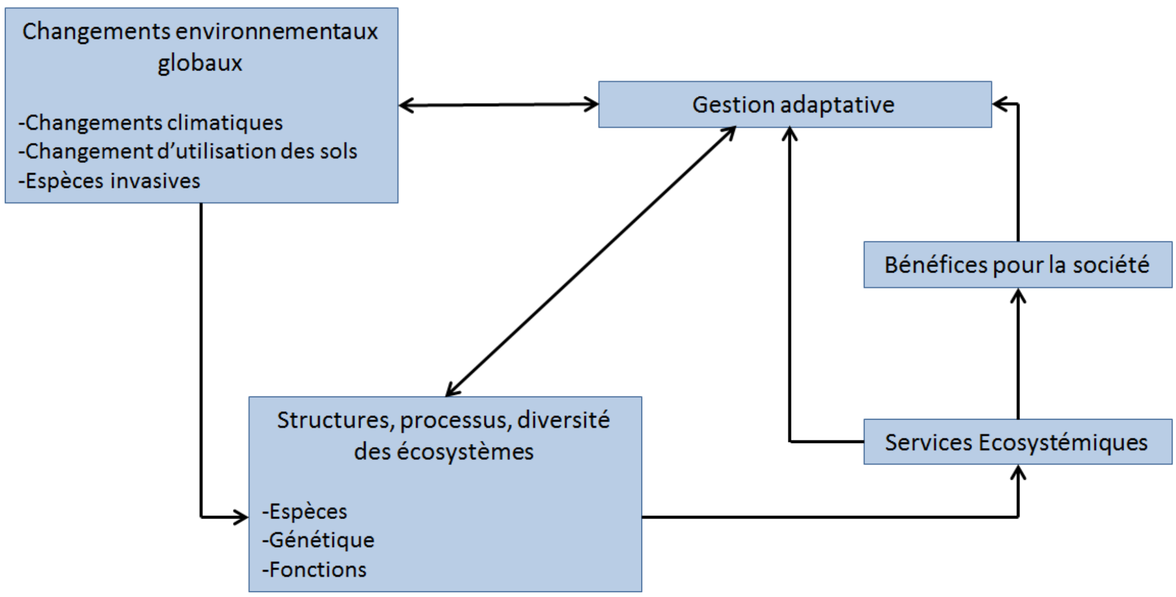

Figure I.2. Cadre liant les relations entre gestion adaptative, CEG, structures des écosystèmes et services écosystémiques. Adaptée et traduite de Birgé et al., (2016)

Plusieurs cadres analytiques ont été développés pour évaluer la vulnérabilité des systèmes socio-écologiques. Le cadre conceptuel de Marshall et al. (Figure I.3.) (2013, 2011) qui a pour objectif d'évaluer simultanément la vulnérabilité écologique et la vulnérabilité socio-économique a été utilisé dans de nombreuses études depuis sa publication (Cinner et al., 2013; Hobday et al., 2016; Metcalf et al., 2015; Thiault et al., 2017a). Cependant, un composant important de ce cadre conceptuel n'a pas été opérationnalisé dans ces études, la capacité d'adaptation écologique (CAE). Cette CAE, qui peut être décrite comme la capacité de l'écosystème à s'adapter aux changements environnementaux en conservant ses fonctions écologiques, et qui est donc liée au concept de résilience, doit être opérationnalisée pour mieux évaluer la vulnérabilité des systèmes socio-écologiques aux effets des CEG.

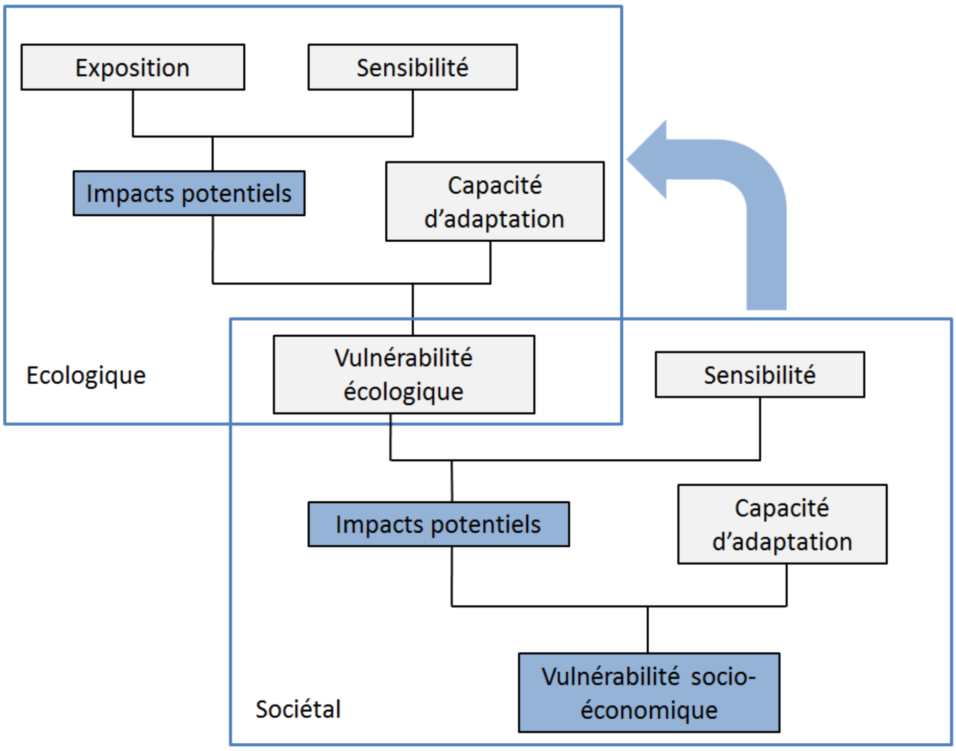

Figure I.3. Cadre conceptuel pour étudier la vulnérabilité des systèmes socio-écologiques aux changements climatiques. Adaptée et traduite de Marshall et al., (2011 ; 2013)

L'opérationnalisation de l'étude des systèmes socio-écologiques à des échelles spatiales multiples est néanmoins difficile. Les concepts généraux doivent être appliqués aux contextes locaux et les liens de gouvernances des systèmes socio-écologiques entre échelle globale et échelles locales doivent être étudiés. La plupart des évaluations de la vulnérabilité des systèmes socio-écologiques se fait à l'échelle locale (Bennett et al., 2015; Cinner et al., 2012; Perry et al., 2010). Dans cette thèse, étudions les socio-écosystèmes coralliens à une échelle globale avant de proposer des pistes d'actions et de recherche à différentes échelles.

De nombreuses études d'évaluation de la vulnérabilité se basent sur la construction et la cartographie d'indicateurs. La construction d'indicateurs pour évaluer la vulnérabilité de systèmes particuliers permet de pallier le manque de compréhension des interactions et de la complexité des relations entre les composantes de systèmes complexes. Elle permet également d'agréger les trois composantes (exposition, sensibilité, capacité d'adaptation) qui caractérisent la vulnérabilité d'un système et qui sont de nature différente. L'utilisation d'indicateurs à également l'avantage de fournir de l'information sur la vulnérabilité des SSE sans recourir à l'évaluation monétaire. Dans la mesure où les évaluations monétaires des services écosystémiques sont peu utilisées par les décideurs (Marre et al., 2016), l'utilisation d'indicateurs de dépendance aux services écosystémiques dans une approche par la vulnérabilité peut aider à la diffusion de cette information et à une meilleure utilisation de ces études par les décideurs et les gestionnaires. Ces outils facilitent la cartographie de la distribution spatiale de la vulnérabilité, et les résultats sont facilement communicables à différents publics. Dans cette thèse, nous avons donc choisi d'évaluer la vulnérabilité et l'adaptation en nous basant sur la construction d'indicateurs.

Ceci nous amène à tester des formes d'intégration entre les approches d'évaluation des services écosystémiques d'une part et des changements climatiques d'autre part dans le cadre d'une évaluation de la vulnérabilité. L'objectif premier est d'améliorer la compréhension des systèmes socio-écologiques en vue de favoriser la prise en compte des dimensions écologiques et économiques des impacts des CEG dans la mise en œuvre des politiques publiques. Pour répondre aux impacts des CEG sur les SSE, nous privilégions une approche interdisciplinaire pour contribuer au développement de concepts et d'applications de gestion adaptative. Dans le premier chapitre, nous nous focalisons sur le milieu marin et côtier en général, milieu moins bien étudié que le milieu terrestre bien qu'essentiel en terme économiques et écologiques. Les autres chapitres se focalisent plus spécifiquement sur les récifs coralliens. La section suivante constitue une introduction aux trois thèmes développés dans la thèse, à savoir les systèmes socio-écologiques et les services écosystémiques, la vulnérabilité et l'adaptation aux CEG, et la formulation de stratégies de gestion pour répondre à ces enjeux du point de vue des systèmes socio-écologiques coralliens.

c. Les effets des CEG sur les systèmes socio-écologiques coralliens

Le système socio-écologique des récifs coralliens est un cas particulièrement intéressant pour la recherche pour de nombreuses raisons. Les récifs coralliens sont présents sur les côtes d'une centaine de pays et territoires à travers le monde (Figure I.4.). Les récifs coralliens sont un des écosystèmes les plus durement et les plus rapidement touchés par l'augmentation de la concentration de CO_2 dans l'atmosphère et l'océan. Ces impacts ont été étudiés depuis plusieurs décennies (Hughes et al., 2003; Smith and Buddemeier, 1992), les récifs coralliens étant déjà un écosystème dégradé à l'échelle globale (Côté et al., 2005). De nombreuses pressions issues des activités humaines locales comme la surpêche et la pollution de l'eau ont diminué la résilience et favorisé l'émergence de maladies et de prédateurs (Graham et al., 2013; Mumby et al., 2007), mais les changements climatiques sont aujourd'hui la plus grande menace sur les récifs coralliens (Hughes et al., 2017). L'augmentation de la température est la cause la plus spectaculaire, menant à des épisodes de blanchissement lors desquelles les algues vivant en symbiose dans les tissus des coraux ne produisent plus d'énergie et sont expulsées par les coraux (Freeman et al., 2001). L'acidification des océans a également un effet négatif sur la calcification et sur d'autres processus physiologiques des coraux (Albright and Mason, 2013). Les cyclones infligent des dégâts physiques sur les récifs coralliens, la modification de leur fréquence et de leur intensité a donc des effets sur les récifs (Wolff et al., 2016). Le deuxième chapitre donne une description plus détaillée des effets des CEG sur les récifs coralliens.

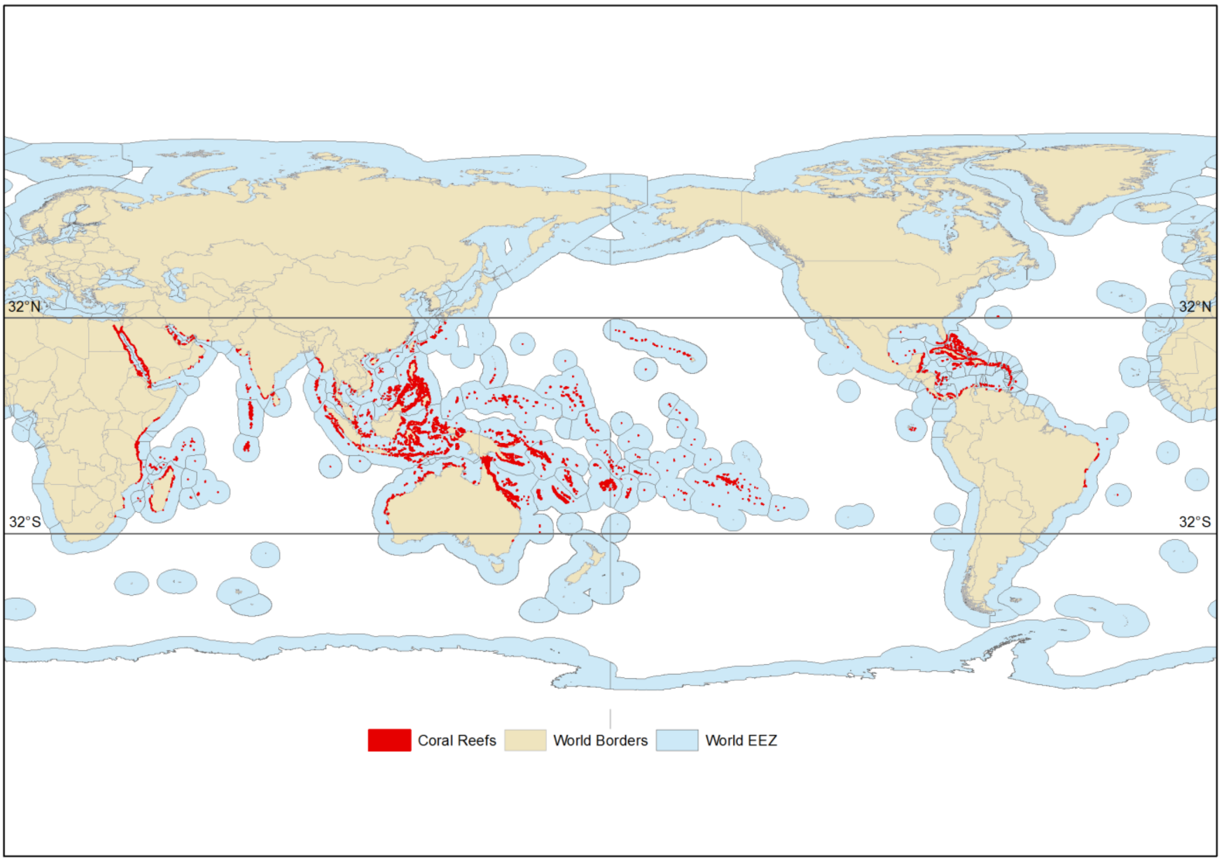

Figure I.4. Localisation des récifs coralliens à travers le monde (en rouge), localisés dans la Zone Economique Exclusive (ZEE - *EEZ* en anglais sur la carte) d'une centaine de pays et territoires à travers le monde. Source : UNEP-WCMC, WorldFish Centre, WRI (2010)

Ce système socio-écologique est un enjeu important car il contient un grand nombre d'espèces marines connues (Roberts et al., 2002) et environ 500 millions de personnes dans le monde en dépendent (Burke et al., 2011). De nombreux services écosystémiques sont produits par les récifs coralliens (Moberg and Folke, 1999), les trois plus importants étant la pêche, la protection des côtes, et les bénéfices du tourisme. De nombreuses communautés côtières dans le monde dépendent des récifs coralliens comme source de nourriture (Sadovy, 2005) et six millions de personnes ont une activité professionnelle de pêche sur les récifs (Teh et al., 2013). Les récifs coralliens jouent un rôle important de protection des côtes face à l'érosion et aux évènements extrêmes et réduisant l'énergie des vagues (Ferrario et al., 2014), et protègent donc les infrastructures et les vies humaines. Les activités touristiques liées aux récifs coralliens sont une source de devises importantes pour de nombreux pays (D. Biggs et al., 2015). D'autres services y sont associés, comme la découverte de molécules pour l'industrie pharmaceutique ou l'importance de ces récifs en termes de biodiversité et de patrimoine culturel.

Les CEG auront un impact important sur le milieu marin, et particulièrement pour les récifs coralliens et les populations humaines qui en dépendent. L'étude des systèmes socio-écologiques coralliens est donc un enjeu important pour la recherche et l'action publique. Différentes approches ont émergé pour caractériser ces impacts et tenter d'y répondre. L'intégration de la dimension humaine dans l'étude des impacts des CEG sur les récifs coralliens est récente (Kittinger et al., 2012), mais est aujourd'hui développée de manière conceptuelle (Cinner et al., 2016b; Marshall, 2010). De nombreuses études essayent d'estimer les impacts des CEG sur le milieu marin. Cependant, ces études sont pour l'instant très segmentées. A l'échelle globale, les évaluations de la vulnérabilité des systèmes socio-écologiques se fait de manière incomplète.

La vulnérabilité socio-économique a fait l'objet de quelques évaluations sous l'angle de la pêche (Bennett et al., 2014b; Guillotreau et al., 2012; Hughes et al., 2012b), mais il n'existe pas d'approche qui tente d'évaluer la vulnérabilité pour un ensemble de services écosystémiques. De même, la vulnérabilité écologique a été étudiée sous l'angle de l'exposition aux CEG (Maina et al., 2011). Aucune étude n'a jusqu'à présent tenté de répondre aux effets des CEG sur les systèmes socio-écologiques coralliens à l'échelle globale.

Bien qu'incomplètes en termes de services évalués et de couverture géographique, des évaluations économiques des services écosystémiques produits par les récifs coralliens ont vu le jour (Brander et al., 2007; Laurans et al., 2013; Stoeckl et al., 2011). Très peu d'études évaluent les impacts des CEG sur ces services écosystémiques (Brander et al., 2012; Chen et al., 2015; Rogers et al., 2015; Speers et al., 2016), et elles le font généralement sans expliciter la distribution spatiale des impacts. La construction d'indicateurs se prête mieux à ce type d'exercices, particulièrement à l'échelle globale (Tonmoy et al., 2014).

Nous étudions les impacts potentiels des CEG sur les récifs coralliens et les services écosystémiques associés dans les chapitres deux et trois. Le troisième chapitre construit des indicateurs de la dépendance des pays et territoires aux services écosystémiques produits par les récifs coralliens à l'échelle globale. A des échelles plus petites, quelques travaux ont été conduits sur la vulnérabilité des systèmes socio-écologiques spécifiquement aux récifs coralliens (Cinner et al., 2013; Marshall et al., 2013; Thiault et al., 2017b). Ces études reprennent le cadre de vulnérabilité des SSE développé par Marshall et al. (Figure I.3.). Nous poursuivons les travaux de recherche sur ce thème dans le cinquième chapitre en nous intéressant à une composante de ce cadre analytique : la capacité d'adaptation écologique.

Les récifs coralliens sont présents dans tout l'océan entre 32°S et 32°N de latitude (Figure I.4.). Plus de cents pays et territoires en possèdent. Les récifs coralliens sont donc un bon exemple de système qui doit être étudié et faire l'objet de politiques climatiques à plusieurs échelles spatiales. A l'échelle internationale, les récifs coralliens font l'objet d'une attention spéciale via des réseaux tel le réseau mondial de surveillance des récifs coralliens (GCRMN – Global Coral Reef Monitoring Network) en lien avec l'initiative internationale pour les récifs coralliens (ICRI – International Coral Reef Initative), ou dans le cadre des politiques internationales (Aichi Target de la CBD, ODD 14 de l'ONU). Certains récifs sont également classés au patrimoine mondial de l'UNESCO. Il y a donc un besoin d'études des impacts, de la vulnérabilité, et de pistes d'adaptation aux effets des CEG sur les récifs coralliens pour informer ces instances internationales. A l'échelle nationale et locale, les récifs coralliens sont des écosystèmes importants pour les populations locales et forment un système socio-écologique important pour les populations côtières. Certains récifs sont gérés à travers des politiques de pêche ou des aires marines protégées. Décideurs et gestionnaires doivent faire face aux effets des CEG sur les récifs coralliens en plus de faire face aux autres menaces locales.

A toutes ces échelles, la gestion des récifs coralliens est faite largement en concertation avec les scientifiques. Les scientifiques étudient l'évolution de ces systèmes socio-écologiques face aux pressions anthropiques locales et globales et proposent des mesures de gestion pour répondre à ces enjeux (Green et al., 2014; Leenhardt et al., 2015; McClanahan et al., 2012). De nombreuses études sur le développement de méthodes pour la gestion basée sur les écosystèmes ont émergé récemment (Anthony et al., 2015; Magris et al., 2015; Weijerman et al., 2016). Les gestionnaires s'appuient sur ces études pour agir. A l'échelle globale par exemple, l'UNESCO vient de commander un rapport scientifique pour évaluer l'état des récifs dans la liste du patrimoine mondial et prendre des mesures adéquates pour les protéger (Heron et al., 2017). A l'échelle locale, de nombreux chercheurs produisent des recommandations pour la gestion des ressources naturelles comme par exemple l'utilisation d'aires marines protégées (Ban et al., 2011; Cvitanovic et al., 2013; Green et al., 2014; Magris et al., 2015). Cependant, les initiatives scientifiques pour évaluer les impacts et la vulnérabilité des récifs et des populations humaines et celles visant à apporter des solutions ne sont pas suffisamment coordonnées. Il y a pour cela besoin d'identifier des priorités de recherche en termes de sujets et d'espaces géographiques. Le quatrième chapitre évalue les contributions de la communauté scientifique à la gestion des systèmes socio-écologiques coralliens dans un contexte de CEG.

4. Contexte de réalisation de la thèse

Cette section décrit le contexte institutionnel, les aspects organisationnels, les valorisations présentes et futures et la démarche méthodologique qui caractérisent la réalisation de cette thèse.

Ce travail a bénéficié d'une aide de l'Etat gérée par l'Agence Nationale de la Recherche au titre du programme « Investissements d'avenir » portant la référence ANR-10-LABX-19, ainsi que d'une aide de la Région Bretagne (allocation de recherche doctorale). Elle s'est déroulée au sein de la chaire internationale du LabexMer sur les services écosystémiques marins hébergée dans au laboratoire AMURE.

Les chapitres de thèse font pour la plupart l'objet de publications dans des revues internationales à comité de lecture. Les deuxième et troisième chapitres sont publiés, le quatrième chapitre est en révision, le premier chapitre est en préparation pour être soumis au journal *Marine Policy* et le cinquième chapitre, bien que moins avancé, est en préparation pour être soumis à la revue *Global Environmental Change*. Plusieurs ateliers de travail regroupant des chercheurs internationaux ont permis d'engager la réflexion sur les différents articles présentés dans cette thèse. En amont de cette thèse, des ateliers de travail dirigés par Linwood Pendleton, Sarah Cooley et Lisa Suatoni et financés par le centre américain SESYNC et la Fondation Albert II de Monaco ont été organisé entre 2012 et 2014 pour construire les cadres analytiques qui ont servi de base pour les analyses développées dans le troisième chapitre de cette thèse. Un atelier de travail a également été organisé en 2015 à Brest avec des chercheurs internationaux en écologie pour réfléchir aux effets des CEG sur les récifs coralliens, qui a abouti au deuxième chapitre de cette thèse. Les auteurs de cet article sont les participants à ce deuxième atelier. Par ailleurs, une première version du premier chapitre a été diffusé en tant que fiche scientifique de la Plateforme Océan et Climat en 2015.

Ce travail de thèse s'inscrit dans une démarche plus large du laboratoire AMURE et de la chaire internationale sur les services écosystémiques marins visant à favoriser le travail en interdisciplinarité. Dans ce cadre, un atelier interdisciplinaire regroupant jeunes chercheurs et chercheurs expérimentés a été organisé durant la conférence internationale MSEAS 2016. Cet atelier a débouché sur un article de recherche (Drakou et al., 2017). Une participation à une école d'été interdisciplinaire portant sur la vulnérabilité du patrimoine récifal organisé à Madagascar en 2016 est également en cours de valorisation sous forme d'un article scientifique, accepté dans la revue Natures Sciences Sociétés (Morandi et al., n.d.).

Un projet a été soumis pour une application de terrain suites aux réflexions sur les impacts des GEC sur les récifs coralliens, l'action publique, et le développement du cadre analytique de la capacité d'adaptation écologique (l'objet du cinquième chapitre). Dans une démarche de recherche et d'appui aux politiques publiques, ce projet a pour objectif d'évaluer la capacité d'adaptation écologique des récifs coralliens en Polynésie française et d'utiliser cette étude de cas pour affiner la méthodologie d'évaluation de la capacité d'adaptation écologique. Ce projet est financé pour une durée de un an par l'IFRECOR et le LabexMer.

Les études qui composent cette thèse reposent principalement sur la littérature et sur des bases de données existantes. Partir sur l'analyse de l'existant nous permet de questionner de manière critique les cadres méthodologiques mobilisés par la communauté scientifique pour évaluer les effets des CEG. Ce qui nous amène à déconstruire les cadres analytiques proposés jusqu'ici. L'utilisation de bases de données existantes nous permet dans un second temps de construire des approches socio-écologiques afin d'évaluer les impacts potentiels des CEG sur les récifs coralliens et les populations qui en dépendent et sur les solutions à ces enjeux proposées par la communauté scientifique. Ces chapitres reposent donc sur des analyses à la fois de nature « positive » et « normative ». En effet, tous les chapitres se basent d'abord sur un état des lieux de ce qui est, en matière d'utilisation des évaluations de la vulnérabilité, de connaissance sur les effets des CEG sur les récifs coralliens, sur la distribution de leurs effets et des services écosystémiques qui pourraient être affectés, sur les activités de recherche en cours pour proposer des solutions à ces menaces et sur les méthodes utilisés pour prioriser l'action. Les chapitres de thèses utilisent ensuite ces analyses positives pour faire des prescriptions normatives sur ce qui devrait être. Ces prescriptions sont d'abord adressées à la communauté de la recherche en identifiant les limites des connaissances et les opportunités futures. Des prescriptions sont également adressées aux décideurs et aux gestionnaires qui doivent prioriser les mesures de gestions pour lutter contre les effets des CEG sur les systèmes marins et côtiers.

5. Plan de la dissertation

Cinq facettes de la problématique générale posée au début de l'introduction sont développées dans les cinq chapitres de la thèse. Les aspects traités couvrent un large champ d'étude interdisciplinaire sur les CEG en utilisant des concepts, des méthodes et des données empruntées à l'économie, la géographie, l'écologie et l'océanographie. Le premier chapitre porte sur l'étude du milieu marin en général, tandis que les quatre autres chapitres se focalisent spécifiquement sur l'étude des récifs coralliens et des populations humaines qui en dépendent. L'enchaînement des chapitres est conçu de sorte à donner une cohérence d'ensemble. Leur construction repose en effet sur les conclusions des chapitres précédents et influencent la construction des chapitres suivants.

Dans le premier chapitre, nous évaluons la contribution des études d'évaluation de la vulnérabilité du milieu marin et côtier pour aider à la création et à la priorisation des politiques publiques internationales. Ceci met en évidence une grande variabilité dans le classement des pays considérés comme vulnérables en fonction de la méthodologie utilisée. Ce constat nous amène à développer un nouveau cadre théorique pour repenser l'utilisation des études d'évaluation de la vulnérabilité en les découpant en deux phases. La première phase se concentre sur l'évaluation d'impacts potentiels à l'échelle globale pour informer l'action et la conduite, dans une deuxième phase, d'évaluations de la vulnérabilité spécifiques à une échelle nationale ou locale. La notion de capacité d'adaptation est en effet abordable de manière plus complète à une échelle locale.

Dans les chapitres deux à cinq, nous nous focalisons spécifiquement sur l'étude des systèmes socio-écologiques coralliens. En effet, les récifs coralliens sont un écosystème important en termes de biodiversité et de services écosystémiques rendus aux sociétés humaines. Les récifs coralliens sont un des écosystèmes les plus menacés par les CEG, nous permettant donc d'imaginer une fenêtre sur ce que peut être le futur d'autres systèmes socio-écologiques. Ces systèmes font l'objet d'une attention particulière de la communauté scientifique et sont donc un sujet intéressant pour questionner l'effort scientifique pour guider les politiques publiques.

Le deuxième chapitre examine les évidences scientifiques provenant d'expérimentations et d'études de terrain sur les effets des CEG sur les récifs coralliens dans un cadre de recherche socio-écologique tenant compte des fonctions écologiques et des activités humaines. Il apparaît que l'acidification et l'augmentation de la température de l'eau semblent être les enjeux les plus importants pour les récifs coralliens dont découle des besoins de recherche pour mieux comprendre les effets de ces relations à toutes les échelles, de la biologie à l'écologie et aux interactions avec les sociétés humaines. Il apparaît clairement que les études futures sur les impacts des CEG doivent prendre en compte des effets multiples et non plus se focaliser sur un effet unique comme la température ou l'acidification.

Le troisième chapitre intègre les réflexions des deux premiers chapitres pour construire une étude globale des impacts des CEG sur les récifs coralliens et les populations humaines qui en dépendent. Ce chapitre est basé sur la construction théorique élaborée dans le premier chapitre qui suggère dans un premier temps de se concentrer sur l'évaluation de l'impact potentiel à l'échelle globale. Il se base également sur le constat du deuxième chapitre que l'acidification et l'augmentation de la température de l'océan sont deux effets importants à prendre en compte. Ces réflexions nous amènent à construire des indicateurs pour cartographier les impacts potentiels des CEG sur les récifs coralliens et les populations humaines à l'échelle du globe. Ces indicateurs cherchent à intégrer la dimension écologique avec la dimension socio-économique. Nous nous focalisons seulement sur la dépendance des Nations aux services écosystémiques fournis par les récifs coralliens. Cet indicateur de dépendance représente une valeur maximale présente des impacts potentiels. La cartographie de l'exposition aux CEG et de la dépendance des pays aux services rendus par les récifs coralliens est une démarche importante car ce système socio-écologique et les décisions qui s'y rapportent sont ancrés dans une géographie spécifique. La création d'indicateurs d'exposition d'une part et de sensibilité (ou dépendance) d'autre part permet d'apporter certaines informations utiles pour prioriser la recherche et l'action en vue de faire face aux effets des CEG sur les récifs coralliens et les populations humaines. Ces résultats nous amènent à réfléchir aux stratégies de gestions possibles pour répondre à ces enjeux.

Le quatrième chapitre contribue à l'évaluation des politiques publiques liées aux effets des CEG sur les récifs coralliens et les populations qui en dépendent en faisant un état des lieux des stratégies de gestion mises en avant dans la littérature scientifique depuis 25 ans. L'identification de ces stratégies est un préalable à leur évaluation et à leur intégration dans les politiques publiques pour lutter contre les effets des CEG. Cette étude adapte une typologie d'actions développée pour informer les décideurs sur les actions à mener face aux effets du CO_2 sur les écosystèmes et les services écosystémiques marins. Pour aborder tous les aspects des impacts potentiels et décrire les stratégies de gestion disponibles, nous adaptons cette typologie au cas des récifs coralliens. Une revue systématique de la littérature nous permet ensuite de décrire les mesures de gestions identifiées par la communauté scientifique. L'identification des catégories de stratégies et des régions du monde peu étudiées fournit des indications pour établir des priorités de recherche. La description de l'éventail de stratégies disponibles nous permet d'explorer les méthodes pour prioriser les stratégies les plus pertinentes dans des contextes de vulnérabilité écologique et sociale différents.

Le cinquième chapitre propose un cadre analytique pour améliorer l'évaluation des stratégies de gestion existantes pour répondre aux CEG. Nous partons du constat que les méthodes d'évaluation de la vulnérabilité de systèmes socio-écologiques n'ont pas opérationnalisés une de ses composantes, la capacité d'adaptation écologique. Cette composante est re-conceptualisée dans le cadre de l'évaluation de la vulnérabilité et de la résilience. Cette re-conceptualisation aborde la question des limites à l'adaptation des écosystèmes, question particulièrement importante dans le cas des récifs coralliens qui pourraient perdre la majorité de leur surface à la fin de siècle selon certaines estimations. Nous développons de nouveaux outils et de nouveaux indicateurs pour opérationnaliser le concept de capacité d'adaptation écologique des systèmes socio-écologiques coralliens. En explicitant les situations dans lesquelles les actions locales auront de l'importance, ces évaluations peuvent aider à prioriser les stratégies de gestion pour lutter contre les effets des CEG.

La discussion synthétise les résultats des cinq chapitres pour faire émerger les contributions de cette thèse à la recherche et à la mise en œuvre des politiques publiques. Cette discussion porte d'abord sur les contributions à l'étude des systèmes socio-écologiques coralliens. Nous en dégageons ensuite des conclusions plus générales, d'ordre méthodologique et épistémologique, pour faire avancer la recherche sur le développement d'indicateurs qui intègrent les aspects écologiques et socio-économiques, ainsi que sur la mise en place et l'évaluation des politiques publiques pour lutter contre les CEG. Les limites de la thèse sont également discutées et des directions futures de recherches proposées.

Chapter 1. Conceptual advances on global scale assessments of marine and coastal vulnerability

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Associated annexes: -

Acknowledgements: This manuscript was developed after an earlier note published in OCEAN AND CLIMATE, 2015 – Scientific Notes.www.ocean-climate.org, 116 pages. This research was possible thanks to a grant from the Prince Albert II of Monaco Foundation and a grant from the Region of Brittany. It was also supported by the "Laboratoire d'Excellence" LabexMER (ANR-10-LABX-19) and co-funded by a grant from the French government under the program "Investissements d'Avenir".

1 The need for global level assessments to identify climate change impacts on coastal populations and their livelihoods to inform action

Climate change is expected to have severe adverse effects on marine and coastal ecosystems and human activities who depend on them (Allison and Bassett, 2015; Gattuso et al., 2015), thus calling for better identification of areas at particular risk to mitigate their impacts. Long-term changes, such as sea-level rise, ocean acidification, and changes in sea surface temperature are expected to put millions of people and billions of dollars' worth of economic sectors at risk (Hoegh-Guldberg et al., 2014). Countries across the globe are not equally vulnerable to, and will not be equally impacted by, the wide-ranging effects of climate change, the large majority of which is expected to be negative. Understanding which countries are most vulnerable to the adverse effects of climate change is important, firstly for equity reasons (Smit and Pilifosova, 2003; Wolff et al., 2015), and secondly to inform investments in research and action including adaptation planning and capacity building (Cutter, Boruff and Shirley 2003).

This issue is raised in article 4.4 of the United Nations Framework Convention on Climate Change (UNFCCC). Article 4.4 states that developed countries shall "[...] assist the developing country parties that are particularly vulnerable to the adverse effects of climate change in meeting costs of adaptation to those adverse effects" (United Nations, 1992). The same mandate was given to global financial institutions such as the Green Climate Fund (GCF) and the Adaptation Fund. For instance, the GCF "[aims] for a floor of fifty per cent of the adaptation [funding] allocation for particularly vulnerable countries, including least developed countries (LDCs), small island developing States (SIDS) and African States" (GCF, 2014, Decision B.06/06). In addition, international development targets such as the Sustainable Development Goals (SDGs) have reinforced the demand for scientific assessments at the global level that can help inform climate and development investment and action. The international climate negotiations embraced the idea of vulnerability and some argue that identifying vulnerable countries is a political process (Klein, 2009). For instance, the Climate Vulnerable Forum was founded to create a coalition and build capacity of countries that identify as vulnerable in international negotiations.

Global level indicator-based vulnerability assessments have become very popular in the hopes of using them as tools to identify "developing country parties that are particularly vulnerable to the adverse effects of climate change" who will receive help from countries that have the means to do so, in the form of financial transfers to "[meet the] costs of adaptation to those adverse effects" (United Nations, 1992).

The Intergovernmental Panel on Climate Change (IPCC) was an early adopter of global level indicator-based vulnerability assessments in order to identify vulnerable places in particular need of assistance to combat climate change. They aimed at communicating the seriousness of climate change more effectively with spatial analyses and maps. Vulnerability assessments are used by the IPCC to communicate places needing investment and action the most.

Vulnerability assessments developed by the research community rely on a scientifically sound understanding of the impacts of climate change on physical, ecological and social systems (Adger, 2006; Cutter et al., 2003; Polsky et al., 2007; Schröter et al., 2005; Turner et al., 2003). They draw from a range of academic disciplines including oceanographic, ecological, and social sciences and use different methods but usually construct composite indicators to be able to rank countries (Tonmoy et al., 2014; Wolf et al., 2012).

Assessing future threats of global environmental change on ocean and coastal socio-ecological systems is important for the sustenance of economies and livelihoods. However, the current lack of understanding of the mechanistic relationships between global changes and socio-economic impacts is hindering the development and establishment of comprehensive modeling approaches by the marine science community. It has been argued that using the IPCC vulnerability framework could help the marine science community move forward to better characterize impacts of climate change on the marine environment and guide decision-makers (Mathis et al., 2015).

Many studies coming from the research community as well as international organizations and Non-Governmental Organizations (NGOs) have attempted to rank countries based on their vulnerability to climate change. In order to do so, composite indexes have been built to establish these vulnerability assessments. There is no unified approach to global indicator-based vulnerability assessment which has resulted in a variety of applications, even for those focused specifically on marine and coastal applications, and a drive for such analyses to become more data intensive and "comprehensive" over time (Füssel and Klein, 2006). Methodologies and results vary greatly across these assessments, which have triggered much debate within the research community on using indicator-based vulnerability assessments at the global level. For example, Hinkel (2011) argues that vulnerability assessment was originally designed and is best suited for application at the local level and not the global level, questioning the validity of using such assessments at all.

While all global vulnerability assessments are based on useful data and indicators, the assumptions and final scores used for prioritizing countries produced by such assessments are difficult to use to understand what drives climate vulnerability and thus opportunities for relevant climate-related investment. Methodologies are rarely explicit, and aggregating all data used into a single score degrades complexity and quality of information. The challenges that confront the global level application of vulnerability assessments for use in targeting climate-related investment include:

• a lack of harmonized conceptualization of vulnerability and associated concepts, in particular impact and adaptive capacity, in addition to how these concepts are operationalized in practice,

• added to an ever expanding number of variables used for such assessments, many of which are not available reliably at the global level, resulting in increased complexity of analysis and combination of very different metrics together which make it difficult to isolate climate impacts on populations from other factors,

• a lack of consideration of the costs of action in addition to climate vulnerability and impacts.

If they are to be useful to climate decision-makers, we propose that current global level assessments should not be designed and applied as comprehensive studies but rather as scoping studies that focus clearly on the basic pathways that link climate change to impacts on people, without extending the analysis to determine overall vulnerability which is context specific. These global level "impact assessments" then could be supplemented by more refined local level assessments and analyses of costs of action to provide information useful to climate action and investment from the global down to the local level.

In this paper, we summarize briefly the current use of vulnerability assessments to understand impacts of climate change on coastal populations, highlight limitations for application at the global scale, and propose a way forward to provide guidance for future vulnerability assessments on coastal and marine issues.

2. Contrasted conceptualizations of vulnerability and associated concepts

Vulnerability is a concept that is intuitively understandable and simple because it is used in many everyday life contexts: we can be vulnerable to diseases, attacks etc. This concept allows for integration of physical, ecological, and human impacts of climate change. The concept emerged in its current form in relation to disaster management at the local level (e.g. Weichselgartner, 2001) and has evolved over time to be used by interdisciplinary research on a number of topics including climate change (Turner et al., 2003). During this evolution, climate change vulnerability assessments have become more complex, building from impact assessments to including non-climate drivers (of environmental or socio-economic nature) and adaptation responses (Füssel and Klein, 2006). However, there is no consistent definition nor conceptualization of vulnerability, let alone measurement for practical applications (Adger, 2006). Vulnerability research efforts are currently focusing on developing independent vulnerability approaches and indexes to test their relevance and applicability. The vulnerability concept lacks an operational definition and measurement for consistent practical applications (Adger, 2006), which means it is difficult to choose among competing approaches or to understand their differences.

The lack of a harmonized definition for vulnerability can be best illustrated through the evolution of the framework used by the IPCC for vulnerability assessments at the global level between 2001 and 2014 (Figure 1.1.a,b).

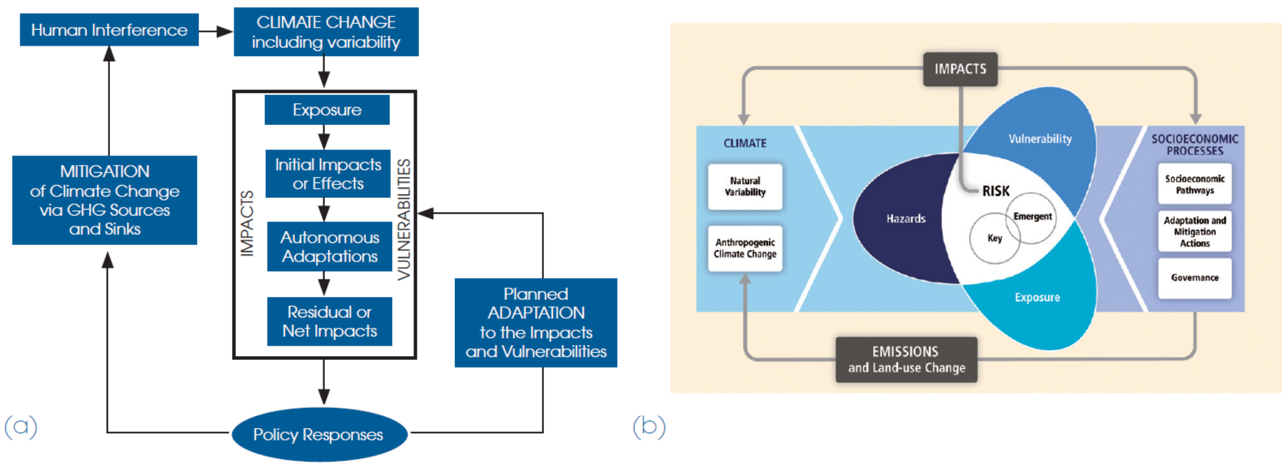

Figure 1.1. 2001 and 2014 conceptual frameworks used by the IPCC for vulnerability assessments. Sources: (a) Places of adaptation in the climate change issue (Schneider and Sarukhan, 2001, p.90) (b) Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk (Oppenheimer et al., 2014, p.1046).

In the IPCC Third Assessment Report, vulnerability was defined as "a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity" (Schneider and Sarukhan, 2001, p.92, Figure 1.1.a). By the Fifth Assessment Report, the definition of vulnerability had already changed and become more complex: "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (Oppenheimer et al., 2014, p.1046, Figure 1.1.b). The vulnerability framework is applied to a variety of perspectives in the IPCC reports (vulnerability of ecosystems, populations, the economy), adding confusion over the message conveyed.

Even though conceptualizations differ for the definition of vulnerability, the core of the vulnerability framework remains relatively unchanged and can be boiled down to its components of hazard, exposure, sensitivity, adaptive capacity and vulnerability (Figure 1.2.). Key differences between the frameworks lie in the way the relationship between vulnerability and the other factors is formalized, and the feedbacks and actions that influence and are influenced by vulnerability - namely adaptation, mitigation, and governance. This flexibility in the framework makes the vulnerability concept well suited to analysis at the local level, where more context specific information is available (Hinkel, 2011). It makes however the concept more difficult to use at the global level in a consistent way, which would require more of a 'blueprint' approach if it is to guide investments across different types of risks and social contexts.

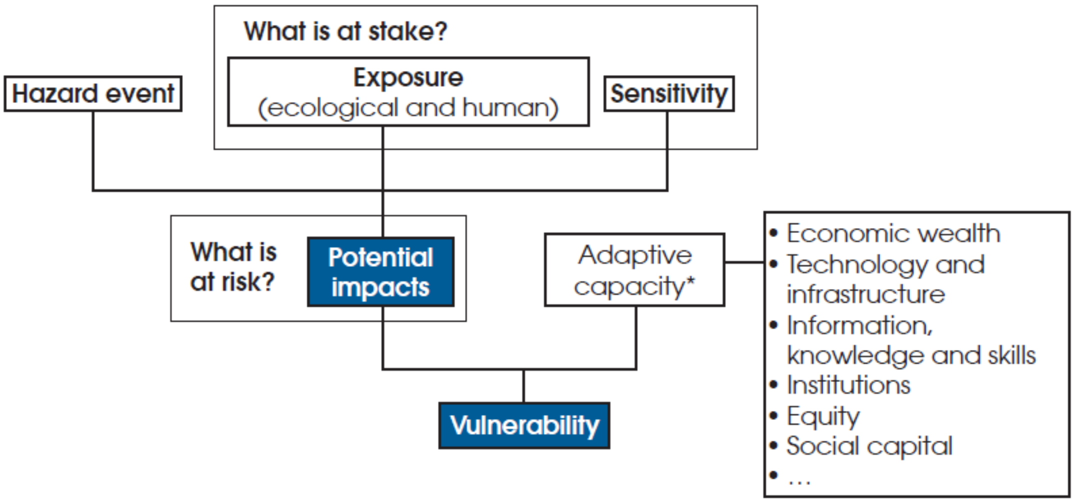

Figure 1.2. Contributing factors to potential impacts and vulnerability (adapted from Ionescu et al., 2009; Schneider and Sarukhan, 2001). Exposure, sensitivity and hazard event (bold) are predictive and speculative outcomes that lead to potential impacts. Vulnerability is the combination of potential impacts and adaptive capacity. *Adaptive capacity is often highly context specific.

A number of global indicator assessments, applied to marine resources, have been conducted by academics (e.g. Allison et al., 2009; Barange et al., 2014; Blasiak et al., 2017; Cooley et al., 2012; Halpern et al., 2012; Hughes et al., 2012; Monnereau et al., 2017) and Non-Governmental Organizations (Beck, 2014; Burke et al., 2011; Harrould-Kolieb et al., 2009; Huelsenbeck and Vorpahl, 2012) to assess ocean health and the specific risks faced by marine ecosystems and the people that depend upon them. Each has appropriated and redefined the core concepts of the approach differently. Even when definitions are common, the indicators and corresponding datasets used to measure hazard, exposure, sensitivity, adaptive capacity as well as the formulae used to calculate vulnerability itself vary across these studies, mostly in relation to available data and specific focus of these studies. While using similar basic frameworks, the existing global-level studies of the impact of environmental change to coastal populations use different indicators composed of multiple variables to determine exposure, sensitivity and adaptive capacity. For instance, these studies differ in terms of the hazards they take into account, exposed population, dependence of livelihood and infrastructure, and capacity to deal with climate change. Starting from the same framework developed by Allison et al. (2009) to study the vulnerability of marine fisheries, two groups of researchers introduced different methodological improvements and choice of indicators that lead in the first case to the conclusion that LDCs are more vulnerable (Blasiak et al., 2017) and in the other case that SIDS are more vulnerable (Monnereau et al., 2017).

Lack of agreed definition and measure of vulnerability, and ambiguous use of the concept for multiple perspectives (what/who is vulnerable to what changes) have partly impaired the establishment of clear unambiguous global assessments. It is therefore of little surprise that such global assessments have, in turn, not been able to help set up clear priorities for climate investment and action.

3. What do global vulnerability assessments actually reveal: understanding conflicting vulnerability rankings from climate change impacts on coastal human populations

As a result of different definitions, conceptual representations, and indicators used in global assessments of coastal and marine risks, very different rankings of priorities for countries at risk have been established. Table 1.1. shows a large number of different countries that appear in the top 10 in terms of vulnerability for six global assessments. Of these, 61% countries (or 36 out of 59) appear in the top 10 of only one of the reports. This finding corroborates a previous comparison of national level studies that found great differences in indicators and countries ranking (Eriksen and Kelly, 2007).

Table 1.1. Top 10 countries at risk from climate change impacts on the coasts and ocean. In orange, countries found in three of the reports, in yellow, countries found in two reports, in white countries found in only one of the reports. *Reefs at Risk revisited report only identifies 9 countries as highly vulnerable

Reefs at Risk Revisited* 2011	Coast at Risk 2014	Oceana 2012	Allison et al. 2009	Ocean Health Index 2014	Oceana 2009
Kiribati	Kiribati	Kiribati	Sierra Leone	Sierra Leone	Philippines
Philippines	Philippines	Sierra Leone	DR Congo	DR Congo	Indonesia
Comoros	Fiji	Comoros	Mozambique	Haiti	Australia
Fiji	Vanuatu	Mozambique	Angola	St. Vincent and Grenadines	France
Haiti	Antigua and Barbuda	Cook Islands	Mali	Dominica	Japan
Indonesia	Bangladesh	Eritrea	Mauritania	East Timor	Malaysia
Vanuatu	Brunei Darussalam	Madagascar	Niger	Ivory Coast	Netherlands
Grenada	Saint Kitts and Nevis	Pakistan	Peru	Liberia	New Zealand
Tanzania	Seychelles	Thailand	Russian Federation	Libya	United Kingdom
	Tonga	Togo	Senegal	Nicaragua	United States

The lack of consistent operational definition and measurement of vulnerability also means it is difficult to discriminate between existing vulnerability approaches to identify the “right one” from a theoretical perspective. In an effort to be more comprehensive and to reflect the different abilities of coastal populations to deal with climate change, recent indicator-based global level assessments include coping and adaptive capacities. All but two of these studies include measures of capacity (Barange et al., 2014; Harrould-Kolieb et al., 2009). Adaptive capacity is often the most complex component of vulnerability to understand and collect data on. Multiple factors influence the capacity of coastal populations to respond to climate change, depending on the local socio-economic characteristics, multi-level governance, but also cultural norms and customs, and perceptions of risk (Evans et al., 2016). Causal relationships between adaptive capacity and impacts are still lacking (Scheuer et al., 2011).

There are two immediate consequences of the use of capacity measures in these assessments. First, developed countries that face large potential impacts from climate change never rank high – even though the value of needed climate change related investment may be extremely large. Second, it becomes difficult to know, using final scores alone, whether a high indicator score is due to vulnerability caused by climate change or inherent vulnerabilities caused by demographic, political, and social factors. Some empirical work suggests that global adaptive capacity indicators can be identified (Brooks et al., 2005) but they so far reflect generic issues such as education and poverty that may be very important for development and well-being but not necessarily for dealing with sectoral impacts of climate change (Hughes et al., 2012a). The recent developments in vulnerability assessments attempt to include more targeted measures of adaptive capacity that are not rooted in empirical evidence.

4. A two-tiered approach for global assessment to inform climate investment and action

To avoid the challenges described above and to move towards a more transparent approach to global indicator assessments that can be used to identify climate action, a simplification and harmonization of assessments is needed to understand the impacts of climate change at the global level for coastal human populations. Specifically, we suggest a two-tiered approach for classifying existing studies to better identify common elements, and guide further global analysis (Figure 1.3.):

1. GLOBAL LEVEL IMPACT ASSESSMENTS (first tier): At the global level, we should focus on simplified and more standardized scoping studies for which good global data are available. These simpler approaches should link climate change directly to impact, be limited to impacts, and not include measures of adaptive capacity so as to clearly separate development issues from threats driven by climate change. A focus on global-level impact assessments can help identify countries where:

a. climate action may be warranted (mitigation, adaptation or other),

b. additional, finer scaled vulnerability assessments may provide crucial information to set up appropriate policy action, and

c. monitoring and science may yield socially relevant results.

The scores used to rank countries could be presented by impact or as a summary measure of how high-ranked countries scored across the impacts considered. Global-level scoping analyses based on impacts are meant to guide more refined and more data-intensive local level analyses, but do not aim to replace such local level analyses. This has been attempted recently (Barange et al., 2014). Ideally, such analyses are accompanied by a global scale analysis of technical, economic and social costs of action for comparison to potential benefits from impact mitigation and adaptation.

2. LOCAL LEVEL ASSESSMENTS (second tier): The global scoping assessments will identify places where more thorough and more comprehensive local level assessments can be used to identify concrete investment actions and the degree to which these places are vulnerable to climate change.

At the local level, more refined, data-intensive analysis can be used to better understand local impacts of global and local changes and behaviors. Such analyses would include, but not be limited to, vulnerability assessments, and would help identify key environmental and ecological factors affecting human dependencies which are most impacted by climate change. There already exists a number of relevant local level assessments which have been successfully applied in developed and developing countries that could be better used to understand climate impacts and actions (e.g. Cinner et al. 2012; Ekstrom et al. 2015; Gupta et al. 2010).

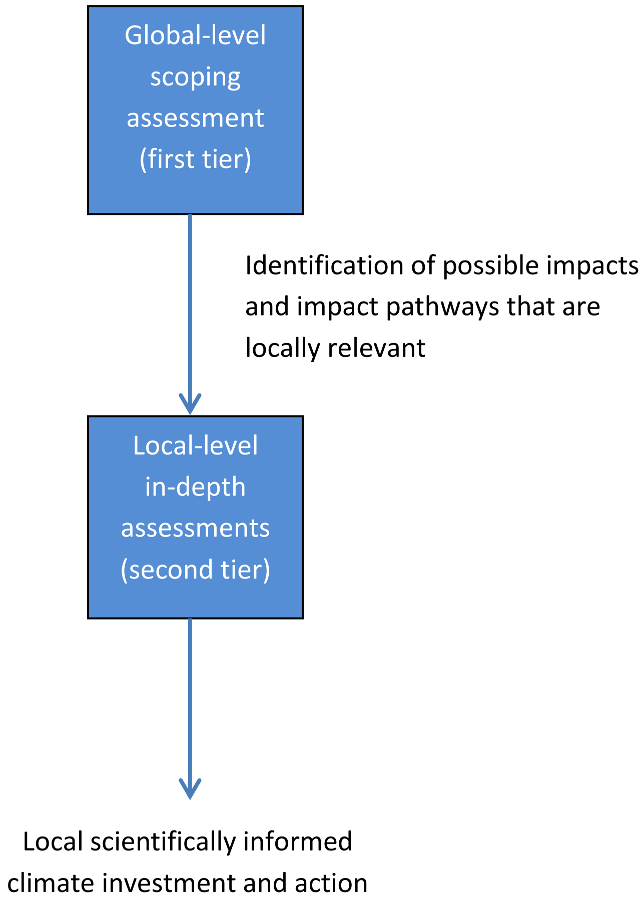

Figure 1.3. 2-tier strategy to conduct assessments

This two-tiered approach is a pragmatic way to make the most of available data, approaches and scientific methods to undertake meaningful assessments that can guide climate action and help prioritize efforts where most urgently needed. It also helps provide a global-level, transparent framework while keeping local flexibility for climate investment and action from the global down to the local level. Like vulnerability assessments, the approach combines natural and social sciences to understand the potential impacts on people of climate change, but it does so at levels that better match the social science concepts to the scale at which relevant data are available. The first tier allows for meaningful policy recommendations at the global level, while the second tier provides the needed flexibility in relation to changing spatial and human contexts.

Such a two-tiered approach still requires continued improvements in the quality and quantity of natural and social science data. While natural science data regarding climate, oceanography, corals and fisheries continues to improve, human data lag behind, especially data about local fisheries, tourism and the built environment. There is a need for better data and science to be able to structure global-level assessments in a globally coherent and meaningful way, with a need for research and data collection efforts to be targeted accordingly.

The semantics used in the international policy arena are framed around the term "vulnerability" and are making it difficult to move past vulnerability assessments at the global scale. Targeting vulnerable countries is a policy agenda that seems hard to replace by targeting potentially impacted countries, even though international funds are not necessarily targeting 'vulnerable countries' that do not have the capacity to apply for funding (Tango International & ODI, 2015).

The suggested way forward corresponds to taking a step back and adopts a simplified approach. Instead of trying to derive meaningful guidance from applying one tool at inappropriate scales of analysis (such as vulnerability assessments applied at the global level), we could apply a combination of scale-relevant tools. This would amount to shifting the emphasis from *using tools at the global level to identify local impacts* (i.e. the downscaling of global results to the local level) to *using tools at the global level to identify potential local impacts and inform local analysis* and take relevant and appropriate action from the local to the global level. It seems that this interfacing of a top-down approach and a bottom-up approach is gaining momentum in the design of new vulnerability assessments (Hobday et al., 2016).

5. Conclusion

The first tier of the two-tiered approach could be useful to identify all countries that are likely to experience large direct or indirect impacts from climate change. If applied to a pool of recipient countries alone (*i.e.* developing countries under Article 4.4 of the UNFCCC receiving international transfers), such a tier could be used to identify places where foreign assistance to meeting the costs of adaptation under the UNFCCC may be most useful and improve efficiency of international climate funding. The second tier could be used by developed and developing countries alike to inform more fine-tuned context-appropriate investment within countries, and not just international transfers. This second tier can consider different types of action, including climate change action but not exclusively, and different investment options into mitigation, adaptation, and science. It can broaden stakeholder engagement at the local level to include civil society and other parties that could improve country ownership and improve effectiveness of climate action (Brown et al., 2013; Lebel et al., 2006). Global mechanisms need to use objective criteria to prioritize investments and actions and vulnerability assessments will remain an important tool to do so.

In addition to the two tiers proposed here, we also urge parallel but separate analyses of costs of action including technical, social and economic factors is conducted at multiple scales. There are enormous gaps in terms of finance, technology, and knowledge for adaptation -particularly in developing countries- (UNEP, 2014), but a detailed estimate of investment needs for coastal populations is lacking. Vulnerability and impact assessments are not sufficient to identify and appraise actions to respond to climate change (Tulloch et al., 2015). The combination of the two-tiered approach and analyses of costs of action should provide necessary information for informed climate investment and action.

Chapter 2. Multiple stressors and ecological complexity require a new approach to coral reef research

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Associated annexes: -

Acknowledgements: The authors would like to acknowledge the SESYNC Project on Ocean Acidification for stimulating ideas for this manuscript. This paper was supported by a grant from the Prince Albert II of Monaco Foundation. Linwood Pendleton's and Adrien Comte's time also was supported by "Laboratoire d'Excellence" LabexMER (ANR-10-LABX-19) and co-funded by a grant from the French government under the program "Investissements d'Avenir". Ove Hoegh-Guldberg's time was funded partially by the Australian Research Council. The Nature Conservancy's Mapping Ocean Wealth program paid for publication costs. Vanessa Gonzàlez Ortiz created Figure 2.1.

1 Review

Major changes are occurring in the state of the world's oceans (Hoegh-Guldberg et al., 2014; Pörtner et al., 2014). Scientists have amassed evidence that changing global conditions in the ocean threaten the health and, in some cases, the existence of the world's most biodiverse marine ecosystem, coral reefs. These threats to coral reefs, in turn, pose serious risks to lives and livelihoods of hundreds of millions of people who depend on coral reefs for food, protection against storms and waves, income and the benefits of coral-based recreation (Burke et al., 2011). Predictions about the impacts of two key elements of global change on corals, increased sea temperature and ocean acidification, are often based on analyses of the historical record (Pandolfi et al., 2011), analysis of field data that attempt to attribute changes at the reef level to only one factor (for a critique, see Iglesias-Prieto et al. 2014) or single organism or single stressor laboratory experiments. Far fewer studies are conducted at a mesocosm scale in which multiple stressors and entire reef systems are considered from an experimental level (e.g. Dove et al., 2013). A recent study (Albright et al., 2016) performs a large scale field experiment by altering a single stressor (increasing pH) along a coral reef gradient.

Both scientists and planners have focused disproportionately on simple relationships (Pandolfi et al. 2011), both linear and non-linear (Ries et al., 2010), including thresholds that have been used to model future coral decalcification (Ries et al., 2010; van Hooidonk et al., 2014) and which link individual components of global environmental change to dramatic impacts like coral bleaching, and the dissolution of carbonate shells and reefs. In reality, much smaller increases in sea temperature and ocean acidification could adversely affect a wide range of critical ecosystem functions, which often interact synergistically, causing impacts that are greater than predicted for each of the stressors on their own (Albright and Mason, 2013; Anthony et al., 2008; Kaniewska et al., 2012; Lürig and Kunzmann, 2015). There is a risk that single or limited pathway approaches may yield projections that significantly overestimate the time to onset and underestimate the intensity of the impacts of global change on coral reef ecosystems.

We believe that future research strategies need to address the effects of multiple environmental factors through the numerous and interacting ways that an organism may be affected by these stresses, and via the many different organisms within an ecosystem that may be influenced in complex ways by global environmental changes (Russell et al., 2011). We argue for an approach that focuses on the key interactions and processes that will potentially help us understand and predict the impact of global changes, such as ocean acidification and increased sea surface temperature, on coral reefs and other ecosystems.

Such an approach must be strategic, coordinated, and representative of the regional ecological contexts in which the effects of ocean acidification and rising temperature on corals will be played out in the real world.

The effects of ocean acidification on coral reefs have attracted significant attention recently. Ocean acidification has been shown in the laboratory and the field to affect the structure and function of the world's oceans (Yang et al., 2015). Current rates of change in ocean chemistry have no precedent in the past 65 million years if not 300 million years (Hoegh-Guldberg et al., 2014) which will push organisms and ecosystems well out of the range of conditions for which they are adapted. While laboratory experiments will continue to advance our still nascent understanding of the mechanisms by which ocean acidification affects coral reef organisms (Kaniewska et al., 2012; Pan et al., 2015; Stillman and Paganini, 2015), it is also important that the research community develops a research strategy that takes into account realistic rates of change, scale and complexity.

Ocean acidification occurs when atmospheric carbon dioxide increases, leading to more carbon dioxide entering the ocean. On entering the water column, carbon dioxide reacts with water to create a weak acid, thereby reducing pH and decreasing the concentration of carbonate ions (critical for calcification). Previous attempts to project the future impacts of ocean acidification on coral reefs focused narrowly on the balance between the formation (calcification) and dissolution (decalcification) of calcium carbonate, and its effects on reef structure (Pandolfi et al., 2011) and generally don't account for strong multi-stressor interactions. Other factors, like elevated sea surface temperature, appear to work synergistically with ocean acidification, greatly enhancing the effect of the individual factors (Bijma et al., 2013; Rodolfo-Metalpa et al., 2011). Exploring the influence of ocean acidification on reef building corals, for example, reveals very different responses when other factors are included (Anthony et al., 2008; Vogel et al., 2015), with evidence of synergistic or antagonistic outcomes between factors like ocean temperature and acidity (e.g. fertilization success (Albright and Mason, 2013)). More than 60 new studies have appeared in the literature addressing the role of ocean acidification on a mix of marine organisms or natural communities (Yang et al., 2015).

While research that has focused on single variables, such as increased sea surface temperature, or single species, has contributed to our understanding of global change (Eakin et al., 2010), such approaches often fail to address the otherwise complex nature of these systems. There is a risk that these approaches may lead to overly conservative estimates of the scale and speed of onset of future impacts. It cannot be assumed that complexity will reduce the real impacts of these environmental stressors. Mesocosm experiments in the

Great Barrier Reef showed that individual coral colonies maintained positive net calcification rates while the net calcification rates for the larger reef community became strongly negative (Dove et al., 2013). Similarly, in Palau Rock Islands, changes in pH were found to affect rates of bio-erosion even though many other community characteristics were unaffected (Barkley et al., 2015). This highlights the potential problem of making community level projections based on studies that focus on too narrow a group of organisms within simplified experimental frameworks.

To illustrate the many stressors, pathways, and outcomes by which environmental change can impact coral reef ecosystems, we present a conceptual diagram (Figure 2.1.A) built upon a recent survey by Cinner et al. (2015) to create a basic model of essential reef complexity. The diagram incorporates findings from empirical studies conducted in the laboratory and the field where corals have experienced changes in temperature (bleaching events) and ocean acidification (e.g. near seeps and upwelling). The conceptual model is built around the basic calcification/decalcification pathway (in black) but also illustrates the multiplicity of stresses (Ateweberhan et al., 2013; Breitburg et al., 2015), the numerous pathways of impacts on organisms, and the many organismal components of the system, including people.

Previous analyses of the impacts of ocean acidification on coral reef ecosystems often build on the most basic, foundational relationship - that coral reefs are shaped by the equilibrium between erosion and accretion of calcium carbonate (Figure 2.1.A). Biotic factors (e.g. grazing parrotfish and invertebrates, excavating sponges, endolithic algae) as well as abiotic factors (e.g. storms and ocean chemistry) contribute to the breakdown and dissolution of accreted calcium carbonate. On the other side of the ledger, a range of organisms, from reef building corals to red coralline algae, deposit calcium carbonate that, under the right conditions, ultimately builds the 3-D framework of carbonate reef systems. When these factors are in balance, reefs retain their structure or even increase in size and complexity. These processes of reef construction and destruction have preoccupied investigators trying to understand the potential impacts of ocean acidification for coral reefs as structures. However, a large range of other organisms and interactions are also present within carbonate coral reef systems (Figure 2.1.A). These other organisms and processes drive a large range of other phenomena within coral reefs such as primary productivity, habitat, nutrient cycles, gas exchange, and genetic diversity and connectivity. Global factors, such as increased sea temperature and ocean acidification, combine with each other and local environmental stresses to alter the state of coral reefs by disrupting the physiology, gene expression, and behavior of many organisms within this system, not just corals (Figure

2.1.A). These impacts are made worse by other global scale changes in frequency and strength of hurricanes and widening anoxic dead zones.

Ocean acidification has a direct impact on the calcification rates of many corals (Dove et al., 2013; Kaniewska et al., 2015), which has implications for the 3-D structure of coral reefs; reflected in a body of knowledge that has increased significantly over the past 15 years. While there have been many studies on the calcification of corals (see Chan and Connolly 2012 and Kroeker et al., 2013 for reviews), identification of the mechanism(s) that results in a change in calcification in the field has been complicated by the fact that multiple factors (e.g. elevated temperature and OA) act simultaneously and often synergistically. Anthony et al. (2008), for example, found that the threshold for thermal bleaching was reduced by ocean acidification, indicating that corals became more sensitive to thermal stress when exposed to ocean acidification.

Understanding the functional changes in coral reefs is as important as understanding the impacts on calcification, yet has been neglected in the majority of previous studies of changes to reefs caused by ocean acidification (Pan et al., 2015). While there are a growing number of studies about the effects of ocean acidification on processes other than coral calcification and dissolution (e.g. productivity, growth, reproduction), they often are restricted to a small number of organisms and processes relative to the high biological diversity and ecosystem complexity of even the simplest coral reefs (Kroeker et al., 2013). Previous studies also provide very little information on the effect of ocean acidification and other factors on the function of microbial organisms and processes that play crucial roles in everything from nutrient cycles to decalcification. Nutrients may play a complicated role in reef structure and have been shown to make corals less sensitive to elevated CO_2, even though at the community level they have been shown to stimulate bioeroders. Macro-organisms such as sea cucumbers, fish, and many other organisms also show changes in physiology and behavior due to ocean acidification which could have important implications for coral reef processes, although the number of studies about this is extremely small (Kroeker et al., 2013).

Finally, the role of humans as prominent drivers of current conditions (i.e. the Anthropocene) needs to be included along more dimensions that normally found in the literature. Prior to the Anthropocene, people had a direct influence on reef functions, through fishing and reef destruction. Presumably, at low levels, these human impacts could occur within the “scope for growth” required to maintain a healthy reef system (Hoegh-Guldberg, 2014). Increasingly, human activities at the local scale, including direct and indirect impacts such as overfishing, mining, nutrient runoff, and pollution are leading to a net loss of coral reefs and coral reef structure (Burke et al., 2011). Today, people worldwide indirectly affect reef state by contributing through actions that cause the release of carbon dioxide and other greenhouse gases that lead to increases in ocean temperature, sea level rise, and ocean acidification (IPCC, 2013).

Human and ecosystem-level adaptation and even some level of evolution could occur if the changes to corals caused by ocean acidification were to occur slowly and evenly, with stabilization by mid-to-late century (what we refer to as the soft landing effect, Figure 2.1.B) or if only one environmental factor changed. The integrated, multiple pathways model of reef processes, however, suggests that simple, linear changes in reef systems are unlikely. Under these more realistic conditions, transitions are unlikely to be slow or smooth. The combination of multiple stressors acting on a variety of organismal processes in many species of reef organisms could well mean that thresholds are further reduced with the result that the combined impacts of climate change, ocean acidification, storms, and local stressors could occur much sooner than currently thought (Figure 2.1.B) and be abrupt, unpredictable, and more severe than predicted by more simplified approaches.

If we are to have the science needed to understand, mitigate, and adapt to the effects of ocean acidification on coral reefs, we have to take bold and coordinated action to build upon traditional laboratory experiments to create new experimental approaches that address the complexity that will determine how coral reefs respond to ocean acidification and other global changes. Given the urgency and complexity associated with this phenomenon, we recognize an important need to build upon single factor approaches to include more strategic coral reef research that addresses the behavior of multiple factors and their interactions, with a stronger focus on coordinated, multi-factorial experiments in the laboratory, new approaches such as the Free Ocean Carbon Enrichment system deployments (Kline et al., 2012), and mesocosm-scale field experiments in addition to, and coordinated with, field experiments. Similarly, the monitoring of the physical, chemical, ecological and human impacts of ocean acidification and related temperatures needs to be coupled with this approach. This level of coordination and attention to complexity is essential if we are to develop a better understanding of the changes and challenges that we currently face as the concentration of carbon dioxide and other greenhouse gases increase rapidly in the atmosphere. Designing field experiments which take into account environmental variability at the full range of scales (and geographies), together with a more representative range of organisms and processes is central to developing the insights needed to create realistic scenarios, and thereby assist in the development of policy and management activities (Figure

2.1.C). Single organism and single factor experiments will continue to be important in unlocking the way organisms respond to environmental change. When combined with mesocosm-scaled field experiments, especially those that are located to reflect regional differences in the responses of coral reefs, these varied approaches could help to unlock the effects that multiple stressors and pathways have on the way global change will affect coral reefs.

We caution planners that univariate expectations about the potential changes that could await coral reef systems, indeed all marine ecosystems, may not reflect the complex and non-linear outcomes that could result. In reality, environmental changes that affect coral reefs will not occur along single dimensions of stress. Changes in coral reef ecosystems caused by environmental change are likely to be highly unpredictable, more rapid, and potentially more substantial than we now anticipate. A combination of laboratory and field experiments, especially those that look at naturally occurring suites of environmental change, are needed to unlock these complexities and the effects of multiple stressors. Complexity and the role of multiple stressors and pathways need to be directly incorporated into experimentation and monitoring to better understand how complex systems such as coral reefs are likely to change in response to multiple and rapidly changing global factors. The only certain way to avoid these unwanted consequences, and a constantly changing set of interacting factors, is by stabilizing the Earth's atmosphere and climate as soon as possible.

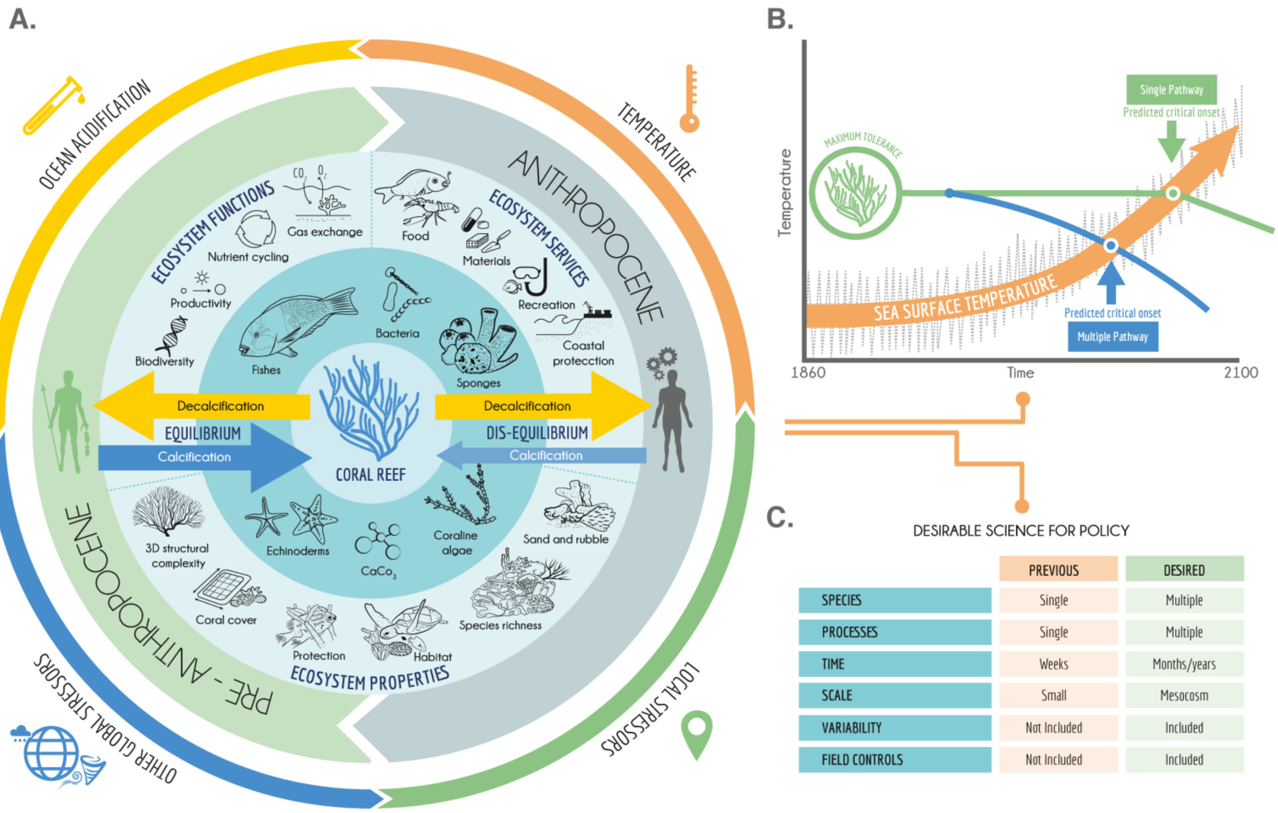

Figure 2.1. A conceptual framework describing ecological processes that contribute to coral reef growth and maintenance versus the biological and anthropogenic factors that can work against these processes. The inner circle depicts important coral reef ecosystem constituent species. The next circle represents ecosystem features that are important to people. The next circle, along with the arrows showing calcification and decalcification illustrates that in pre-Anthropocene times coral reefs experienced net growth where calcification probably exceeded decalcification; the balance has been reversed at some time during the Anthropocene. The outermost circle captures key environmental stressors that affect coral reef health and determine whether coral reefs grow or decline (inspired by Cinner et al. 2015).

Chapter 3. Coral reefs and people in a high-CO_2 world: Where can science make a difference to people?

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[¶] These authors contributed equally.

Associated annexes: A, B

Acknowledgments: Figure 3.1. and 3.6. were created by Vanessa González Ortiz. The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of NOAA or the Department of Commerce. Antoine Rivière helped immensely with manuscript preparation and submission.

1 Introduction

Hundreds of millions of people worldwide depend on coral reef ecosystems (Burke et al., 2011). Coral reef ecosystems create natural barriers that protect shorelines from storm surge and erosion - defending villages, businesses, and coastal residents (Ferrario et al., 2014). Coral reef ecosystems also support fisheries that provide food (Brander et al., 2012), jobs, and income for local communities (Cinner et al., 2016b; Hoegh-Guldberg et al., 2014) as well as tourism and recreation that contribute to jobs, profits, taxes, and foreign income (Brander et al., 2012). The recreational and cultural services provided by these ecosystems also benefit local communities and people.

Increasing levels of carbon dioxide in the atmosphere put shallow, warm-water coral reef ecosystems, and the people who depend upon them at risk from two key global environmental stresses: 1) elevated sea surface temperature (that can cause coral bleaching and related mortality), and 2) ocean acidification (OA). Bleaching and OA can compound local reef stresses that will hasten the loss of the ecosystem services provided by reefs (Figure 3.1.). Structural damage to coral reefs can result in more severe coastal inundation that puts lives and property at risk (Sheppard et al., 2005). These environmental stresses will also decrease coral ecosystem health and productivity (Yang et al., 2015; Chapter 2), which in turn could jeopardize nutrition, livelihoods, and local incomes that depend on reef fisheries and could impact reef-related tourism (Cinner et al., 2016b). We acknowledge that coral reef ecosystems are also threatened by other local stressors that include overfishing, destructive fishing, disease, predators, pollution, eutrophication, sedimentation, and episodic de-oxygenation (Newton et al., 2007). Nevertheless, we focus on elevated sea surface temperature and OA because these factors are largely beyond the control of coastal communities, managers of marine protected areas, and other management bodies that exist at the country level or smaller (Mora, 2008). Coral reef countries have four primary options to counter the threats to reefs caused by the emission of CO_2 (Gattuso et al., 2015): 1) urge governments of major CO_2-emitting nations (many of which are also home to coral reefs) to reduce carbon emissions that cause both climate change and OA, 2) reduce damages to corals caused by local environmental stressors that can make these problems worse, and 3) improve and/or restore associated ecosystems (e.g. mangroves) to a state that could replace lost ecosystem services and thus minimize impacts on people. Engineering responses, other than green infrastructure and restoration, to counter these global threats have also been proposed (Kwiatkowski et al., 2015; Rau et al., 2012), but they are largely untested. Without these measures, countries dependent on coral reef ecosystems may need to cope with a world with greatly diminished coral reefs – a response that could spur human migration.

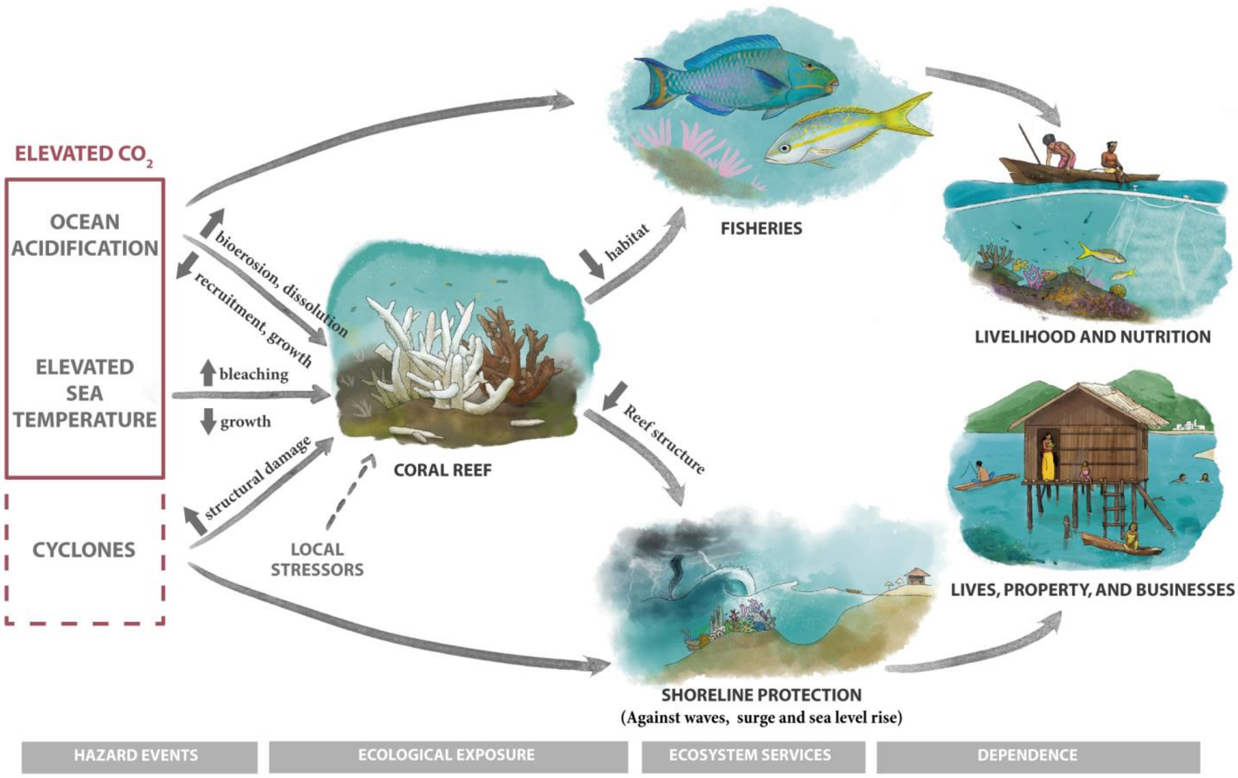


Figure 3.1. A conceptual diagram linking stresses related to increased atmospheric CO_2 (elevated sea surface temperature and ocean acidification), storms, and local stressors to coral reef condition, selected ecosystem services provided by reefs, and human dependence on these ecosystem services. Solid lines represent relationships evaluated in this study.

The ecological and social impacts of CO_2-related threats to reefs will not be the same across the globe (Cinner et al., 2016b; Hoegh-Guldberg et al., 2014; Wolff et al., 2015). Increasing levels of atmospheric CO_2 will cause the most immediate and serious problems where a) human dependence on coral reef ecosystems is high, b) sea surface temperature reaches critical levels soonest, and c) OA levels are most severe. Where these elements align, swift action will be needed to protect people's lives and livelihoods, but such policy action must be informed by data and science. Correspondingly, places where the threats of OA and climate change are low may serve as potential refugia for coral reef organisms and larvae.

Sufficient indicator data exist to create preliminary maps of the potential threats to coral reef ecosystems posed by a high-CO_2 world and the people and countries that will be affected. Two previous studies examined the combined threats faced by coral reefs from local and global stressors as well as an array of human dimensions that include human dependence and adaptive capacity (Bryant et al., 1998; Burke et al., 2011). We update and build on previous studies by developing an indicator analysis that focuses specifically on the threats to coral reefs and people from a high-CO_2 future. Our analysis also differs from previous studies in that we focus on the dependence of people on coral reef ecosystem services without attempting to assess their adaptive capacity. Adaptive capacity, while an important factor in evaluating vulnerability and risk within a region, is often represented with metrics that do not accurately convey conditions of coastal communities (Chapter 1; Hinkel, 2011). By focusing on fewer dimensions, we are able to: leverage data that allows us to increase the granularity of the analysis, increase the transparency of the analysis, and improve our ability to link high-CO_2 threats to human outcomes.

There still is much to be learned about the impacts of global change on coral reef ecosystems and the people who depend on them. We need to better understand the ecological science regarding how coral reefs are affected by both global and local environmental stressors and how people, in turn, respond to these changes. Social and economic factors should be directly considered in setting research priorities about locations for new science. An examination of current human dependence on coral reef ecosystems and our current state of knowledge about the large scale and unavoidable threats that will result from increasing concentrations of CO_2 in the atmosphere can help us identify where new science and data are needed to help people deal with these environmental changes and coral reef decline.

2. Why sea surface temperature and ocean acidification matter

Coral bleaching, mortality, and disease caused by elevated sea surface temperature, have direct impacts on coral reef ecosystems (Chapter 2). Sustained bleaching events can cause coral reef death (Hoegh-Guldberg, 1999). Historically, the time between mass mortality events allowed coral reef ecosystems to recover from the damage caused by coral bleaching as new coral larvae could settle and grow in damaged areas. As these mortality events become more frequent, it is harder for coral reef ecosystems to recover. Coral bleaching has been shown to damage coral reef ecosystems (Donner et al., 2005; Fabricius et al., 2008) and can lead to bioerosion if corals die, eventually leading to the loss of reef height and structural complexity, also known as rugosity (Alvarez-filip et al., 2009). Reef structure provides shoreline protection (Fernando et al., 2005; Sheppard et al., 2005). Ferrario et al. (2014) found that coral reefs can dissipate approximately 97% of wave energy. The reef crest is the most important attenuation factor, contributing to 86% of wave attenuation. Roughness or rugosity is the next most important attenuation factor (Ferrario et al., 2014). Moreover, the three-dimensional structure of coral reefs also provide habitat for reef fish and other organisms that support the livelihoods of coastal areas (Wilson et al., 2006). To maintain these services, reefs must not only maintain their structure, but must keep pace with sea level rise.

The ability of coral reef ecosystems to recover from damaging events is likely to be suppressed by the elevated sea surface temperature and OA expected to occur in a high-CO_2 world. Van Hooidonk et al. (Maynard et al., 2015b; van Hooidonk et al., 2014) used projections under the Intergovernmental Panel on Climate Change's RCP8.5 emissions scenario to show the potential spatial distribution of sustained, future high sea surface temperatures measured as the year when an area experiences at least 8 degrees Celsius degree-heating weeks (DHW) annually. A degree heating week is a standard measure of heat accumulation over the previous twelve weeks and represents the number of weeks an area has experienced temperatures in excess of 1 degree Celsius above the highest mean summer time temperature. Here we use this same threshold of 8 DHWs to indicate where future increases in sea surface temperature will lead to sustained bleaching and a high likelihood of coral mortality. Changes in ocean carbonate chemistry due to increasing atmospheric CO_2, known as OA and often measured by aragonite saturation state (Ω_{ar}), also poses a severe threat to corals and reef ecosystems (Hoegh-Guldberg et al., 2014). While much of the research focus, and debate, to date has been on the role of OA in the reduction of calcification rates on coral reefs (Albright et al., 2016; Howes et al., 2015; Yeakel et al., 2015), OA can significantly impair other ecological and physiological functions. For instance, coral larval success may be impaired at much more modest levels of OA. Ω_{ar} levels of 3.1 or less, a level some coral reefs will experience in the next decade, are known to impair larval recruitment of some corals (Albright et al., 2010; Manzello et al., 2014). Similar levels of OA can also reduce growth rates in some corals (Chan and Connolly, 2013). Experimental evidence shows that increased OA and thermal stress combined have a greater harmful effect on both larval success and growth rates than either factor alone (Albright and Mason, 2013), which could make coral recovery even more difficult when both stressors occur simultaneously (and at less severe levels than those required to induce harm by either stressor alone). Additionally, a variety of other coral reef organisms have also been shown to suffer from thermal stress and OA (Lürig and Kunzmann, 2015; Yang et al., 2015).

3. Materials and methods

a. Where are the greatest potential risks to reefs and people in a high-CO_2 world?

We use an indicator approach to identify places where key environmental factors driven by a high-CO_2 world may put coral reef-dependent people most at risk (Ekstrom et al., 2015). Mapping indicators has been proposed as a way of "integrating natural and social sciences to identify actions and other opportunities while policy, stakeholders and scientists are still in relatively early stages of developing research plans" to combat global environmental change (Lürig and Kunzmann, 2015). As such, an indicator approach allows for a focus on a spatial understanding of key characteristics of the social-ecological system, even in the absence of a complete set of science and data that would be needed to create more complex models of ecological processes and people's responses to change in ecosystem conditions.

To identify where people are at risk from CO_2-driven threats to coral reefs, we map indicators of two key aspects of current human dependence on coral reefs (people who benefit from the shoreline protection provided by reefs and reef-related fisheries) and two key indicators of oceanic change in a high CO_2 world (the onset of high thermal stress in terms of the year that sea surface temperature reaches 8 DHW annually (Maynard et al., 2015b; van Hooidonk et al., 2014) and the expected level of OA in year 2050). Recent studies show that the precise role that increased sea surface temperature and OA have on coral reef ecosystem conditions and health is complicated (McClanahan et al., 2015; Mongin et al., 2016b; Yeakel et al., 2015) and may vary regionally (Roff and Mumby, 2012). With that in mind, these indicators are not intended to be predictive of coral reef death. Instead, we use an indicator approach to reflect the spatial distribution of the intensity of environmental stress on corals that could result from increased levels of atmospheric CO_2 that are projected to occur during the twenty first century, if emissions continue under assumptions of business as usual (Alexander et al., 2013).

We score and map two indicators of human dependence on coral reefs at the country level: shoreline protection and coral reef fisheries. We map human dependence at the country level so that our results are commensurate with similar country-level studies of coral reef vulnerability conducted at a global scale (Beck, 2014; Bryant et al., 1998; Burke et al., 2011). To score the relative human dependence of each country in terms of the shoreline protection provided by reefs, we use calculations from Reefs at Risk Revisited (Burke et al., 2011) of the number of people in 2007 who lived at less than ten meters above sea level (Center for International Earth Science Information Network (CIESIN)/Columbia University, 2013), near a shoreline that is within 3km of a coral reef and up to 4km inland (Table 3.1.). For each country, we create a normalized score of the people at risk by taking the Z-score of log(number of people) and rescaling this from 0 to 10 (Table 3.1.) (Juwana et al., 2012). To score and map the reliance of countries on coral reef fisheries, we use data from Teh et al. 2013 (Teh et al., 2013) based on the Sea Around

Us project which estimates two components of reef-dependent fisheries landings in 2005: jobs and value (Table 3.1.). Using the Sea Around Us data, we create similar normalized scores of log(jobs) (Z-score re-scaled from 0-10) associated with reef fisheries and the estimated value of coral reef harvests (in real 2005 USD). (Value is also highly correlated with landed weight of reef fish, r=0.86). To create a summary score of human dependence, we take the average score of: a) shoreline protection, and b) the higher score of reef fish jobs or value and renormalize it to obtain a score of 0-10 (Figure 3.2.). We use only one score for fisheries dependence (the higher) in order to equally weight shoreline protection and fisheries dependence. These estimates are not projected into the future.

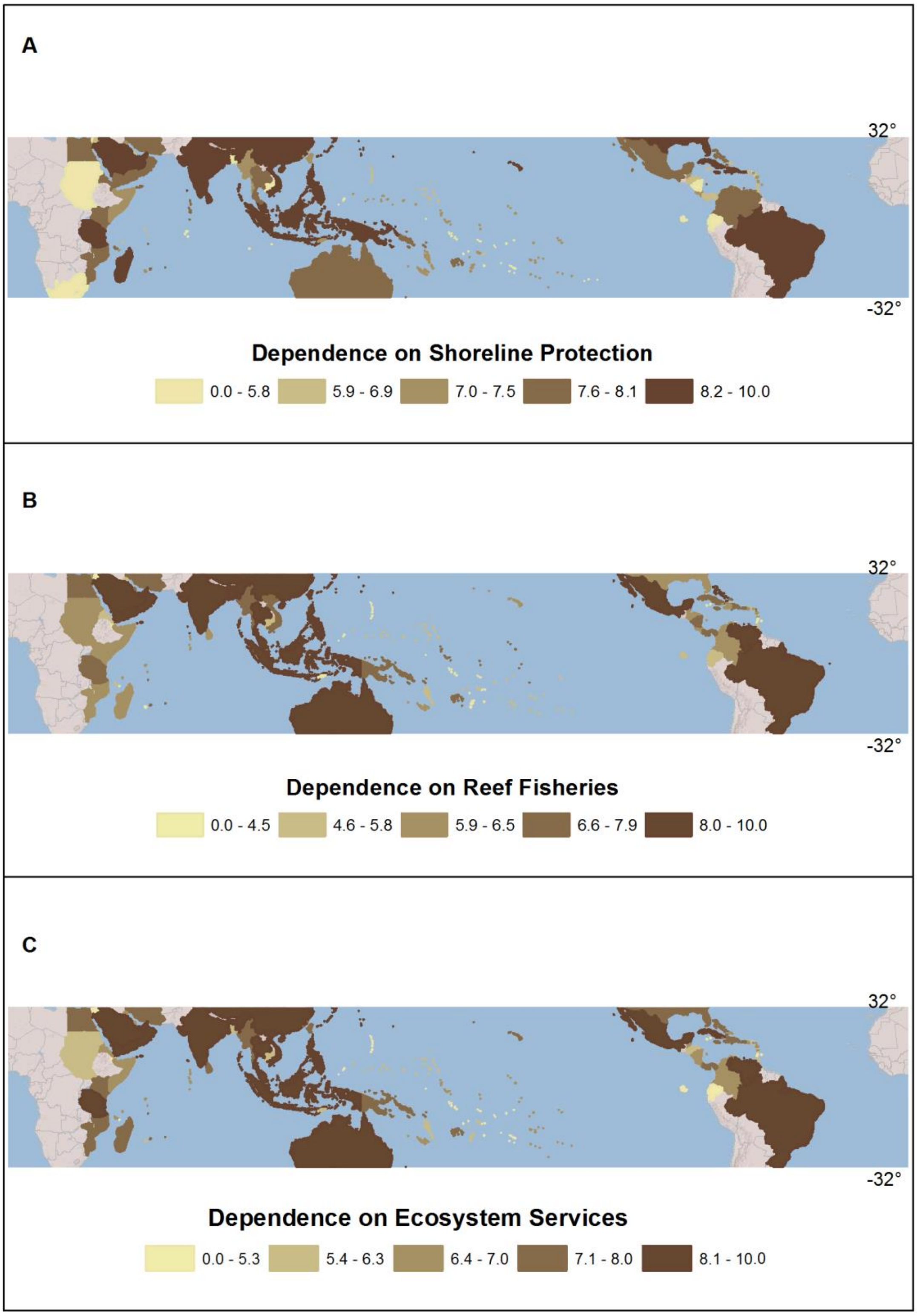


Figure 3.2. Scores of human dependence on coral reef ecosystem services, by country. Panel A provides the normalized scores for human dependence on shoreline protection, Panel B shows the normalized scores for dependence on reef fisheries, and Panel C shows combined human dependence. All scores are normalized on a scale from 0-10. Higher scores reflect higher human dependence. Countries are binned by quintile in the legend

Table 3.1. Raw data and results of the normalized scoring for human dependence, by country (only countries for which data are available are shown). Ocean Provinces: Brazilian (B), Caribbean (C), Central Pacific (CP), Great Barrier Reef (GBR), Central Indian Ocean (CIO), Eastern Pacific (EP), Middle East (ME), Polynesia (P), South East Asia (SEA), Western Australia (WA), Western Indian Ocean (WIO)

Country	Population protected by coral reefs, # of people (2007) (CIESIN)/Columbia University, 2013)	# of Fishers involved in coral reef fisheries (2005) (Teh et al., 2013)	Value of reef fish harvest (2005, in real $) (Teh et al., 2013)	Normalized Score Population Protected (0-10)	Normalized Score Maximum of Fishers, Value (0-10)	Ocean Province
American Samoa	33,296	1,847	121,901	6.4	3.7	CP, P
Anguilla	4,174	208	788,289	5.1	5.0	C
Antigua and Barbuda	24,649	2,134	10,621,547	6.2	6.8	C
Aruba	70,982	1,018	331,268	6.8	4.4	C
Australia	316,027	29,593	467,219,756	7.7	9.4	GBR, SEA, WA
Bahamas	260,184	12,000	89,287,977	7.6	8.3	C
Bahrain	575,191	7,200	63,046,838	8.1	8.0	ME
Bangladesh	1,318	230,498	N/A	4.4	8.0	SEA
Barbados	91,611	566	23,101	7.0	2.5	C
Belize	98,020	6,926	7,681,824	7.0	6.5	C
Bermuda	58,903	2,158	1,296,462	6.7	5.3	C
Brazil	1,239,637	144,433	180,174,864	8.6	8.8	B
British Virgin Islands	17,678	1,579	2,682,973	6.0	5.8	C
Brunei Darussalam	0	920	N/A	0	2.4	SEA
Cambodia	8,000	14,364	N/A	5.5	5.2	SEA
Cayman Islands	47,154	1,318	N/A	6.6	2.7	C
China	1,212,378	189,467	708,521,292	8.6	9.7	SEA

Christmas Island	994	N/A	N/A	4.2	N/A	SEA
Cocos (Keeling) Islands	643	N/A	N/A	3.9	N/A	SEA
Colombia	345,743	12,188	4,930,352	7.8	6.2	C, EP
Comoros	334,444	12,077	N/A	7.8	5.0	WIO
Cook Islands	13,919	3,971	430,936	5.8	4.5	CP, P
Costa Rica	92,470	12,303	5,959,548	7.0	6.4	C, EP
Cuba	1,299,087	11,890	34,226,998	8.6	7.6	C
Curacao	82,604	N/A	N/A	6.9	N/A	C
Djibouti	333,054	901	N/A	7.8	2.3	ME
Dominica	35,073	1,377	N/A	6.4	2.8	C
Dominican Republic	790,588	9,000	13,812,145	8.3	7.0	C
Ecuador	3,100	10,439	N/A	4.9	4.8	EP
Egypt	571,170	205,260	32,826,014	8.1	7.9	ME
Eritrea	251,926	11,255	1,744,782	7.6	5.5	ME
Federated States of Micronesia	85,748	23,413	198,862	6.9	5.7	M
Fiji	383,845	43,475	15,703,945	7.9	7.0	GBR,M, P
French Polynesia	221,276	21,495	1,765,467	7.5	5.6	P
Grenada	42,931	1,953	1,585,918	6.5	5.4	C
Guada-loupe	220,058	2,446	3,610,737	7.5	6.0	C
Haiti	1,475,746	55,045	3,973,142	8.7	6.5	C
Honduras	37,825	12,454	4,959,989	6.4	6.2	C
India	6,555,868	958,530	274,882,625	9.6	9.4	SEA, CIO
Indonesia	12,198,508	1,657,757	107,542,434	10.0	10.0	SEA
Iran	257,039	15,953	50,506,029	7.6	7.9	ME
Israel	0	400	3,370,972	0	6.0	ME
Jamaica	617,623	20,000	16,599,802	8.1	7.1	C
Japan	623,273	30,576	234,793,089	8.1	8.9	SEA
Jordan	33,519	90	59,792	6.4	3.2	ME
Kenya	521,948	12,938	5,338,532	8.0	6.3	WIO

Kiribati	94,244	14,260	11,241,006	7.0	6.8	CP, M, P
Kuwait	148,967	3,566	2,541,630	7.3	5.8	ME
Madagascar	833,698	30,000	3,991,132	8.3	6.1	WIO
Malaysia	1,142,333	83,720	248,586,246	8.5	9.0	SEA
Maldives	223,017	30,223	990,466	7.5	5.9	CIO
Marshall Islands	50,258	21,743	N/A	6.6	5.6	M
Martinique	146,793	2,500	5,793,451	7.3	6.4	C
Mauritius	265,262	7,127	18,934,530	7.6	7.2	WIO
Mayotte	147,666	1,005	8,594	7.3	2.5	WIO
Mexico	425,711	64,705	231,700,594	7.9	8.9	C, EP
Montserrat	1,715	N/A	N/A	4.5	N/A	C
Mozambique	253,243	50,326	126,557	7.6	6.4	WIO
Myanmar	180,331	123,746	N/A	7.4	7.4	SEA
Nauru	6,916	292	653	5.4	1.2	M
New Caledonia	136,153	23,539	3,542,389	7.2	6.0	GBR
Nicaragua	5,814	6,755	29,463,860	5.3	7.5	C
Niue	827	607	N/A	4.1	1.9	P
Northern Mariana Islands	53,678	603	N/A	6.6	1.9	M
Oman	314,288	10,287	90,832,869	7.7	8.3	ME
Palau	13,043	3,795	109,462	5.8	3.8	M
Panama	84,304	6,551	53,387,993	6.9	7.9	C, EP
Papua New Guinea	609,016	107,952	2,420,370	8.1	7.2	GBR
Philippines	12,963,664	911,754	705,110,034	10.0	9.7	SEA
Puerto Rico	897,188	1,163	11,208,717	8.4	6.8	C
Qatar	42,443	4,505	30,795,948	6.5	7.5	ME
Reunion	109,925	1,060	375,123	7.1	4.4	WIO
Samoa	110,024	3,586	704,204	7.1	4.9	P
Saudi Arabia	2,190,247	24,500	132,227,485	8.9	8.5	ME
Seychelles	59,299	2,000	5,485,708	6.7	6.3	WIO

Singapore	78,342	1,529	803,050	6.9	5.0	SEA
Sint Maarten	26,959	N/A	N/A	6.2	N/A	C
Solomon Islands	307,616	58,390	N/A	7.7	6.6	GBR
Somalia	176,955	3,694	4,509,732	7.4	6.2	ME, WIO
South Africa	17	N/A	N/A	1.8	N/A	WIO
Sri Lanka	944,093	22,417	4,752,304	8.4	6.2	CIO
St. Kitts and Nevis	19,664	488	2,156,335	6.0	5.7	C
St. Lucia	96,101	1,040	192,170	7.0	4.0	C
St. Vincent & the Grenadines	42,323	587	33,632	6.5	2.8	C
Sudan	3,555	27,254	50,237	5.0	5.8	ME
Taiwan	186,430	26,516	100,911,037	7.4	8.3	SEA
Thailand	233,667	99,807	568,253,338	7.5	9.6	SEA
Timor Leste	97,846	5,415	11,354	7.0	4.2	SEA
Tokelau	1,250	179	N/A	4.4	0.7	CP
Tonga	84,729	7,170	249,913	6.9	4.5	P
Trinidad and Tobago	27,285	6,005	2,335,424	6.2	5.7	C
Turks and Caicos Islands	20,480	2,524	38,212,573	6.1	7.7	C
Tuvalu	9,611	2,708	N/A	5.6	3.5	M
United Arab Emirates	1,217,577	12,385	153,922,439	8.6	8.6	ME
United Rep. of Tanzania	1,612,870	108,789	28,586,374	8.7	7.5	WIO
United States	1,983,056	29,596	N/A	8.9	5.9	C, CP
US Virgin Islands	34,003	981	6,598,431	6.4	6.4	C
Vanuatu	112,666	9,410	67,499	7.1	4.7	GBR
Venezuela	396,002	21,291	160,788,383	7.9	8.7	C
Viet Nam	1,581,789	204,546	N/A	8.7	7.9	SEA
Wallis & Futuna Islands	12,037	10,357	18,776	5.7	4.8	M, P
Yemen	553,291	20,993	106,057,336	8.1	8.4	ME

To understand where humans may be most exposed to changes in coral reef health caused by increased atmospheric CO_2, we combine our map of scores for combined human dependence on coral reefs with a) projections that show when sea surface temperature may reach levels that will cause bleaching (Figure 3.3.) and the intensity of OA in the near future (2050) (Figure 3.4.) (Jiang et al., 2015).

Specifically, we use published projections (van Hooidonk et al., 2014) of the year when sea surface temperature is expected to reach 8 DHW on an annual basis. These previously published projections are based on an ensemble of models that are included in the IPCC Fifth Assessment Report (CMIP5) for the emission scenario RCP8.5, OISST V2 1982–2005 climatology (Hoegh-Guldberg et al., 2014). Corals are known to bleach when 6 DHW occur (Hoegh-Guldberg, 1999). The annual occurrence of 8 DHW has been cited as a level of thermal stress that will lead to significant coral mortality (Maynard et al., 2015b; van Hooidonk et al., 2014). Other measures of elevated sea surface temperature could be used, but give the same spatial distribution. The numerical data for the projected year when 8 DHW are predicted to first occur annually are presented Table 3.2. To understand where high thermal stress will put people at risk, we overlay maps of 8 DHW with the indicator scores of human dependence (Figure 3.3.).

Table 3.2. Oceanic Province Level Data on Sea Surface Temperature (Year When Annual DHW = 8) (Maynard et al., 2015b; van Hooidonk et al., 2014). Derived from an ensemble of models that are included in the IPCC Fifth Assessment Report (CMIP5) for the emission scenario RCP8.5, OISST V2 1982–2005 climatology (Muehllehner et al., 2016)

Ocean Province	COUNT	MIN	MAX	Mean Year when DHW8 Occurs Annually	STD
Brazilian Province	17	2041	2045	2043	0.76
Caribbean	161	2038	2055	2044	2.41
Central Indian Ocean	45	2036	2063	2046	5.72
Central Pacific	70	2031	2053	2043	6.45
Eastern Pacific	21	2043	2059	2052	4.40
Great Barrier Reef	210	2027	2068	2044	9.12
Micronesia	130	2023	2042	2035	4.06
Middle East	60	2040	2072	2057	5.97
Polynesia	160	2036	2066	2048	6.85
South East Asia	411	2030	2076	2042	5.83
Western Australia	16	2033	2061	2046	9.50
Western Indian Ocean	75	2041	2058	2049	4.34

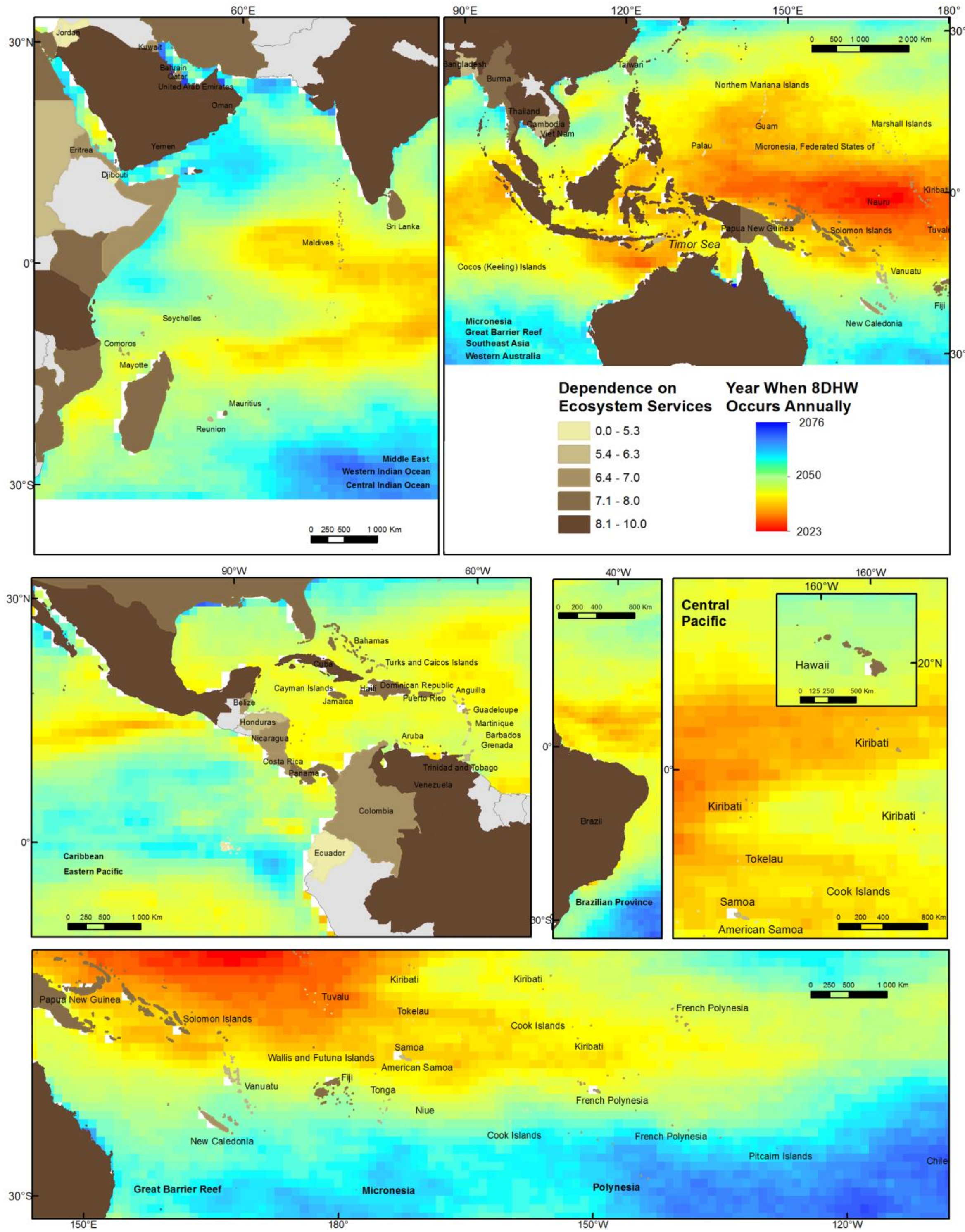


Figure 3.3. Country-level dependence on coral reef ecosystem services and future risk of coral bleaching. Bleaching risk is indicated by the year when DHW8 is first reached annually, under RCP8.5 scenario (Maynard et al., 2015b; van Hooidonk et al., 2014). Ocean Provinces are indicated in each panel in bold. Earlier years indicate increased bleaching risk

OA will affect a number of physiological and even behavioral processes that are important to coral reef ecosystems (Yang et al., 2015), each affected differently by changes in ocean carbon conditions. As a result, there is no agreed-upon, single threshold that represents when coral reefs will be compromised by OA. So, we do not set a given threshold and map when that threshold will be reached (as we did for bleaching risk). Instead, to understand where the contribution of CO_2-driven OA to reef conditions may be severe in the future, we map projections of omega aragonite (Ω_{ar}) for the year 2050 under the business-as-usual (RCP8.5) emissions scenario (Jiang et al., 2015). Ω_{ar} is a measure of carbonate chemistry, related to OA, that reflects the level of carbon saturation of ocean water. It is a measure originally intended to reflect the challenge that OA poses for organisms with calcium carbonate skeletons. Lower levels of aragonite indicate more severe OA. To calculate Ω_{ar} in year 2050, we use the same technique provided by (Jiang et al., 2015) based on global data from the sites included in the Global Ocean Data Analysis Project (GLODAP), Carbon in Atlantic Ocean (CARINA), and Pacific Ocean Interior Carbon (PACIFICA) datasets. We calculate projected Ω_{ar} in 2050 using the projected atmospheric pCO_2 and sea surface temperature in 2050 under the RCP8.5 emissions scenario, in-situ total alkalinity (assuming total alkalinity does not change), as well as the salinity, silicate, and phosphate data, as well as calculated surface water pCO_2 from the base year 2000. Data regarding the predicted Ω_{ar} levels for 2050 are presented in Table 3.3.

Table 3.3. Oceanic Province Level Data on Ocean Acidification in Year 2050 (Omega Aragonite). Based on GLODAP, CARINA and PACIFICA data (Jiang et al., 2015)

Ocean Province	COUNT	MIN	MAX	Mean Omega Aragonite	STD
Brazilian	17	3.17	3.37	3.31	0.06
Caribbean	199	2.91	3.32	3.17	0.11
Central Indian Ocean	61	2.99	3.24	3.15	0.08
Central Pacific	71	3.00	3.39	3.16	0.13
Eastern Pacific	33	2.17	2.99	2.70	0.20
Great Barrier Reef	223	2.44	3.24	3.10	0.14
Micronesia	130	3.15	3.31	3.20	0.04
Middle East	109	3.03	3.11	3.07	0.02
Polynesia	162	2.63	3.39	3.23	0.14
Southeast Asia	544	2.74	3.18	3.07	0.08
Western Australia	43	2.59	3.13	3.00	0.13
Western Indian Ocean	76	2.87	3.22	3.13	0.09

We use these projected Ω_{ar} levels in 2050 as broadly indicative of OA severity, noting that biological processes on the reef can significantly alter Ω_{ar} up or down relative to the oceanic value (Muehllehner et al., 2016; Unsworth et al., 2012; Yeakel et al., 2015) and that bio-regulation of pH in the face of OA is energetically costly for corals (Allemand et al., 2011; Venn et al., 2013). As before, to understand where OA risk could most affect people, we overlay projected Ω_{ar} in 2050 with indicator scores for human dependence (Figure 3.4.).

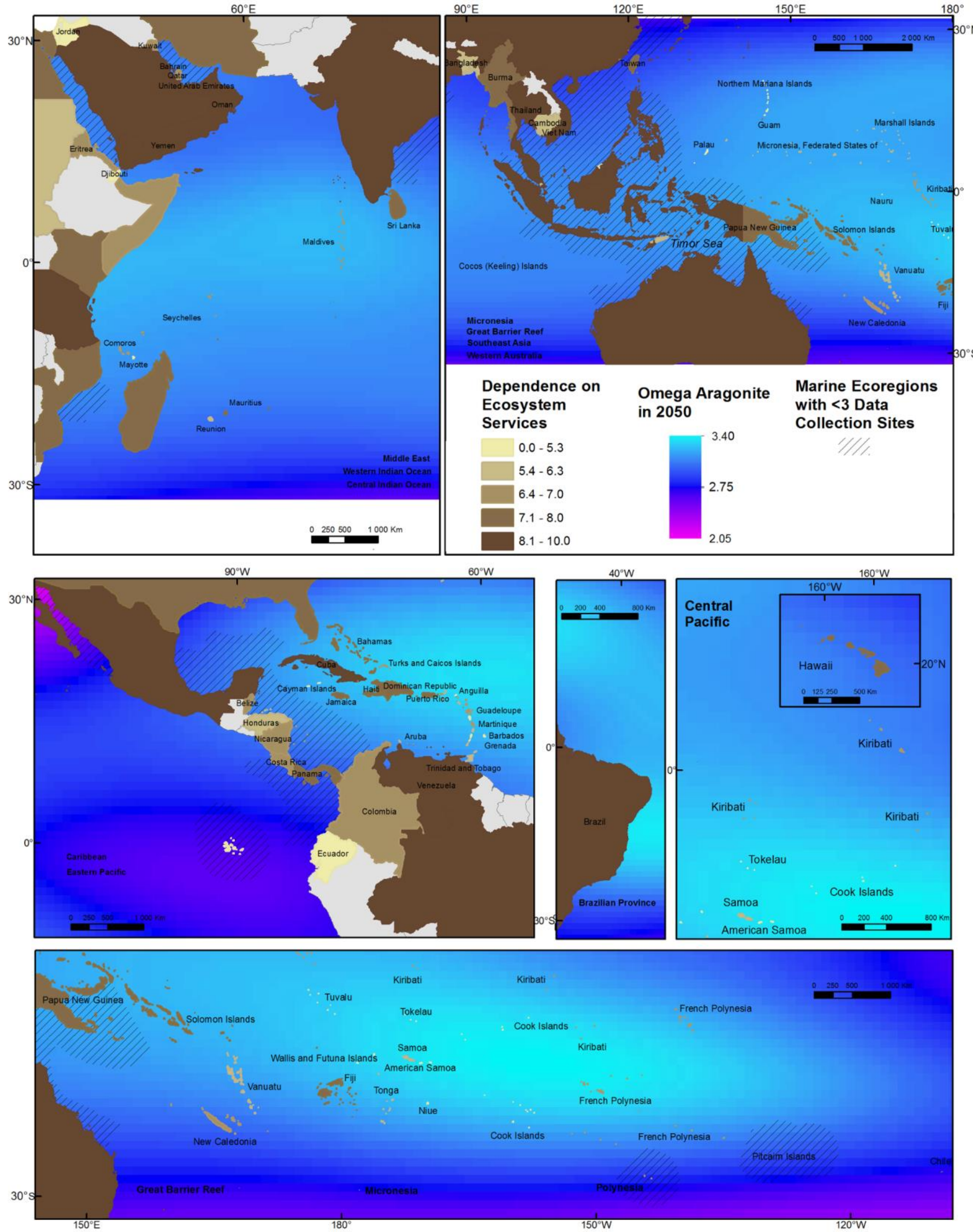


Figure 3.4. Country-level dependence on coral reef ecosystem services and future risk of ocean acidification as omega aragonite level in 2050 based on GLODAP, CARINA and PACIFICA data, (Jiang et al., 2015). Ocean Provinces present in each panel in bold. Lower omega aragonite levels reflect higher ocean acidification risk

Model projections of OA often extend to cover all waters of the world (Hoegh-Guldberg et al., 2014). These projections, however, can only be verified using existing data to calibrate the correspondence of the projection with current and past conditions. These data are limited to a large set of collection points, which are not distributed across all coral reef areas and thus do not necessarily reflect OA conditions at all coral reefs (Jiang et al., 2015), especially for coastal areas. To show areas where data are scarce, we use hatched areas that represent marine ecoregions as defined by Spalding (Spalding et al., 2007) for which there are fewer than 3 collection sites that are used in current OA projections (Figure 3.4.) (Jiang et al., 2015). For a more detailed explanation on the construction and mapping of these indicators, see Annex A.

4. Results

a. Country-level results

Not all coral reef ecosystems or the human communities that depend upon them will experience the same effects as a consequence of a higher-CO_2 world. First, countries differ substantially in how much they depend on coral reef ecosystems and services (Table 3.1., Figure 3.2.). Because we focus on country-level dependence on coral reefs, countries with long coastlines that are bordered by coral reefs tend to have higher than average dependence. For instance, Australia, much of Southeast Asia, Brazil, and Mexico all have high combined human dependence scores when both low elevation coastal population and fisheries are considered. It is noteworthy that a number of smaller countries (e.g. Cuba, Kenya, Fiji, and Madagascar) still have high combined dependence scores owing to their long coastlines and the high density of people in coastal areas.

Figures 3.3. and 3.4. show the juxtaposition of human dependence with exposure to future sea surface temperature (and thus widespread coral bleaching) and CO_2-driven OA, respectively. The countries of Oceania are predicted to suffer from mass coral bleaching soonest, followed by the Coral Triangle countries of Southeast Asia and Australia. All of these areas have high human dependence on coral reefs. Van Hooidonk et al. (van Hooidonk et al., 2014) show that changing patterns of sea surface temperature and OA differ spatially, particularly by latitude, due to increasing gas solubility (which affects OA) with colder temperature. As a result, the countries most likely to experience severe OA are generally different from those that will experience the earliest onset of coral bleaching. Baja California (Mexico), Japan, China, and southern Australia are projected to be most exposed to future OA partly because they are at the upper and lower latitudinal bounds of coral reef distribution (and thus generally in cooler waters). Countries that span large ranges of latitude will be exposed to a range of future ocean conditions. For instance, the coastline of Australia most at risk from OA (southeast) is different from that most at risk from bleaching (northwest). The Great Barrier Reef spans areas of high future bleaching and OA.

Many of the countries most dependent upon coral reefs are also the countries for which we have the least robust data on OA (hatched areas in Figure 3.4.). Southeast Asia, India, the Coral Triangle, the Western Caribbean, and northern Australia stand out as areas of high human dependence on coral reefs and possibly low confidence in OA projections due to the scarcity of regular OA data collection points (Jiang et al., 2015).

To understand where coastal communities will face high combined stress from both increased bleaching and more intense OA, we rescale (Juwana et al., 2012) each global threat from 1 (lowest score) to 10 (highest score), sum the normalized scores of both elevated sea surface temperature and Ω_{ar}, and map these (Figure 3.5.). Areas that face the highest combined threats from both CO_2-driven stressors (thermal stress and OA) are highly concentrated, mostly in the Western and Eastern Tropical Pacific. Because OA and increasing sea surface temperature follow different latitudinal gradients (van Hooidonk et al., 2014), no area experiences both the worst possible sea surface temperature and OA conditions (a score of 20). Also, there are no coral reef areas that are completely free from both global stressors (a score of 2) and thus there are no perfect coral reef refuges from the impacts of climate change and OA.

Human dependence on coral reefs and a high combined score for stress from both OA and coral bleaching (e.g. scores approaching 15) are projected to occur along the coasts of much of Western Mexico and Micronesia as well as the coastlines of Indonesia and Australia on the Timor Sea and parts of Southeast Asia. These places may require swift action to protect people from the combined impacts of warming seas and increasingly acidified oceans (e.g. many parts of Southeast Asia).

We offer a sensitivity analysis in Annex B on the results using an IPCC scenario in which future emissions of GHG are reduced to stay on target with the 2°C increase in temperature by 2100, scenario called RCP2.6.

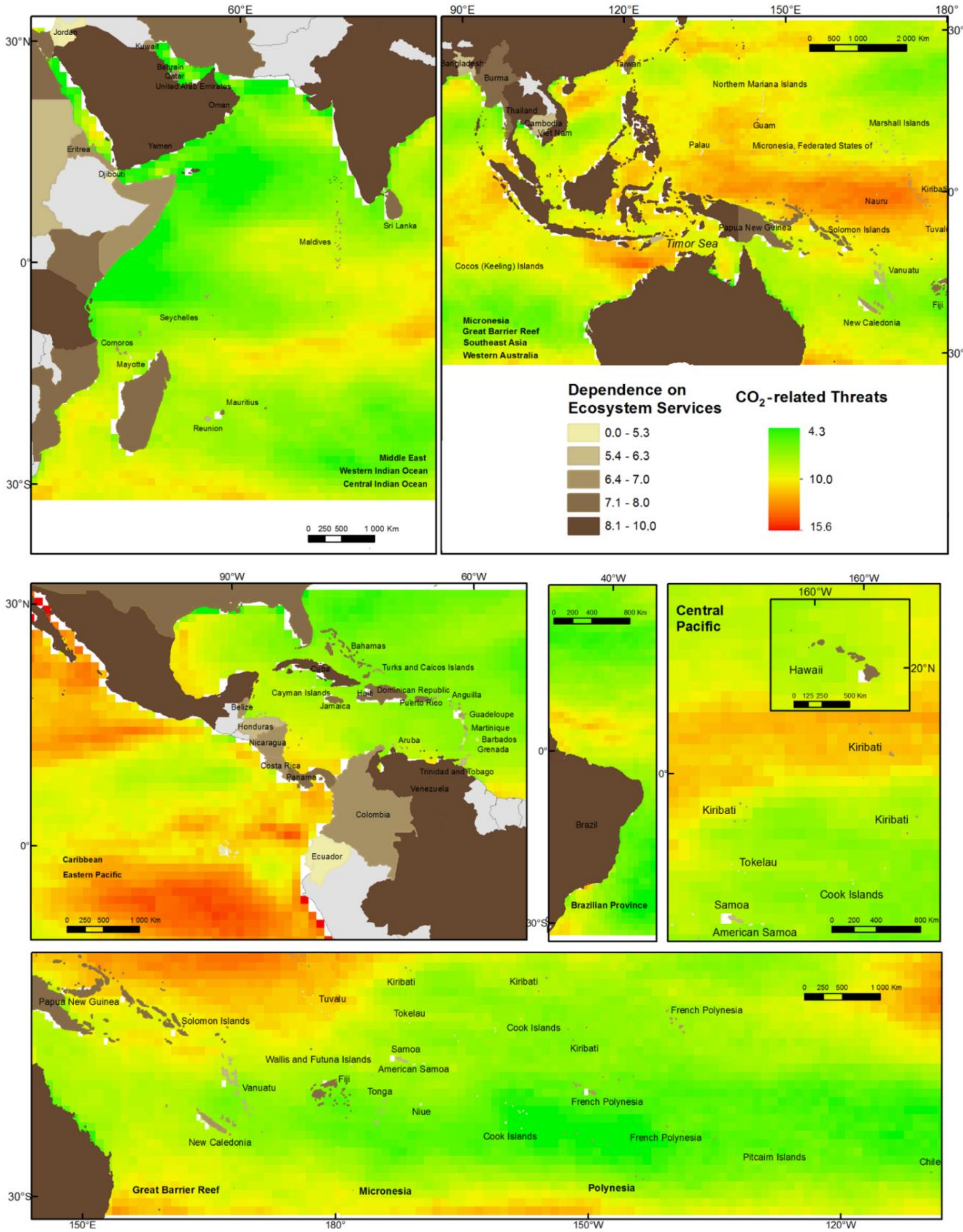


Figure 3.5. Country-level dependence on coral reef ecosystem services and future combined normalized scores (2-20) for CO_2-related threats (e.g. ocean acidification and thermal stress). Ocean Provinces are indicated in each panel in bold. Higher scores indicate higher dependence and higher ecological threat

b. Regional results

The ecological response of coral reefs is likely to vary regionally due to different species composition, varying rates of change in temperature and acidification conditions, and differences in the conditions that promote coral reef resilience (Roff and Mumby, 2012) (bottom panel of Figure 3.6.). To visualize the regional threats to coral-reef dependent communities from a high CO_2 world, we merge coral reef areas into the biological ocean provinces proposed by both Donner (Donner, 2009) and Maina (Maina et al., 2011). Within these provinces, we focus only on sea surface temperature (year 8 DHW, Table 3.2.) and OA (Ω_{ar}, Table 3.3.) conditions that spatially co-occur with coral reefs within the province (lower panel Figure 3.6.). Using the same data developed for the country level analysis, we also present province-level results for the total regional human dependence on coral reef ecosystem services (Table 3.4., upper panel Figure 3.6.). Note that when a country's Exclusive Economic Zone falls within more than one ocean province, we assign human dependence values to each ocean province separately if data were available, e.g. Hawaii and Florida, or we proportionally assign the human dependence data to each province using the same proportion with which reef area was distributed across provinces. More information on these methodologies can be found in Annex A.

Two of the biological oceanic provinces that will likely face mass, climate-related coral bleaching soonest (e.g. the Micronesian and Brazilian Ocean Provinces) will be exposed to aragonite levels that are less severe than the average across all provinces. Meanwhile, places facing the most severe future OA conditions tend to face a later onset of bleaching (e.g. Middle East). Southeast Asia faces both a rapid projected onset of bleaching (by 2042) and an above average risk from OA (Ω_{ar}=3.07, which is below the level known to cause reduced growth and recruitment in some corals (Albright et al., 2010; Manzello et al., 2014)). Southeast Asia also stands out as the biological ocean province that has, by far, the greatest overall dependence on coral reef ecosystem services as measured by total number of people in the region who live at low elevations that are protected by reefs, by number of fishers, and value of fisheries. The Caribbean, the Middle East, and both Indian oceanic provinces also have high human dependence. The Middle East has a high human dependence and faces an above average threat of OA, but a low relative risk of future coral bleaching compared to other regions. The Caribbean faces an above average threat of onset of coral bleaching, but an OA risk that is somewhat below average (note, though, the level of confidence for the Caribbean may be low due to the low number of data collection sites). Similarly, several regions face threats that are above average for one threat and near average for another (e.g. Polynesia and Central Pacific) or near average for both threats including both the Indian Ocean provinces which have high human dependence on coral reefs.

Table 3.4. Oceanic Province Level Data on Human Dependence on Coral Reef Ecosystems: Fisheries (Teh et al., 2013) and Low Elevation Coastal Population (Center for International Earth Science Information Network (CIESIN)/Columbia University, 2013)

Ocean Province	Fishers (jobs)	Value of catch (US$ 2005)	Low Elevation Coastal Population Protected by Coral Reef (# of people)
Brazilian Province	144,433	180,174,864	1,239,637
Caribbean	276,826	726,828,415	8,300,897
Central Indian Ocean	620,974	168,726,685	5,054,227
Central Pacific	25,495	1,811,215	1,536,879
Eastern Pacific	23,123	17,415,220	108,616
Great Barrier Reef	225,201	413,564,715	1,441,968
Micronesia	72,340	11,688,205	407,388
Middle East	345,455	669,087,061	6,535,613
Polynesia	84,622	17,189,967	809,403
South East Asia	3,971,693	3,768,035,428	33,187,672
Western Australia	2,902	45,816,675	30,990
Western Indian Ocean	228,112	66,251,593	4,271,981

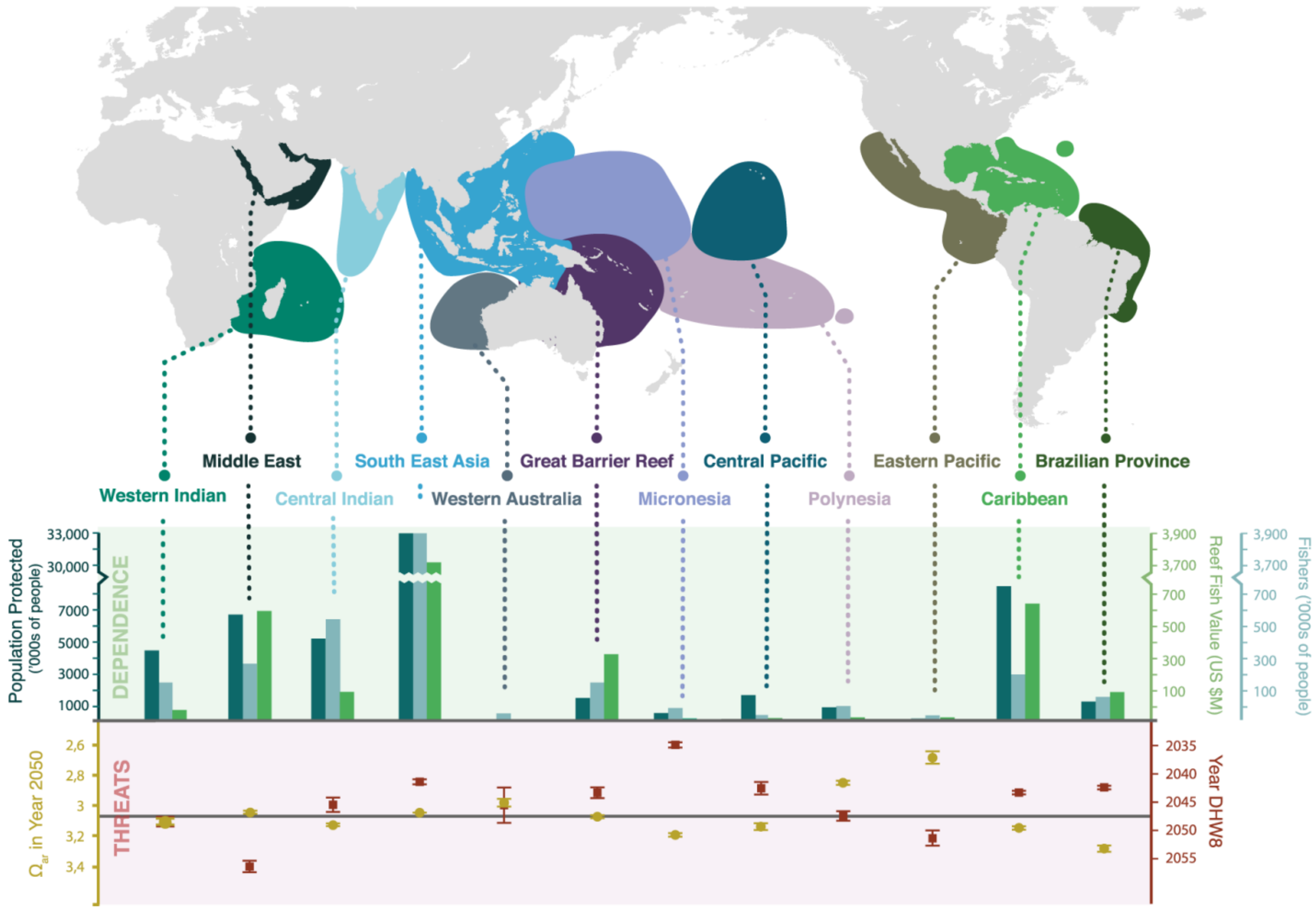


Figure 3.6. Regional dependence, by ocean province (Donner, 2009), on ecosystem services and average CO_2-related threats (ocean acidification measured as projected Ω_{ar} levels at coral reefs in 2050 and elevated sea surface temperature as measured by year that 8 DHW are projected to occur annually). The horizontal line in the threats panel represents the mean threat for all regions (scores above this line indicate above average severity of threat). The scales for the reef fish dependence scores are broken to reduce the size of the graph. Note that the Great Barrier Reef Ocean Province includes, but is not limited to, the Great Barrier Reef.

5. Discussion

While we are now able to identify many places where coral reefs and the people dependent upon them will be threatened by global environmental changes caused by increased atmospheric CO_2, we need to do more. Our analysis shows, however, that in many places (see Figure 3.4.) we lack sufficient, routine data collection on OA factors that is needed to identify with confidence the full set of coral reef communities at greatest risk from the combined threats of global environmental change. Areas that have high human dependence and face future stresses from coral bleaching and OA (e.g. Southeast Asia and the Caribbean) would benefit from data that could better monitor global and local threats to reef health and could be used to design policies to react to reef decline. Also, better human dependence data are needed: data on ecosystem services provided by coral reefs are not regularly collected and no future projections of these data exist.

Model projections about OA in coastal areas, where most coral reefs exist, require data on a large number of local factors (including strong primary production, upwelling, fresh water input, and nutrient overloading (Mongin et al., 2016b). Collecting data everywhere would be infeasible. Not all new data would be equally valuable for decision makers. Therefore, we propose a global strategy, using indicators of human dependence and potential future global climate threats, in order to geographically target areas where new data collection and science will have high social relevance. These are areas where new science and data are needed to inform decision makers about the potential future impacts of bleaching and OA on coral reefs and the people who depend upon them. Similarly, without better data on localized OA conditions, it is difficult to know where future marine protection could most effectively protect potential reef refugia – areas where corals will naturally avoid the stresses of a high CO_2 world.

The Global Ocean Acidification Observing Network (GOA-ON) was established to better achieve "socially relevant" OA monitoring (Goal 3) (Newton et al., 2014), and could help focus effort on these areas for better data collection and scientific capacity building. We also need to do more to collect local-level data on the many other environmental stressors that will exacerbate the effects of global environmental change. There are no fully global databases of coral bleaching or the conditions that cause widespread coral mortality.

We focus only on two key stressors associated with increased atmospheric CO_2, but we recognize that the ecological health of coral reefs depends on many factors (McClanahan et al., 2015; Chapter 2). Coral death and loss of coral reef cover already is being experienced in many places around the globe (e.g. see estimates of coral reef loss in the Great Barrier Reef (Ainsworth et al., 2016; De'ath et al., 2012)). Knowing how coral reefs and reef-dependent human communities will fare in a world of rapidly changing global and local environmental conditions will require a better scientific understanding of how combined environmental change affects coral reefs, how coral reef ecosystems may change, and how these reef changes ultimately impact people. Regionally targeted, mesocosm-level or larger field experiments are needed to study the combined effects of global stressors in a way that reflects the regional variation of coral ecology, local human uses, and local environmental stressors.

Finally, we need more and better social and economic science to understand how humans will respond to projected environmental changes in coral reef ecosystems (e.g. the Capturing Coral Reef and related Ecosystems Project, CCRES, project funded by the World Bank and Global Environmental Facility is one such example). New research on human responses to coral reef change is emerging (Anthony et al., 2015; Graham et al., 2015; McClanahan et al., 2012; McLeod et al., 2012; Obura and Grimsditch, 2009). While the literature focuses on the vulnerability and resilience of coral reef ecosystems and the people that depend on them, more empirical study is needed to identify solutions to the socio-economic vulnerability posed by projected changes in coral reef health (Cinner et al., 2013; Hughes et al., 2012a). Human dependence on coral reef ecosystem services is only partially characterized for the present, and rarely projected into the future. The factors that may determine how people will adapt to coral reef decline remain poorly understood (Barnett and O'Neill, 2010; Breshears et al., 2010; Evans et al., 2016). Because planning for a high-CO_2 world has already started, for example through the UNFCCC process (Pramova et al., 2011), science needs to improve fast enough to prevent locking-in approaches that are ineffective or worse. To this aim, empirical research looking at the human responses to ecological changes in coral reefs (e.g. protection, restoration, and socio-economic adaptation planning) and the barriers that impede effective strategies is needed.

To expedite action to combat the changes corals may experience in a high CO_2 world, new, interdisciplinary science should be conducted in regions where the likely social and economic impacts of bleaching and OA on humans could be high, and thus the potential societal relevance of such science could also be high. Unfortunately, carrying out science and data collection in many of the coral reef regions most at risk of global environmental change is a challenge. Many of these regions lack the financial or human capacity to carry out large-scale experiments and routine data collection. It is often difficult for scientists to obtain permission to sample in coastal ocean areas or where national maritime jurisdictions are disputed. Both international and regional efforts are needed to overcome the impediments to obtaining data in these areas. GOA-ON and other international bodies (e.g. the United Nations Environment Program) should begin to facilitate such cooperation without delay because elevated sea surface temperatures and critical levels of OA are upon us. While reducing atmospheric CO_2 should remain a primary goal, a portion of international climate change funding that will become available for developing countries in the coming years should go towards supporting this research.

Chapter 4. Management Strategies for Coral Reefs and People under Global Environmental Change: 25 Years of Scientific Research

Authors: Adrien Comte*, Linwood H. Pendleton

Associated annexes: C, D, E, F

Acknowledgements: This work was supported by the "Laboratoire d'Excellence" LabexMER (ANR-10-LABX-19) and co-funded by a grant from the French government under the program "Investissements d'Avenir", and by a grant from the Regional Council of Brittany. We declare no conflict of interest. We thank Jean-Pierre Gattuso and Alexandre Magnan for their input on designing the typology. We acknowledge Morgane Le Gall and Bibliothèque La Perouse, Ifremer for her help in the data collection and treatment. We also acknowledge Claire Bissery and Didier Dacunha-Castelle for their help in designing the statistical analyses. Figures 4.3. and 4.9. are reproduced with the permission of Vanessa Gonzalez-Ortiz.

1 Introduction

Ocean acidification (OA) and climate change, including rising sea surface temperatures (SST), change in cyclone patterns, sea-level rise, and de-oxygenation, will adversely affect coral reef ecosystems in the coming decades (Cinner et al., 2016b; Hoegh-Guldberg et al., 2014) (Chapter 2). These global environmental changes (GEC) and their interactions will impact the goods and services provided by coral reefs upon which human populations depend (Chapter 3). Coral reefs support local and national economies (Burke et al., 2011), for instance by providing habitats for many species of fish on which local fishermen depend (Teh et al., 2013), but also providing revenues from tourism and coastal protection. People, communities, and nations are vulnerable to the effects of GEC on coral reefs (Hughes et al., 2012a).

Identifying ecosystems and human communities that are vulnerable to environmental change does not shed much light on appropriate response strategies (Hinkel, 2011). Vulnerability or impact assessments do not systematically identify which actions could reduce vulnerability (Tulloch et al., 2015). A necessary approach to reduce impacts and vulnerability is to identify the range and mix of possible actions (Ranger and Garbett-Shiels, 2012; Wilby and Dessai, 2010). Several scientific papers have attempted to help decision-makers and managers deal with the adverse effects of GEC on coral reefs by identifying management options (e.g. Mcleod et al., (2013); Rau et al., (2012)). However, papers in the literature often focus on a narrow set of actions that can be taken within a specific management approach such as Marine Protected Areas (e.g. Green et al., 2014; Keller et al., 2009), a specific threat (e.g. ocean acidification) or a specific ecological process such as coral adaptation to warming (van Oppen et al., 2015). Of course, not all strategies are available or recommended in every situation, but a focus on too few strategies can be misleading (e.g. protective measures (Hilborn, 2016)). Evaluating a broader range of available strategies, and indeed combinations of actions, helps managers to estimate the trade-offs of different management approaches (Bozec et al., 2016). Multiple strategies may be needed to deal with different parts of the problem.

A new science of solutions is emerging to help guide the choice of action, especially regarding climate change adaptation (Hinkel and Bisaro, 2015; IPCC, 2014). A synthesis of management strategies, based on an understandable conceptual framework, can help managers and decision makers consider different policy actions within the complexity of coral reefs socio-ecological systems (SES). Such a typology of management strategies has the advantage of making sense of a large number of actions while enabling conditions to evaluate and articulate their advantages and barriers (Biagini et al., 2014). It is therefore important to evaluate the broad range of possible management strategies available in a typology, in order to implement the most appropriate strategies and to avoid maladaptation (Magnan et al., 2016).

One common way of dividing solutions to climate change, used by the Intergovernmental Panel on Climate Change (IPCC), is between mitigation and adaptation (IPCC, 2014). Mitigation involves reducing the amount of greenhouse gases (GHG) while adaptation involves solutions to cope and to adapt to the adverse effects of climate change. This dichotomy reflects societal decisions but does not fully reflect the complexities of social-ecological systems. Indeed, a number of management strategies that apply to coral reefs SES contribute to both mitigation and adaptation. The concept of adaptation to climate change usually only includes human adaptation, therefore fails to reflect the ecological components of coral reefs SES. A typology that encapsulates the societal as well as the ecological components of the system is therefore needed.

Gattuso et al. (2015) proposed a typology to deal broadly with the impacts of carbon dioxide (CO_2) on the marine environment. Four major categories of actions are described in this typology to reduce the risk posed by CO_2 on ocean ecosystems and ecosystem services: mitigate, protect, repair, adapt. We do not know of literature reviews that attempt to use this typology for coral reefs SES and therefore we build on this typology to refine it specifically for coral reefs SES.

In addition to constructing a typology, a systematic literature review is important to investigate how science is currently addressing solutions to respond to the challenge posed by GEC on coral reefs. First, science has a critical role to play in shaping adaptation policy and reducing vulnerability of the marine environment (Ekstrom et al., 2015), and in guiding the allocation of resources (Di Marco et al., 2017). An understanding of the global scientific endeavor can help guide future research and better integrate science in policy-making. Second, we do not know of any evaluation that attempts to link the current scientific effort devoted to managing GEC and that evaluates the degree to which this scientific effort covers places that contain high biodiversity, provides ecosystem services, and will be the most affected by GEC. The spatial distribution of exposure and of dependence on ecosystem services is not homogeneous (Chapter 3). Because of this uneven spatial distribution, it is important to evaluate whether the scientific literature sheds light on the places that will be the most affected.

The first goal of this paper is to review the scientific literature to structure, using a typology, the suite of management actions that could be available to deal holistically with the entire chain of GEC impacts from climate change and OA on coral reefs, their resilience, and the services they provide to people. This typology organizes information to enable managers and decision-makers to assess the effectiveness of actions in their local settings. The second goal of this paper is to understand how the scientific effort targeted at coral reefs, GEC, and management is distributed through space, time, and categories of action. Through this systematic literature review, we hope to identify gaps in the global coverage of research and also gaps in our understanding of the range of strategies to deal with the impacts of GEC.

2. A revised typology of management strategies

a. Constructing a typology for management strategies of coral reefs and people under GEC

The typology presented in Gattuso et al. (2015) classifies management strategies into four major categories: mitigate, protect, repair, and adapt. This typology was designed to broadly identify actions to tackle climate change and ocean acidification for ocean ecosystems and the services they provide. To apply this typology to management strategies that tackle the impacts of GEC on coral reefs ecosystems and ecosystem services, we created sub-categories that take into account specific aspects of coral reef management (Figure 4.1.). When refining Gattuso et al.'s typology to deal with coral reefs ecosystems, the same four categories of management strategies can be used: reduction of global and local environmental hazards (mitigate), repairing and restoring damaged reefs and associated ecosystems (repair), protecting existing healthy ecosystems to improve resilience and maintain ecosystem functions (protect), and adapting human societies to the reduction of ecosystem services when damage from global and local environmental change is not avoidable (adapt) (Burke et al., 2011; Gattuso et al., 2015; Mumby and Anthony, 2015).

Coral reef management actions focus on different aspects of the chain of impacts. Some are dedicated to conservation, while others target socio-economic vulnerability. Some studies focus on local threats, while others on global threats. We focus on public policy options to tackle the threat that high CO_2 poses on coral reefs and human populations who depend on them. Private responses to these threats have been analyzed in Evans et al. (2016). We compile management options from the literature, across spatial scales, from local options to national and global policy responses and use the analytical framework developed by (Gattuso et al., 2015) as the basis to categorize possible options. Taken together, they give a broad picture of actions across all components of coral reefs SES. We provide a brief overview of the Gattuso et al. typology and an explanation of our modifications. Differences between the two typologies are presented in Figure 4.2. For a more exhaustive list and discussion of available actions, see Annex C.

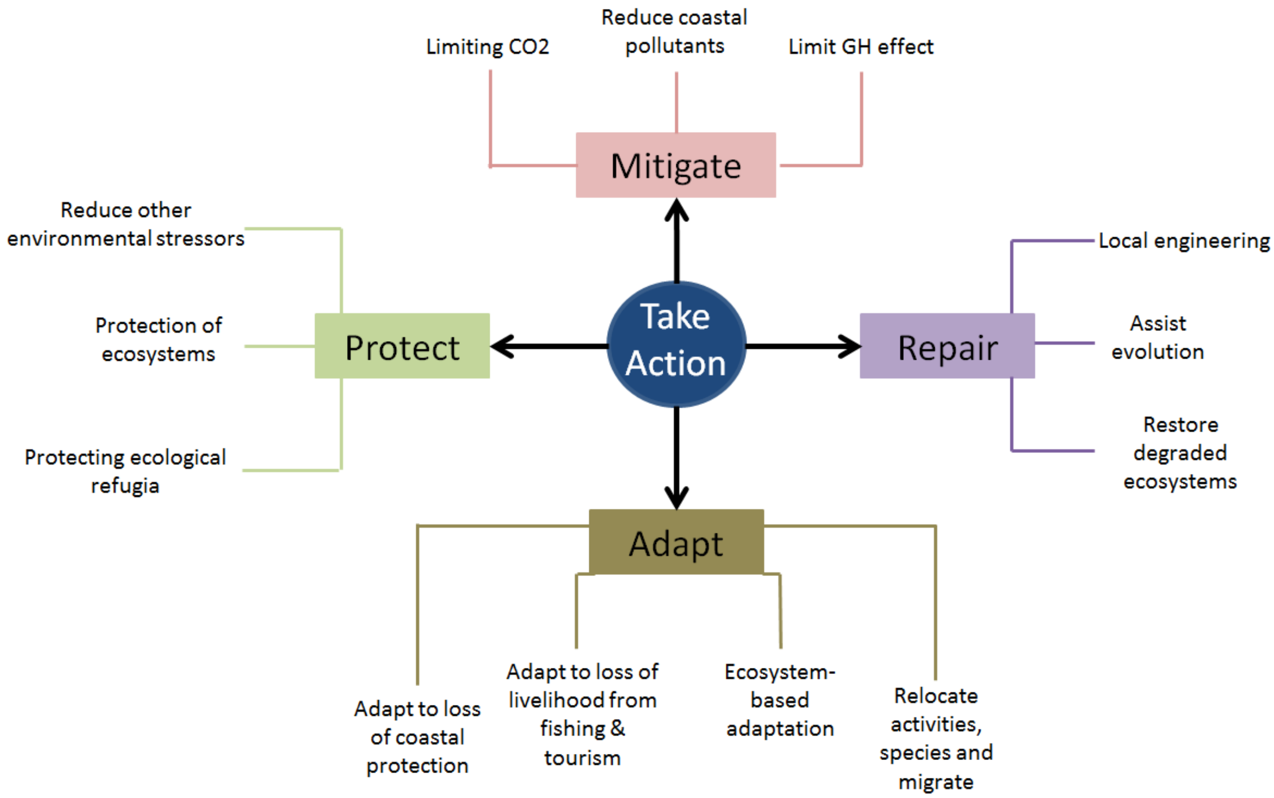


Figure 4.1. Typology of management strategies to deal with GEC on coral reefs and people who depend on them; modified from Gattuso et al. (2015)

The main strategy to deal with climate change and ocean acidification is the reduction of greenhouse gases and coastal pollution. These "Mitigation" strategies can be broken down into three major sub-categories, limiting CO_2 emissions, reducing the greenhouse effect, and reducing coastal pollution. In agreement with Gattuso et al. (2015), we include coastal pollutants in the mitigation category, since these actions directly interact with ocean acidification and sometimes temperature (with turbidity). Measures to improve water quality can mitigate the effects of ocean acidification locally (Kelly et al., 2011). Reducing pollution, nutrient loading and sediments runoff also affects the state and resilience of coral reefs. Other environmental factors influence the resilience of ecosystems, and are addressed in the category Protect.

Another set of actions builds on the notion of "Protection" of coral reefs from local anthropogenic activities to improve the resilience of coral reefs to global environmental changes, broadly interpreted to include Marine Protected Areas (MPAs), marine spatial planning, and fisheries closure areas. Following the original framework, protect strategies can be broken down into three major sub-categories, reducing local stressors to improve resilience, protection of ecosystems and associated ecosystems in MPAs, and protection of ecological refugia. We distinguish between fully protected MPAs or no-take marine reserves (Roberts et al., 2017) and other area-based management approaches placing the former in the "protection of ecosystems" sub-category and the latter in the "reduce other environmental stressors" sub-category.

Once coral reefs and associated ecosystems are degraded due to human impacts or natural phenomena (e.g. diseases and cyclones) and after they experience the effects of GEC, it could be possible to implement actions to restore biodiversity and lost ecosystem functions. These "Repair" strategies can be broken down into three major sub-categories, restoring lost ecosystems, assisting evolution, and using local engineering to buffer against global environmental change. It could be possible to restore un-harmful environmental conditions for coral reefs at a very localized scale. These actions are categorized under the "local engineering" sub-category and include a more diverse set of actions than those enumerated in the Gattuso et al. (2015) typology that only considered adding alkaline material. Various other techniques are being developed to locally buffer against the unavoidable changes in ocean temperature and pH such as artificial shading to cool local areas (Rau et al., 2012). These methods are different from mitigation measures because they repair harm after it is done, while mitigation is here to prevent environmental changes.

Finally, "Adaptation" strategies are those that assume future impacts of GEC will occur and help people cope with this new reality. The three types of strategies described above focus mainly on the ecological health and resilience of coral reefs, but not on the human activities and livelihoods that depend on coral reefs. Actions that address human adaptation to the loss of ecosystem services provided by coral reefs needs to be understood since climate change will and is already damaging coral reefs worldwide. While the typology developed by Gattuso et al. (2015) broadly addressed the adaptation of human activities and communities, we tailor these management strategies to the ecosystem services associated with coral reefs, the main ones being coastal protection, fisheries, and tourism. In addition, humans can harness nature to help societies adapt to the adverse effects that climate change will have on human systems, an approach that has been categorized by several authors as ecosystem-based adaptation (Jones et al., 2012). Adaptation strategies can be broken down into three major sub-categories: adapting to the loss of ecosystem services, using ecosystem-based adaptation, and relocation or migration of activities and populations.

In addition to these four types of strategies, there also are indirect strategies that focus on improving the underlying social, governance, and economic conditions necessary for the other four types of strategies to be effective. They can be divided in two categories: research and monitoring, and building capacity and are also detailed in Annex C.

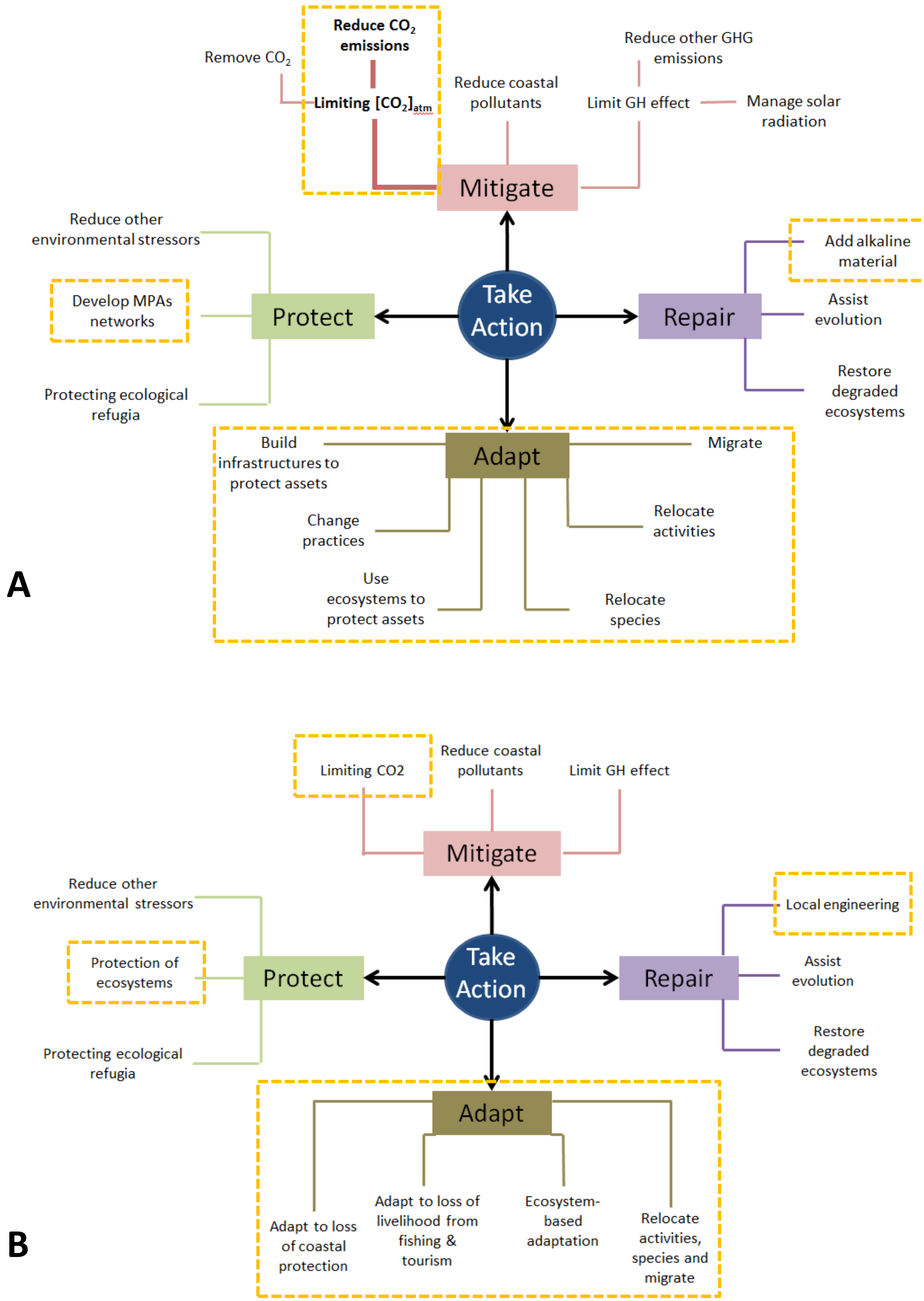


Figure 4.2. Differences (orange boxes) between (A) the typology developed by Gattuso et al. (2015) and (B) the one adapted here for coral reefs SES

b. Linking Management strategies to the impacts of GEC on coral reefs SES

The chain of impacts that link global environmental change to coral reefs and societies who depend on them is complex (Figure 4.3.). In addition to local threats (e.g. pollution, fishing), global threats including sea temperature change, OA, and cyclones already have adverse impacts coral reefs. For instance, ocean acidification will impact calcification, but also other processes important for coral reefs development including reproduction, growth, and metabolism (Chapter 2). In turn, the degradation of reefs will affect ecological functions and species diversity that support the provision of services to human populations, including coastal protection, fisheries, and tourism. The purpose of management strategies is to reduce ecological exposure or sensitivity (Figure 4.3.) (Engle, 2011). Ecological exposure refers to the hazards (global and local environmental changes) as well as the health of coral reefs. Social vulnerability refers to the dependence of people on healthy coral reefs and their capacity to adapt.

All mitigate strategies target the reduction of ecological exposure, through the reduction of global and local environmental changes. Repair strategies also target ecological exposure, since they aim to improve coral reefs health under climate change. However, there is a possibility that restoration of degraded ecosystems could increase ecological exposure if it is done in regions where hazards will be more severe in the future (Fadli et al., 2012). In addition, the impacts of repair strategies on social vulnerability are not clear. Repair strategies could improve ecosystem services in the future by increasing coral reef cover and functions, but the distribution of these potential benefits across space and time has not been addressed in the literature. Protect strategies also target ecological exposure since their main purpose is to reduce and prevent anthropogenic pressures. The effect of protect management strategies on social vulnerability is unclear since these strategies, particularly no-take marine reserves, may have beneficial effects (e.g. through spillover of fish or by protecting reef structure important for shoreline protection), but could exclude some or all human activities and populations including those who depend on reefs for nutrition (Hilborn, 2016). Of course, even in the absence of protection, unsustainable levels of exploitation may also imperil the future of coral reefs in the future. Adapt strategies are the only strategies explicitly targeted at reducing social vulnerability and the dependence of populations on provision of services by coral reefs. Adaptation policies on land may threaten coral reefs socio-ecological systems (Evans et al., 2016). The use of ecosystem-based adaptation has the co-benefit of protecting ecosystems and restoring ecosystems, but these may not be viable solutions if climate change affects the capacity of these systems to provide ecosystem services (Chapter 3).

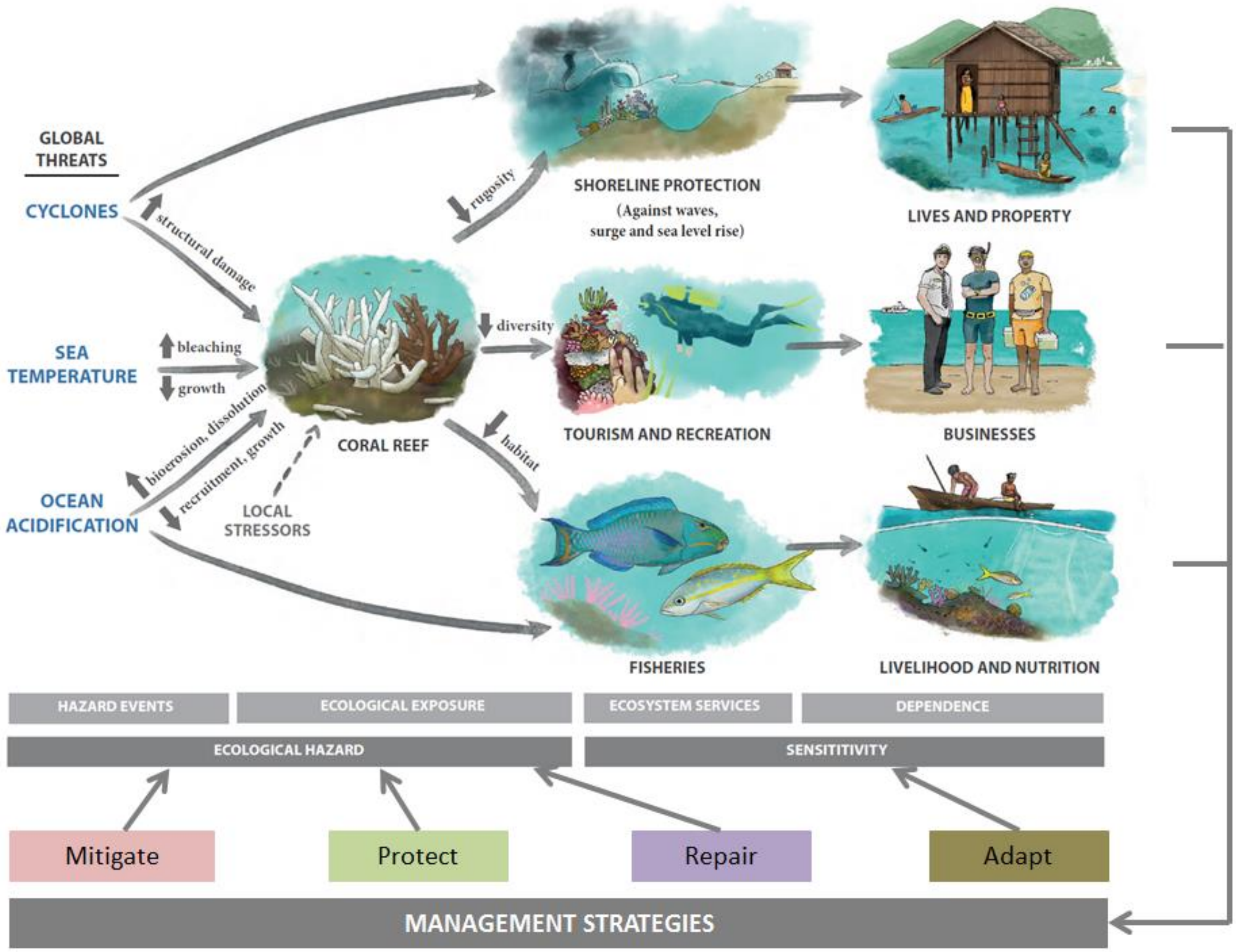


Figure 4.3. Influence of the four categories of management strategies on the chain of impacts of climate change and ocean acidification on coral reefs and people dependent on the services provided by coral reefs; modified from Chapter 3.

c. Conceptual ramifications of constructing a typology of management strategies for coral reefs SES

The typologies used in the literature are not always consistent. In several research articles, especially focusing on vulnerability (Cinner et al., 2013; MacNeil et al., 2010), "adaptation" is used to refer to strategies that increase the ecological resilience of the biological system while others use climate adaptation to refer to actions that enhance ecosystem services provisions under climate change (Arkema et al., 2013). Since this definition of adaptation refers to the reduction of vulnerability to the impacts of climate change, such measures may fall in three of our categories: protect, repair, and adapt depending on the definition of the systems under study. For example, mangrove restoration contributes to carbon sequestration (mitigation), resilience of coral reefs ecosystems, and coastal population adaptation (adaptation) (Duarte et al., 2013). Gattuso et al. (2015) use the term "adapt" to refer to adaptation of the society to the loss of ecosystems and ecosystem services, thus distinguishing between actions focusing on the ecology and actions focusing on human populations. Measures to improve the resilience of the ecosystem, as opposed to the resilience of the human society, are presented in the protect section. However, there are measures that use ecosystems to help human societies adapt to the adverse effects of climate change (i.e. ecosystem-based adaptation), and these are presented as adaptation strategies but rely on other strategies such as restoration.

As described above, management actions tend to reflect approaches that differ along two important dimensions: 1) maintain/change – where actions fall along a gradient from those that seek to maintain the ecological and environmental status quo (or some previous state) to those that deal with future change, and 2) nature/society – where some actions attempt to directly influence natural conditions and others focus on influencing human aspects (Figure 4.4.). These two dimensions are important to understanding which disciplines focus on which approaches. They may also reflect the preferences of managers and institutions that promote climate action and management. The protect and mitigate management strategies can be thought as conventional strategies since they involve a reduction in human activities (e.g. pollution, emission of CO_2, fishing) that has been promoted for many decades. Repair and adapt management strategies are the focus of recent innovation since they often require the change or the initiation of new activities (e.g. restoring coral reefs, changing economic activities) that has emerged more recently in the literature (Füssel and Klein, 2006). The mitigate and adapt categories of management strategies parallel the ones developed by the IPCC and used in the UNFCCC and apply mostly to societal responses and actions (Schipper, 2006). The protect and repair categories of management strategies mostly apply to natural systems. Together, these two dimensions serve to ground management strategies in a socio-ecological system framework.

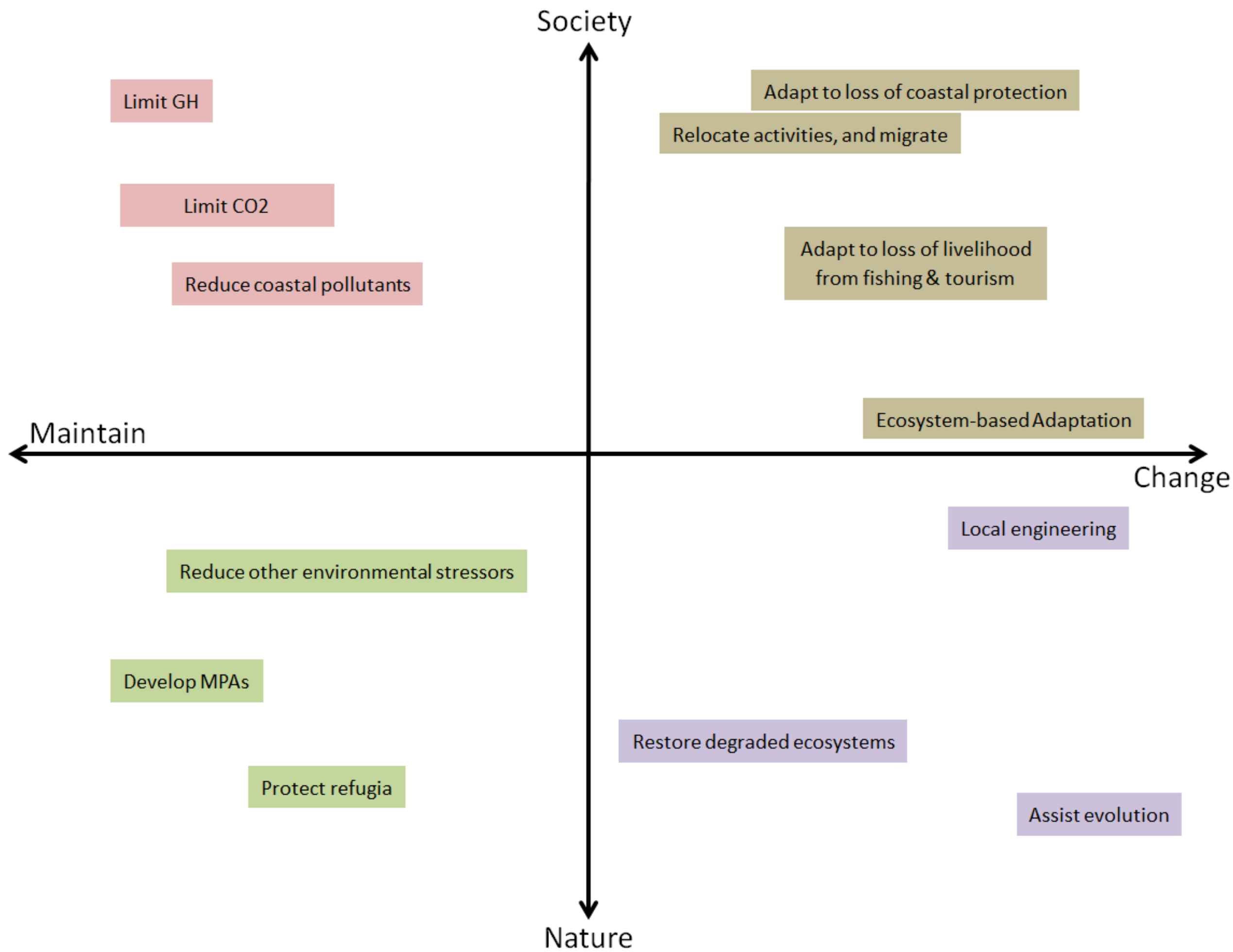


Figure 4.4. The sub-categories belonging to the four categories of management strategies (mitigate in red, protect in green, repair in purple, and adapt in brown) fall along two axes: maintain/change and nature/society

3. Material and Methods

We systematically searched the Web of Science and Scopus databases for articles, published from 1990 to 2016, that addressed coral reefs, climate change or ocean acidification, and that were action-oriented (see Annex D for equations to retrieve these articles). After deleting duplicates, 1177 references were found. A first screening on title of publication, title of journal, abstract, and key words removed articles that did not apply to coral reefs and associated ecosystems (e.g. general papers on CO_2, on cold water corals). Only peer reviewed articles were selected, acknowledging that important contributions may come from books, book chapters and the grey literature. 885 papers remained. After selecting for remaining references that were action-oriented, had a component relevant for management or explicitly stated management implications based on title of publication and abstract, 767 publications remained. The fifteen most important journals in number of research articles were assigned a category: Biology and conservation focus (N), Societal focus (H), or Pluri-disciplinary (P) (Annex E).

Key words were used to assign categories of management strategies (mitigate, protect, repair, adapt, indirect) to the research articles. The Intellixir© software used for the treatment of the literature produced its own list of around 20,000 candidate concepts. A list of action-oriented concepts for each category was created based on this list. Several candidate concepts that describe actions were not explicit enough to fit a category of the typology (e.g. "Facilitate coral persistence" or "build resilience") and were therefore discarded. Strategies are not always single-objective so some could apply to more than one category in the typology. For example, "ecosystem management" or "ecosystem recovery" were terms that included a very broad category of actions and that could not be assigned to a category. Other concepts indicating properties of a system such as "adaptation" and "resilience" could be applied to different parts of the systems, therefore limiting our ability to categorize research articles.

The final list of action-oriented concepts contains 228 concepts for the mitigate category, 138 for the repair category, 210 for adapt, 414 for protect, and 267 concepts in the indirect category. These concepts were applied to the title, abstract, and key words of articles to categorize them. It was possible to assign one or more categories of management strategies to 690 out of 767 papers, or 90% of them. The remaining research articles either were too vague, broadly mentioned having implications for management without detailing how in their abstract, or in a few cases abstract was not accessible.

All contributing authors to the articles reviewed here were assigned to a country based on their affiliations. One caveat is that countries with overseas territories (France, UK, USA, and Netherlands) sometimes have affiliations in both overseas territories and the mainland. (Note these countries already produce the largest number of articles). Titles and abstracts of the 767 articles were screened to determine if they referred to case studies and the country or countries where these case studies were located. To understand whether social, demographic, economic, or ecological characteristics played a role in the location of studies, we collected data on attributes of countries including Gross Domestic Product (GDP) per capita (average between 2006 and 2013 in current USD, source: The World Bank, 2017), coral extent (source: UNEP-WCMC, WorldFish Centre, WRI, 2010), and ecosystem services (source: see Chapter 3). A Principal

Component Analysis (PCA) with hierarchical classification was conducted using the software "R" (with the packages Rcmdr and FactoMineR) to determine how the variability of countries was distributed across these variables and to understand how countries clustered around these variables. More in-depth statistical analyses are provided in Annex F.

4. Results

a. Distribution of the scientific efforts

There are 767 peer-reviewed research articles included in this analysis. Seventy-seven research articles contain no explicit management action in their title, key words or abstract but state that their work is relevant for management. Actions that can be associated with at least one of the four management categories (mitigate, protect, repair, and adapt) are found in 599 research articles. Indirect actions are found in 362 research articles. For the articles that identify action in the four categories of direct management strategies, 61% discuss only a single category, while 39% discuss actions in two, three, or the four categories of management strategies (31%, 7%, and 1% respectively; Figure 4.5.). This suggests that a majority of research articles target a specific management strategy or a specific part in the chain of impacts, and therefore very few have a holistic scope. Nonetheless, this also shows that there are interactions between categories of management strategies that could be of two kinds (i) actions that address two types of categories or (ii) research discussing a range of different solutions.

Several actions could be assigned to more than one category depending on their objectives. Typically, restoration of degraded ecosystems linked to coral reefs, including mangroves, wetlands, and seagrass, could fall in the repair, protect, or adapt category depending on their purpose and timing. Some of these measures actually serve more than one purpose. Mangrove restoration is beneficial in terms of carbon sequestration and therefore mitigates CO_2 emissions, at the same time it improves the resilience of coral reefs as an important habitat for young reef fish and through buffering pH locally, and serves as a natural substitute for lost coral ecosystems services (including as a cite for fisheries and a natural barrier for coastal protection of human population). Similarly, fisheries management can improve reef resilience and provide food security to people. MPAs managers can implement fisheries management, disease control, and marine and coastal pollution management (Keller et al., 2009), thus fitting in the protect and the mitigate categories.

Mitigate strategies are identified in 180 articles, protect in 411 articles, repair in 110 articles, and adapt in 181 articles (Figure 4.5.). The protect category, and especially MPAs is the most cited strategy in the research articles reviewed here. Many articles exclusively discuss this strategy with respect to climate change, particularly the design of MPAs, their effectiveness, or their implementation. This is coherent with the historic way of thinking and tools used for biodiversity conservation (Lubchenco et al., 2003; Roberts et al., 2002).

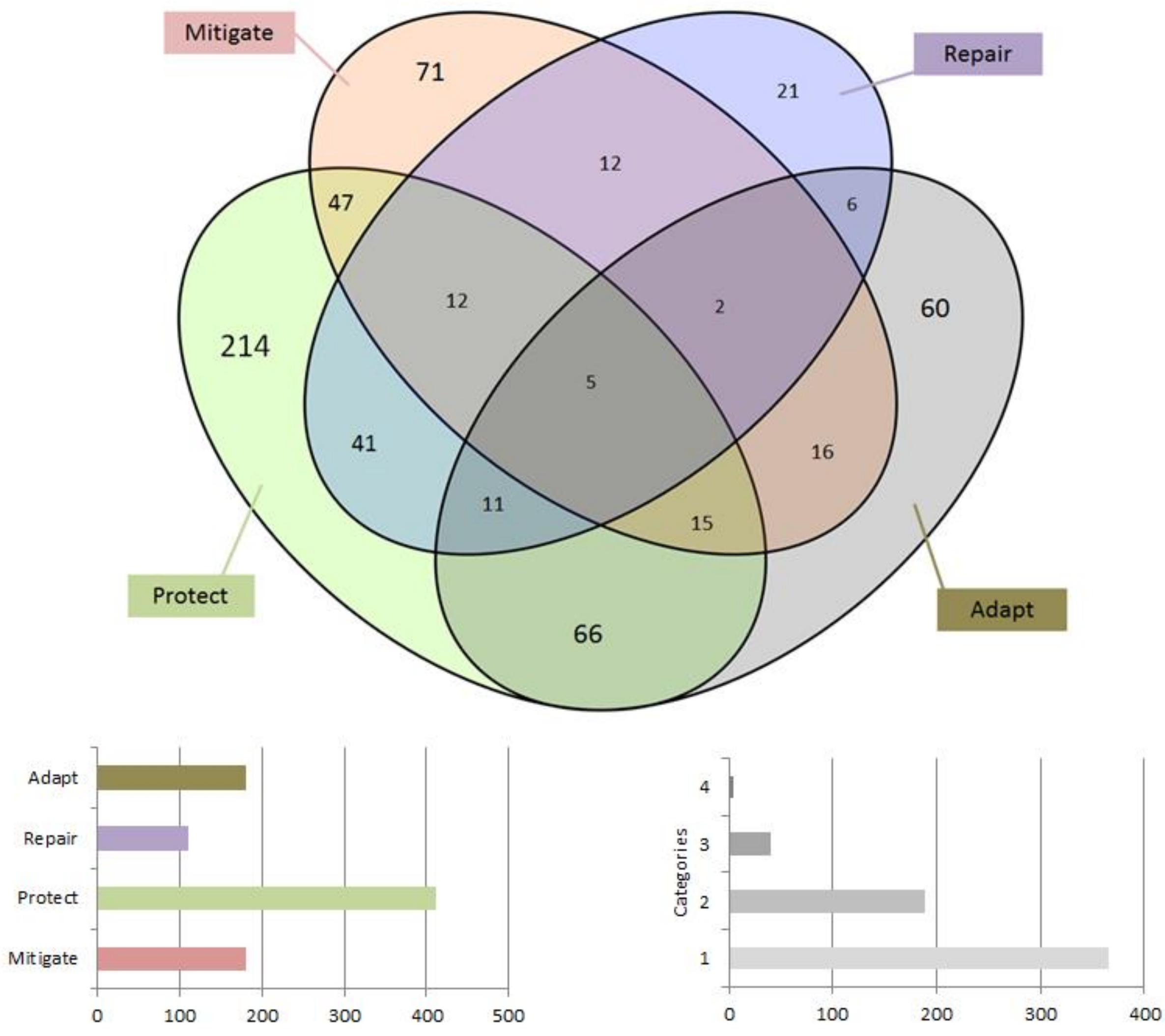


Figure 4.5. Euler diagram of the number of actions identified in each category of management strategies, and the ones that overlap one or more categories. The same information is then broken up by category of management strategy or by number of categories address in articles

b. Changing scientific effort over time

There is a growing literature on the management of coral reefs and human populations to combat GEC (Figure 4.6.A). The engagement of the scientific community with this topic started later for coral reefs than for climate change in general, after the first global bleaching event of 1998. The number of peer-reviewed articles on the subject has steadily increased over the years especially after the second global bleaching event that occurred in 2005. The acceleration in publication rate started ten years ago and the number of articles tripled between 2009 and 2016, from 45 in 2009 to 156 articles in 2016. This rapid increase in publications over the years directly parallels the increase in scientific production in peer reviewed journals for the whole field of climate change (Figure 4.6.B). The increasing number of publications can be explained by the same factors that influence climate change and ocean acidification research in general, including global recognition of this topic, international collaborations (Riebesell and Gattuso, 2015) and the global review of ecosystems and ecosystem services (Millenium Ecosystem Assessment, 2005). Indeed, the focus on management of coral reefs under threat started with the creation of the International Coral Reef Initiative (ICRI) and the Global Coral Reef Monitoring Network (GCRMN) in 1994.

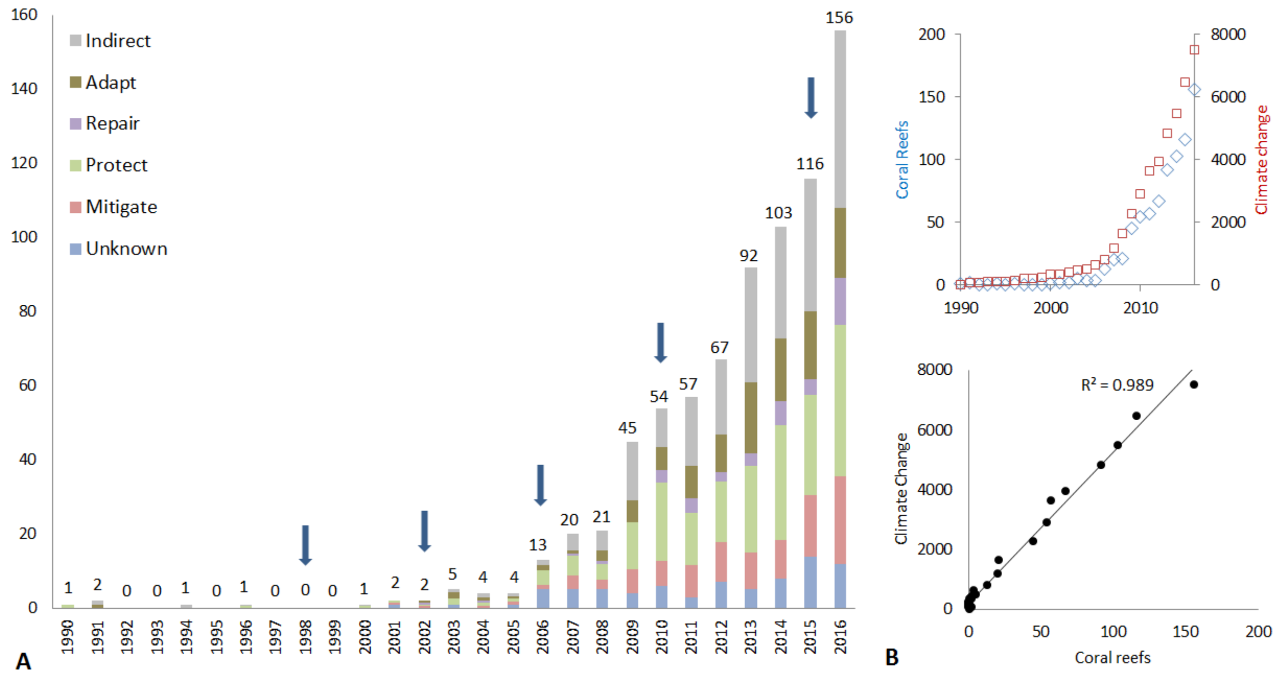


Figure 4.6. Temporal analysis of action-oriented scientific effort on coral reefs and GEC, compared with climate change as a whole. (A) Number of research articles found per year, from 1990 to 2016, broken down by categories. Arrows represent global bleaching events in 1998, 2010, and 2015-16. Large scale bleaching also happened in Australia in 2002 and 2006, and in the Caribbean in 2006; (B) Comparison of coral reefs publications over the years with publications for the whole field of climate change research.

Over the past ten years, the relative effort, in the literature focused on the four direct action categories has remained fairly constant (Figure 4.7.A). About 20% of the actions identified are mitigation actions, about 50% are protection actions, about 10% are repair actions and 20% are adaptation actions. The relative proportion of the repair category has increased just recently. The rates of change, however, are different across the four categories of management strategies (Figure 4.7.B). Protect has the highest rate of increase in publications over the years, followed by mitigate, adapt, and repair. The relative stability of these proportions over time could reflect a dominant thinking in the research community towards the use of protection measures, with a minority of researchers considering solutions for social and economic consequences of a loss of coral reefs (and therefore human communities and ecosystem services).

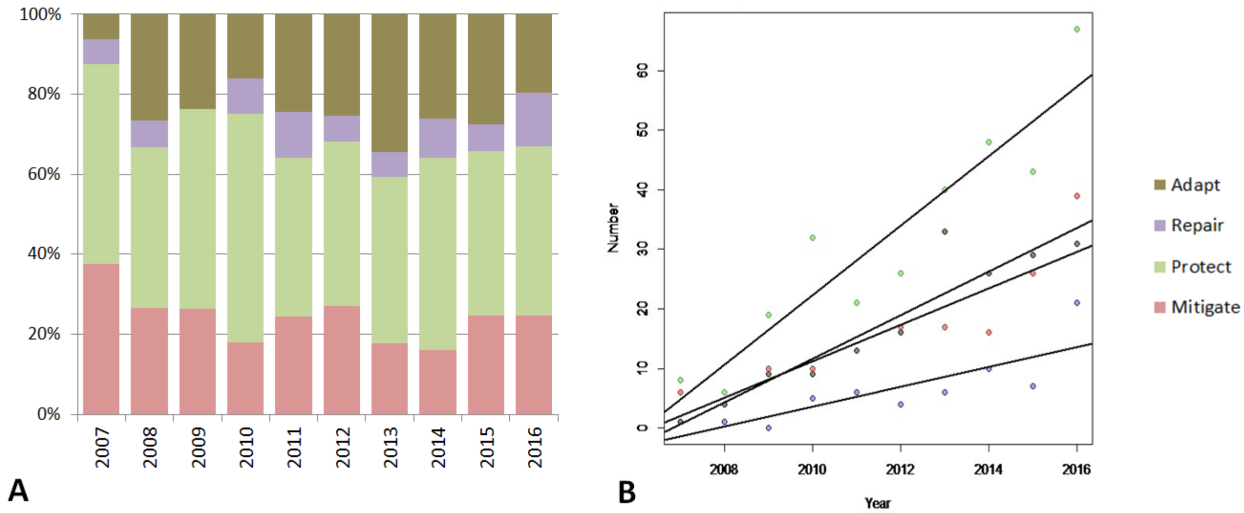


Figure 4.7. Temporal evolution of the four management strategies over the last decade (2007-2016), (A) in proportional terms and (B) in absolute terms (with ANCOVA, r^2=0.8849)

c. Scientific effort varies around the world

The scientific literature is authored by researchers from 89 countries or territories. The vast majority of scientific articles reviewed here are co-authored by researchers who are affiliated with institutions in Australia (388) and/or in the United States (335). Authors' affiliated with institutions in other developed countries, including Canada and European countries also represent a large share of the publications. This pattern holds on aggregate and for all four types of management strategies (Figure 4.8.), suggesting that the origin of authors does not influence the type of management strategy studied. Forty-four countries or territories containing coral reefs do not have any authors publishing management-focused studies on coral reefs and GEC, including in the Caribbean and the Indo-Pacific region.

Half of the studies (50.5% or 387 out of 767) include case studies, which are located in 84 countries or territories. In addition to these 387 case studies that range from focusing on a single reef to a handful of countries like the Coral Triangle, 19 research articles focus on regional scale management (10 in Caribbean, others in Indo-Pacific or Pacific Islands) and are not counted as case studies. The highest number of case studies in the literature focus on Australia (132 case studies) and particularly the Great Barrier Reef (Figure 4.9.). Other case studies are mainly located in the United States, the Coral Triangle, the Caribbean, and the Western Indian Ocean. The case studies examined focus primarily on protect strategies, and focus the least on repair strategies (the highest number of case studies focusing on repair strategies in a single country is 14 in the United States). This proportional distribution of case studies focusing on the four categories of management strategies is the same for each region of the world. The same pattern holds looking at affiliations or case studies (Figures 4.8., 4.9.).

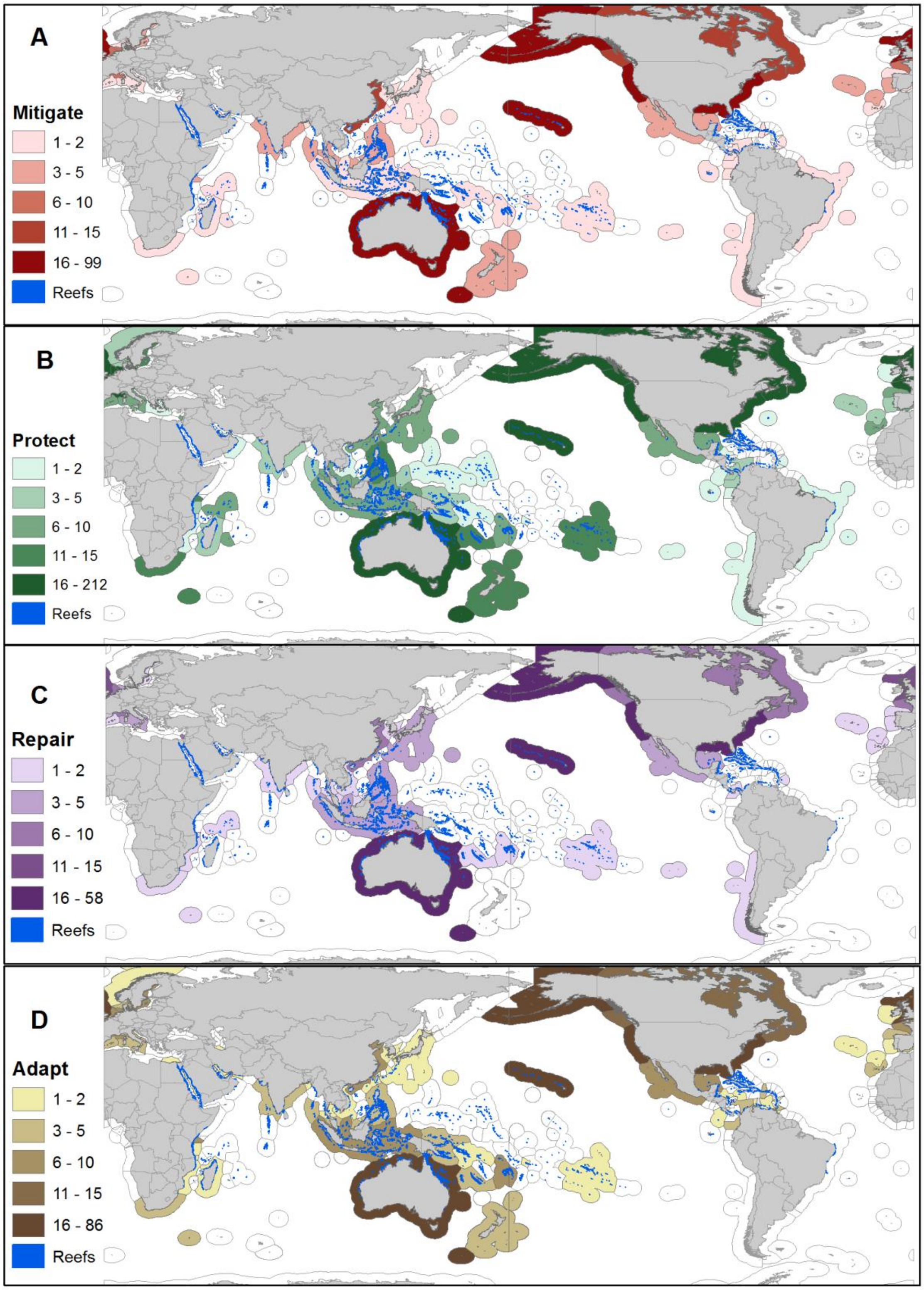


Figure 4.8. Authors affiliations per country for the four categories of management strategies (A-D)

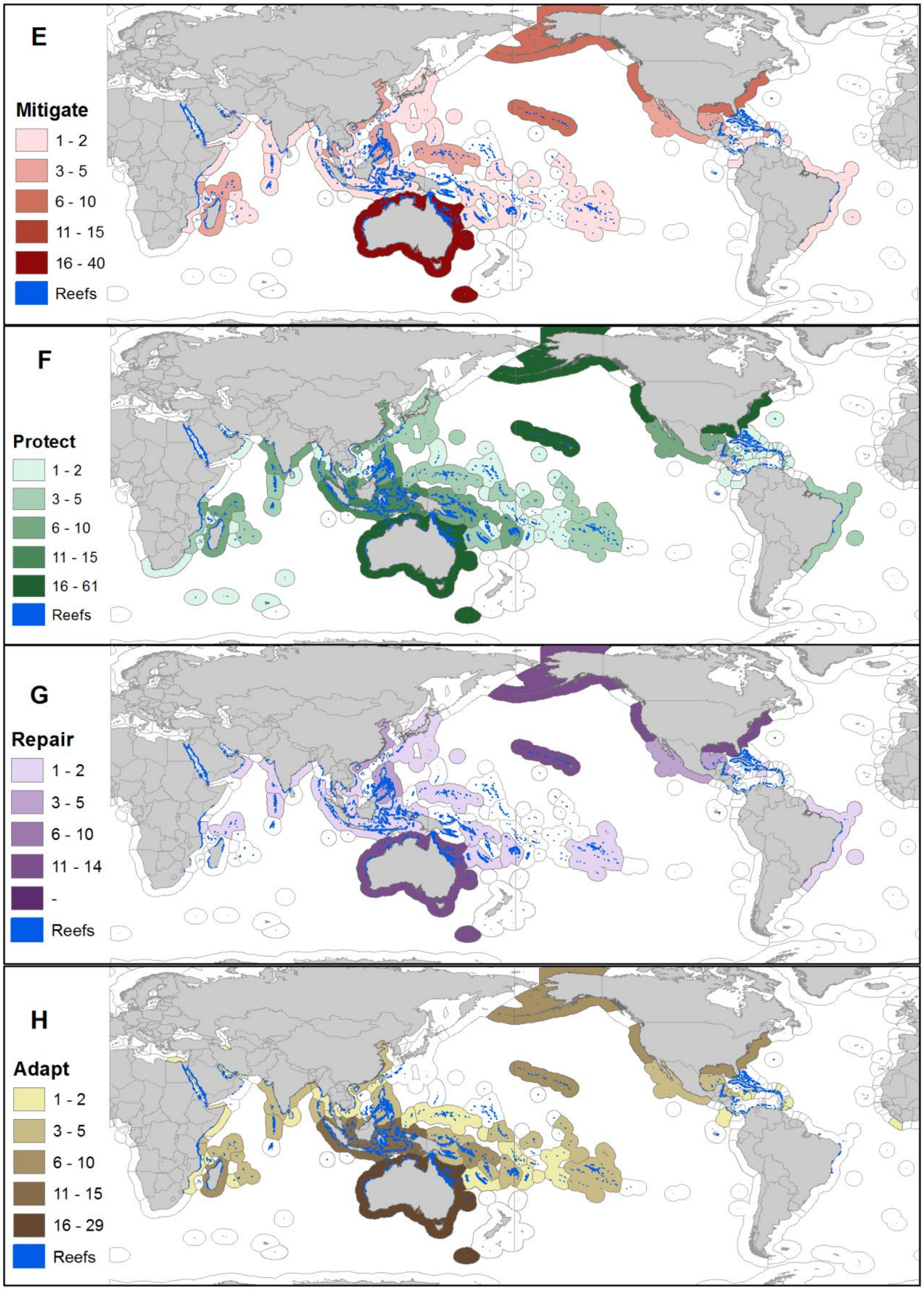


Figure 4.9. Case studies per countries for the four categories of management strategies (E-H)

Three main factors could explain the spatial distribution of authors and case studies across the globe: the locations of corals, the wealth of countries that are able to sustain research institutions and the services that reefs critically provide to populations. Authors tend to be located in institutions in countries of high income and not necessarily in the countries with the highest coral extent. Developed countries have played a major role in conducting research on coral reef management in developing countries in which the resources need to conduct research is limited. Indeed, 42% of case studies are from authors affiliated in a different country or territory than where the case was located. Twenty-nine percent of case studies are authored exclusively by researchers in the country where it is located, 27% include both authors affiliated in the country of the case study and foreigners, and 2% of the studies were conducted in overseas territories by authors affiliated in the mainland. For instance, 80% of the case studies co-authored by researchers affiliated in the United States are located outside of the United States. This pattern is surely influenced by at least two factors: (1) coral reefs are only spread across the tropics, where most developing countries are also located, and (2) several developed countries, including the United States, the United Kingdom, and France possess overseas territories where coral reefs are located.

To gain deeper insight into the factors influencing why and where case studies are conducted, a PCA was applied to the same factors that could influence their locations in different countries (excluding two outliers, Australia and the United States, that are characterized by very high amounts of case studies and high amounts of research funding). Two dimensions of the PCA account for 74.45% of the variability in the data (Figure 4.10.). The variables factor map (Figure 4.10.A) shows that coral extent is a primary explainer of where case studies are conducted. The value of ecosystem services co-varies with coral extent and case studies but does not seem to be a primary determinant of where coral reef management studies are targeted. GDP per capita is orthogonal to these two variables, suggesting that all things being equal, GDP per capita does not play a role determining where case studies are located. The choice of case studies is therefore primarily driven by where vast areas of corals are located.

A hierarchical clustering shows that countries fall into four distinct groups of countries when trying to understand the role of GDP, coral cover, and case studies (Figure 4.10.B). The first cluster represents countries with very high GDP per capita like the Gulf countries, Bermuda, or Singapore. These countries could have the means to study coral reefs extensively but do not do so since the amount of coral reefs and services they provide is low. These countries, however, may find it beneficial to invest in research about coral reef management since these are places that may be home to corals that are acclimated to future conditions (Fine et al., 2013). The second cluster contains small developing countries and island states such as Nauru, Aruba, Brunei Darussalam that are characterized by small coral extent, few case studies, and low GDP per capita. This cluster also includes middle-sized developing countries that have little or no case studies such as Cuba, Vietnam, or Panama. While these countries have less coral than other countries, local communities are likely to be highly dependent upon coral resources. As a result, investment in more research on coral reef management may still have significant returns on investment. Lower middle income countries (as defined by the World Bank) found in this group are under-studied compared to their relative importance in terms of coral extent. The third cluster contains large countries such as Brazil and India, and countries with high coral extent and high levels of ecosystem services including Thailand, French Polynesia and China for example that contain more than average case studies. Finally, the fourth cluster regroups the Philippines and Indonesia that contain vast areas of coral reefs and high levels of ecosystem services, combined with numerous case studies. The number of case studies in these countries shows that regional and international research programs in the Coral Triangle should be encouraged. Twenty-six countries or territories containing coral reefs do not have case studies located in them. This is a serious gap, especially for Cuba and Eritrea which both contain large areas of coral reefs.

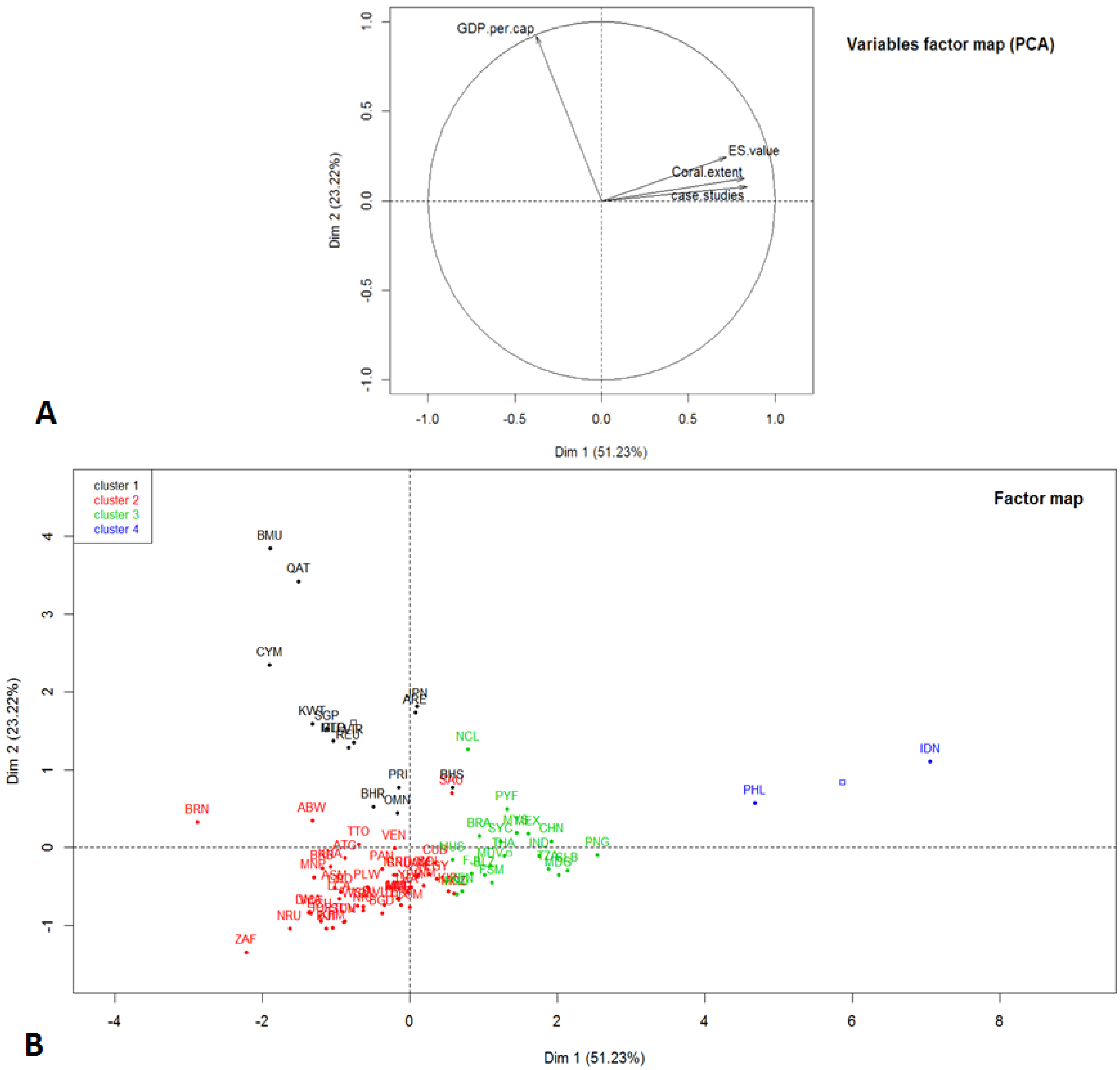


Figure 4.10. PCA analysis with hierarchical clustering on countries containing case studies. Variable factor map with GDP per capita, ES values, coral extent, and number of case studies (A) and factor map (B) along the two first dimensions

The distribution of future global environmental change is not homogeneous and science needs to study the effectiveness of management actions in those places where coral reefs and people may be most at risk from GEC. Current modelling suggests that SST warming will impact the Pacific and Southeast Asia first, whereas OA will be more important towards the pole (Chapter 3). In addition, the distribution of the demand for ecosystem services is also heterogeneous, and Southeast Asia is the most dependent on reefs for ecosystem services, followed by the Middle East, the Caribbean and the Indian Ocean (Figure 4.11.). Comparing the average proportions of ecosystem services across the ocean provinces with the proportion of case studies, there is a deficit of case studies in the Middle East, the Southeast Asia, and the Brazilian ocean provinces.

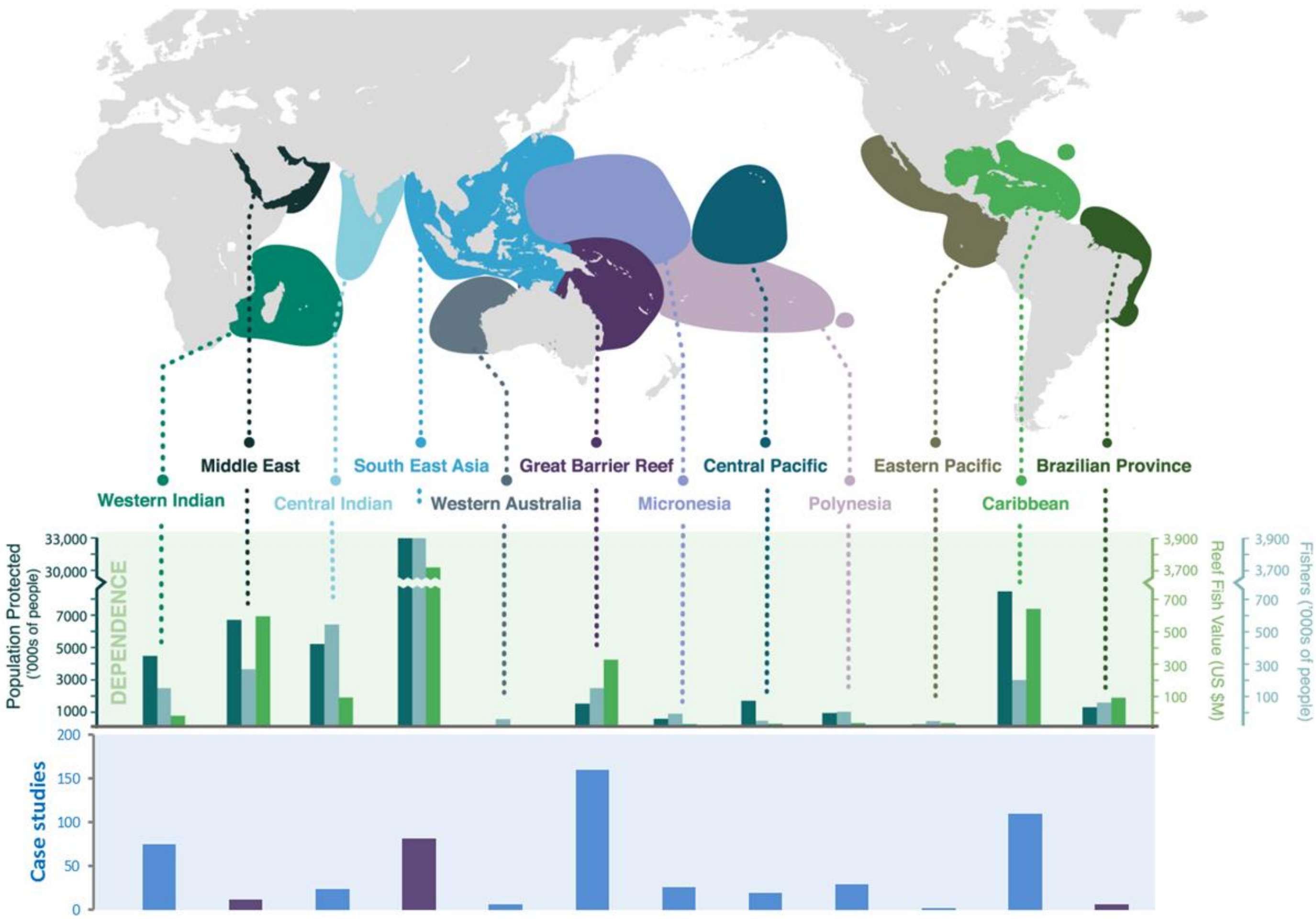


Figure 4.11. Regional dependence, by ocean province (OP), on ecosystem services and number of case studies per ocean province, modified from Chapter 3. For case studies, purple OPs contain proportionally less case studies than their share of ecosystem services

5. Discussion

a. The literature focuses disproportionately on maintain the ecological status quo

The literature has focused disproportionately on efforts to hold the ecological line for coral reefs (with more than 60% of studies focused on mitigate or protect) and less on helping people and coral ecosystems in a future in which the natural world will look quite different. Considerable scientific effort has gone into discussion of designing and effectiveness of MPAs, identification of sites and refugia, and managing fishing pressure and other environmental stressors. On the other hand, very little work has focused on repair measures that are more active management strategies aimed at rebuilding coral extent and ecosystem services after disturbances. Future research efforts need to focus on the effectiveness of repair strategies. Assisting the evolution of coral reefs to sustain them in a changing climate is in its early stage of development. In addition to the prohibitive cost of these techniques (Bayraktarov et al., 2016), ethical issues to do so persists. Still, some argue that assisting evolution can be included in coral reefs restoration (van Oppen et al., 2017).

Despite the growing focus on adaptation in the climate change literature (Füssel and Klein, 2006), this new trend is not reflected in the coral reef literature with less than 25% of the studies focusing on adaptation. One reason for a lack of focus on human adaptation may be the ecological focus of much of the literature to date regarding coral reef management. Indeed, out of the top 15 journals that account for 41% (314 articles out of 767) of the research articles reviewed, almost half (144 articles) are published in conservation or natural science oriented journals, 98 in pluri-disciplinary journals, and only 72 in social science oriented journals (Annex E).

There are two particularly striking gaps in the study of management strategies that relate specifically to human populations dependent on reefs. First, migration of human population was mentioned as a broad category of action but was discussed nowhere in the 767 articles we reviewed from the coral reefs literature. This is surprising given that this topic is well-covered the general climate change adaptation literature (McLeman and Smit, 2006) and given that coral reefs are sometimes located in low-lying islands where populations are particularly exposed to sea-level rise. Second, the issue of using indigenous knowledge for management under climate change was also barely touched on in the papers we reviewed despite its important role for management (Veland et al., 2013). There are two possible explanations for the lack of coverage in the literature on these management strategies. It is possible that these are research frontiers that will be explored in the future. Alternatively, we may have missed important contributions even though we reviewed 767 papers to identify management actions.

While numerous studies (e.g. (Gattuso et al., 2015)) argue for a reduction of GHG emissions since the effectiveness of all other management strategies will depend on our success at stabilizing the climate around 1.5°C or 2°C of warming, the most optimistic emission pathway scenario will already lead to high impacts for coral reefs (Frieler et al., 2012). Reducing GHG emissions is now a matter of politics and not of science since the 1.5°C target is written in the article 2 (a) of the Paris Agreement (UNFCCC, 2015), and given that dealing with local anthropogenic threats is already well studied (Ateweberhan et al., 2013; Kroon et al., 2014; Magris et al., 2015). It is therefore crucial to scientifically explore a full suite of solutions, including repair strategies and adaptation to the loss of ecosystem services and to explore combinations of these solutions.

b. The literature is not addressing many places where coral reefs and people are threatened

Current scientific efforts do not target the full range of countries where coral reefs are located, including many places where corals and people are at risk from GEC. Most of the case studies examined are conducted in developed countries, and particularly Australia and the United States, which parallels their disproportional share of scientific contribution on biodiversity conservation in Oceania (Kingsford et al., 2009) and in general (Di Marco et al., 2017; Falkenberg and Tubb, 2017). It is important to note that there could be a bias in our analysis towards English speaking countries because only international peer-reviewed journals in English are included in this analysis (Falkenberg and Tubb, 2017). There are few studies on coral reef management effectiveness for areas like Southeast Asia, which has the highest dependence on coral reefs and also contains the highest coral diversity (Veron et al., 2015). Southeast Asia, Brazil and the Middle East are all areas for which more scientific study is needed to understand the human and ecological dimensions of coral reef management in the face of GEC.

The literature also reveals a tremendous patchiness in the distribution of human capacity to study the effectiveness and consequences of coral reef management actions to deal with GEC. Forty-two coral reef countries and territories were completely unrepresented in the affiliations of authors in these peer reviewed studies. The implications of such concentrations of authors at institutions in high income countries, studying coral reefs in other countries, are not clear. This aspect of research needs serious consideration given the disproportionate vulnerability of developing countries to the effects of GEC on coral reefs (Burke et al., 2011; Wolff et al., 2015) and given the fact that 26 developing countries and territories containing coral reefs also do not contain case studies.

6. Conclusions

We refined a typology of management strategies in order to review the comprehensiveness of scientific investigation into the effectiveness and consequences of coral reef management in the face of GEC. The typology also reveals that management strategies differ along two key dimensions: (i) whether they seek to maintain an environmental status quo or accept environmental change and (ii) whether they focus on ecological and environmental aspects or human dimensions of coral reef social-ecological systems. Few studies examine a very broad suite of ecological and human oriented approaches. The typology discussed in this article could also be applied to other SES, both marine and terrestrial. Typologies like the one refined and presented here can assist in conveying scientific knowledge to decision-makers (e.g. IPBES or IPCC) and build a dialogue between scientists, managers, and decision-makers around the issues of global environmental change in general (Moser, 2010) and of coral reefs in particular (Crosby et al., 2002). It is the role of managers and decision-makers to appropriate this knowledge and produce decisions and management plans that will shape the future of coral reefs and people who depend on them. We hope to have clarified the range of potential management strategies to respond to these threats so that this work can be used as a first step in the identification and appraisal of actions, for instance in adaptive management frameworks (Birgé et al., 2016).

If managers are to be able to weigh the tradeoffs of the full suite of management options, scientific efforts need to be broadened across management options and also across coral reef geographies. The existence of barriers and limits to the effectiveness of existing management strategies needs to be recognized (Barnett et al., 2015; Feagin et al., 2010). Yet, we find that the scientific literature has not focused enough on adapt and repair management strategies that deal with the inevitable impacts of GEC. It is clear that current research is biased towards developed countries (especially Australia and the United States) and towards protection management strategies. A re-organization of scientific research on the subject is needed. Under-studied geographic locations including developing countries in Southeast Asia, and developing countries in the Western Indian Ocean, the Middle East, the Pacific, and the Caribbean should be the focus of future research. New research is also needed on adaptation of people who depend on coral reefs. Future research should attempt to study multiple strategies at the same time to understand trade-offs and synergies between management strategies. This reorganization is possible without undermining scientific efforts on traditional topics of protecting biodiversity thanks to the increase in the number of papers and scientists working on this field.

Chapter 5. The role of ecological limits in prioritizing impacts, resilience, and action for coral reefs under global environmental change

Authors: Adrien Comte*, Linwood H. Pendleton

Associated annexes: -

Acknowledgements: This work was supported by the "Laboratoire d'Excellence" LabexMER (ANR-10-LABX-19) and co-funded by a grant from the French government under the program "Investissements d'Avenir", and by a grant from the Regional Council of Brittany. We declare no conflict of interest. We thank Patrice Guillotreau, Alexandre Magnan and Jean-Pierre Gattuso for their input on designing the study. Figure 5.4. is reproduced with the permission of Vanessa Gonzalez-Ortiz.

1 Introduction

Coral reefs, already under pressure from local threats (e.g. overfishing, coastal pollution), are one of the socio-ecological systems most vulnerable to global environmental change (Burke et al., 2011; Hoegh-Guldberg et al., 2007). Indeed, global environmental change, including elevation of sea surface temperature and ocean acidification, threaten the functioning of coral reefs on a global scale, leading to coral bleaching, mortality, loss of biodiversity, and loss of services to human populations who depend on them (see Chapter 2, 3).

Managers and decision-makers need scientific evidence and guidance to better understand 1) where the impacts of climate change and ocean acidification will be the greatest and 2) where to undertake action to counter the effects of such change on coral reef state, function, and services they provide to humans. Connecting science to policy in the face of climate change is made difficult by: the complexity of coral reef socio-ecological systems, the diversity of management tools available, and gaps in our understanding (Chapter 2, 4).

Indicator-based assessments, using scientific evidence, have been developed to understand changes in socio-ecological systems (SES) and guide decision-makers and managers and to monitor and evaluate progress towards environmental management under global environmental change (Hinkel, 2011; Quinlan et al., 2016). Indicator-based vulnerability assessments have been proposed for coral reefs socio-ecological systems (Cinner et al., 2013; Hughes et al., 2012a) as a mean to target coral reef fisheries management and policies. While these assessments are useful to understand where coral reefs or human populations are vulnerable to change, they don't necessarily lend themselves to the prioritization of specific actions (Burton et al., 2002).

Another approach that emerged recently to guide managers to plan for the effects of climate change on coral reefs is resilience-based management (RBM). Resilience theory is increasingly used to guide management and decision-making, including in international development (Barrett and Constas, 2014). RBM approaches to coral reef management in the face of GEC often focus on the assessment of ecosystems conditions that could influence whether a reef system will be pushed beyond thresholds into undesirable alternative states or whether the system will recover to desirable states after disturbances, in other words properties that make coral reefs resilient to change (Cheal et al., 2010; Maynard et al., 2015a). RBM studies, however, have been used to inform a relatively small set of management options, including marine protected areas and fishery management. Because RBM approaches focus on ecological resilience, they often fail to provide information (or guidance) about actions that should be considered when reef change is unavoidable, which limits their usefulness in identifying social adaptation measures to the impacts of GEC on corals.

The diversity of the human and ecological contexts of coral reefs, as well as the great range and numerous dimensions of GEC, requires a diverse set of tools and management strategies to best handle the increasing intensity of threats posed by climate change and ocean acidification in specific environmental contexts. A number of strategies are available to deal with the impacts of CO_2 on coral reefs and ecosystem services (Chapter 4). Four categories of action exist: mitigate, protect, repair, and adapt. Mitigation actions involve limiting the level of CO_2 or other gases that cause temperature rise and ocean acidification, as well as reducing coastal pollution that increases the effect of global changes. Protection involves management actions such as Marine Protected Areas that reduce environmental stressors on coral reefs, promote its resilience, and protect places that may be spared from global environmental changes. Repair involves human action to reverse the declines in environmental conditions and ecosystems in order to artificially produce favorable ecological conditions (e. g. adding alkaline material), restore degraded ecosystems, or artificially increase their tolerance to global environmental change (e.g. through assisted evolution, van Oppen et al., 2015). Adaptation actions are available to manage the impacts due to the loss of ecosystem services to human populations, through the modification of socio-economic activities (e.g. aquaculture, coastline protection, diversification of revenues) or the modification of ecosystems (e.g. ecosystem-based adaptation, replacing ecosystems).

Furthermore, in the face of large scale global change, we need to recognize that there are ecological limits that will influence the effectiveness of management actions taken to counter the impact of climate change and ocean acidification on coral reef ecosystems (Mora et al., 2016). These ecological limits affect the costs and final outcomes of management actions in terms of their impact on diversity, function, resilience, and ecosystem services. These limits are due to two factors: 1) natural ecological and physiological conditions that determine reef state even in the absence of any human pressures and 2) the effect of environmental stressors (e.g. climate change and OA) that are beyond the control of most managers and decision makers. Failing to account for limits in the ecological capacity of coral reef ecosystems could lead to maladaptation (Barnett and O'Neill, 2010; Magnan et al., 2016).

An integrated approach that recognizes human and ecological limits is needed to improve management of social-ecological systems under the threats of global environmental change (Evans et al., 2016; Hilborn, 2016). With this in mind, we propose a merging of the indicator approach with the synthesis of resilience and vulnerability frameworks, that already has appeared in the literature (Adger, 2000; Engle, 2011; Turner, 2010; Turner et al., 2003), with a specific approach to coral reefs and people. As Engle and Turner, we identify adaptive capacity as the logical point of entry to link the resilience and vulnerability frameworks. In a social-ecological systems (SES) setting, both social and ecological adaptive capacities are essential components to assess. Because the literature already addresses issues of social adaptive capacity (Bennett et al., 2014a; Magnan et al., 2016), we focus on ecological adaptive capacity – a concept that has not yet received attention in the literature.

The objective of this paper is to provide managers and decision-makers with a single, synthetic framework that elucidates the role of ecological adaptive capacity and to provide example indicators to operationalize this concept with an explicitly application to management strategies for coral reefs SES under global environmental change. The framework developed here illuminates how global environmental changes and local ecological "endowments" influence the choice and effectiveness of management options. We will first explore how ecological conditions are included or not in current analytical frameworks. Then, we will discuss what are ecological limits, how to include them in management and policy-making. Finally, this paper will 1) identify potential indicators and 2) design a decision framework to operationalize the concept of ecological adaptive capacity.

2. How do current approaches deal with ecological conditions

The literature reveals a number of studies that aim at appraising management options to tackle the impacts of climate change on marine ecosystems. The methods used to classify options are directed towards the goal of prioritizing specific actions to decrease the vulnerability of socio-ecological systems, or to improve the conservation of marine ecosystems (e.g. Anthony et al., 2015; McLeod et al., 2012; Mumby and Steneck, 2008). We focus here on vulnerability assessments and resilience-based management (RBM), to approaches that link global environmental change to SES and that are used for managing these systems. In this section, we review how these studies incorporate ecological conditions and limits in their frameworks.

a. Vulnerability of social-ecological systems

Vulnerability is function of exposure, sensitivity, and adaptive capacity (Adger, 2006; see Introduction générale and Chapter 1). Vulnerability frameworks are used to assess impacts, adaptive capacity and thresholds that make a system vulnerable in order to build resilience and guide adaptation (Adger, 2006). Vulnerability assessments are now popularly applied to the effects of climate change on marine systems (Allison et al., 2009) and other socio-ecological systems (Turner et al., 2003). In the past, vulnerability assessments have been used to both characterize socio-economic systems (Chollett et al., 2014a; Ekstrom et al., 2015) or to describe the threats posed by climate change and ocean acidification on marine species or ecosystems (Chin et al., 2010; Hare et al., 2016; Hendriks et al., 2010). Approaches that integrates the two sides of socio-ecological systems (SES), both human and ecosystem perspectives, have been offered (Adger, 2006; Turner et al., 2003), but have only recently been applied to coral reefs - at the global scale (Burke et al., 2011; Hughes et al., 2012a) and the local scale (Cinner et al., 2013), each time focusing on fisheries.

In the SES vulnerability framework developed by Marshall et al. (2013a, 2011, 2009), vulnerability is applied to both the ecological system and the socio-economic systems in an integrated framework. Ecological vulnerability is assessed along three dimensions (exposure, sensitivity, and adaptive capacity), which then becomes a dimension of socio-economic vulnerability (Figure 5.1). While ecological exposure can be thought of as the environmental threats or hazards that will impact the SES, ecological sensitivity and adaptive capacity are harder to characterize. Ecological sensitivity is linked to life history variables for the species in question while adaptive capacity, as defined by Marshall, simply refers to the magnitude of other non-climate stressors. These factors defining ecological sensitivity and adaptive capacity do not address or account for the role of ecosystem functions, resilience and limits that will determine how coral reef ecosystems respond to different environmental conditions or management strategies.

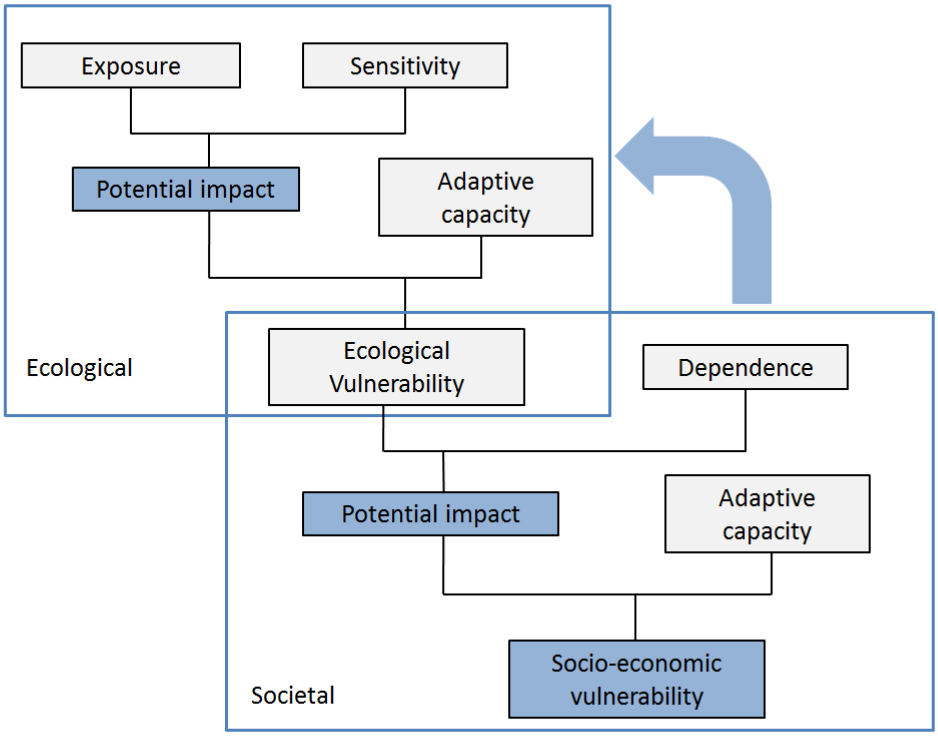


Figure 5.1. Framework to assess the vulnerability to climate change in socio-ecological systems, redrawn from (Marshall et al., 2013)

Building on Marshall et al., Metcalf et al. (2015) also propose a framework of socio-economic vulnerability to climate change on marine SES. Ecological adaptive capacity in Marshall's model is not found in Metcalf's framework. While this framework attempts to differentiate between the vulnerability of the ecological and socio-economic subsystems, it does not consider the effect of ecological constraints that determine the potential outcome (and thus effectiveness) of management actions. Both the frameworks of Marshall et al. and Metcalf et al. are now used widely in other studies marine socio-ecological vulnerability (Cinner et al., 2013; Hobday et al., 2016; Thiault et al., 2017b). By expanding these frameworks to include EAC, we hope to improve the usefulness of these frameworks in future research and management.

b. Resilience-based management approach

A parallel approach to socio-ecological vulnerability assessment, Resilience-based management (RBM), addresses directly the issues of ecological resilience developed by Folke (Folke et al., 2004) and by Norström (Norström et al., 2009) in order to guide decision-making about possible management actions in the face of environmental threats. In RBM, the ecological resilience of a system is defined as its capacity to respond to changes and to recover after disturbance (Folke et al., 2004; Holling, 1973). RBM has been used by local managers and is starting to be used at the global scale as well (Norström et al., 2016). The functioning of an ecosystem can be overwhelmed and change significantly if certain environmental thresholds are exceeded. Surpassing these thresholds may push the system into alternative states, with very different ecosystem composition and function, and therefore different levels and types of ecosystem services (Worm et al., 2006). For instance, many Caribbean coral reefs have shown low levels of resilience to human pressures and have transitioned to an alternative state dominated by macro-algae (Mora, 2008) (Figure 5.2.).

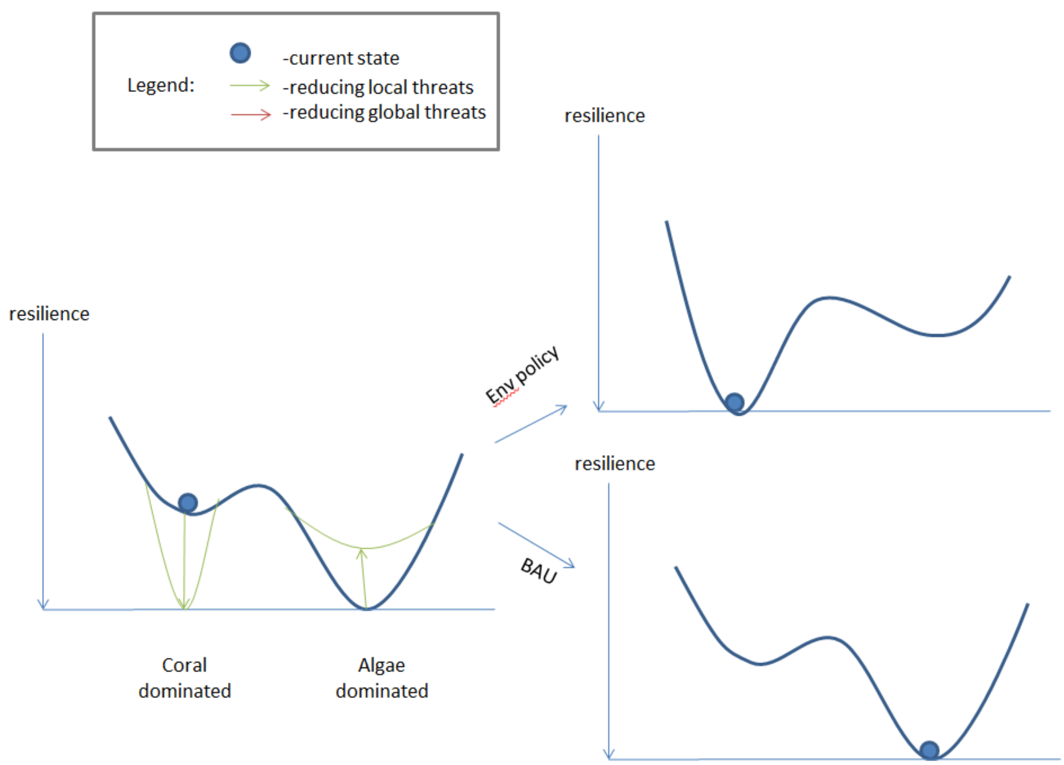


Figure 5.2. The effects of management on ecological phase shifts, re-drawn from (Graham et al., 2013). Two scenarios, environmental policy (Env policy) and Business as usual (BAU) lead to different ecological states

The goal of RBM is to identify factors (ecological or related to human activities) that influence the resilience of an ecosystem to shocks. Comparative studies of coral reefs that have recovered with those reefs that have undergone a phase shift when faced with similar changes allow researchers to test whether certain factors determine the trajectory of coral reefs (Magris et al., 2015). These factors can then be used to develop, standardized and measureable indicators. Monitoring these indicators could then be used to better estimate the state of a system (or its vulnerability), information useful to prioritize management strategies (Magris et al., 2015; Mumby and Anthony, 2015). Like vulnerability assessments, RBM assessments identify those local factors could be addressed to help improve ecological resilience, and thus to reduce impacts on people, in the face of global environmental change. The argument is that the resilience of coral reefs resilience to global environmental change and especially warming (Anthony et al., 2011) can be improved by managing these local factors directly (see Chapter 4 and Annex C for examples).

While vulnerability assessments tend to have few specific ecological indicators, RBM methods focus on a wide variety of ecological conditions (Anthony et al., 2015; McClanahan et al., 2012, 2009; Obura and Grimsditch, 2009). In some cases, these indicators are used to create a typology of situations that corresponds to different recommendations for management. While these studies have not converged on a single set of resilience indicators for coral reefs, measures of local and global stressors, coral diversity, coral cover, macroalgae, herbivorous fish abundance and diversity, coral growth, and connectivity, are commonly found metrics (Table 5.1.). According to Mumby et al (Mumby et al., 2014a), selecting indicators for resilience (like herbivores biomass or history of SST) is place-specific. The growing list of indicators has recently been reduced from around 40 originally proposed by McClanahan et al (2012) to a smaller set of to 11 indicators (Anthony et al., 2015; Maynard et al., 2015a) (Table 5.1.). While the trend of scientific research on resilience indicators has been to reduce the number of indicators used for monitoring, evaluation, and decision-making (McClanahan et al., 2012; Quinlan et al., 2016), a lack of explicit measurement of ecological limits is problematic.

c. Integrating vulnerability and resilience to assess coral reefs SES under GEC

Several authors have attempted to integrate vulnerability and resilience thinking in a synthetic theory and conceptual framework (Adger, 2000; Engle, 2011; Turner et al., 2003). While these efforts have remained theoretical thus far, the use of indicator-based assessments to characterize vulnerability and resilience in the recent years may offer a way forward in the operationalization of these conceptual frameworks.

Even though their theoretical origins are in different disciplines, vulnerability and resilience thinking are beginning to converge (Gallopín, 2006; Timmerman, 1981). The concept of social-ecological resilience was developed and operationalized to describe a system's characteristics that enable resistance to external shocks, recovery after experiencing a shock, but also transformation and re-organization of a system to remain in a stable state (Carpenter et al., 2001). Vulnerability approaches for SES generally incorporate notions of resilience in adaptive capacity (Adger, 2006; Marshall et al., 2013; Turner et al., 2003). Resilience-based management approaches incorporate elements of vulnerability, including environmental stresses and social adaptive capacity (Anthony et al., 2015; McClanahan et al., 2009). Considered separately, these two approaches do not address the full complexity of these systems. Because the concept of adaptive capacity appears in both approaches, it is a logical entry point to link these two conceptual frameworks (Engle, 2011; Figure 5.3.).

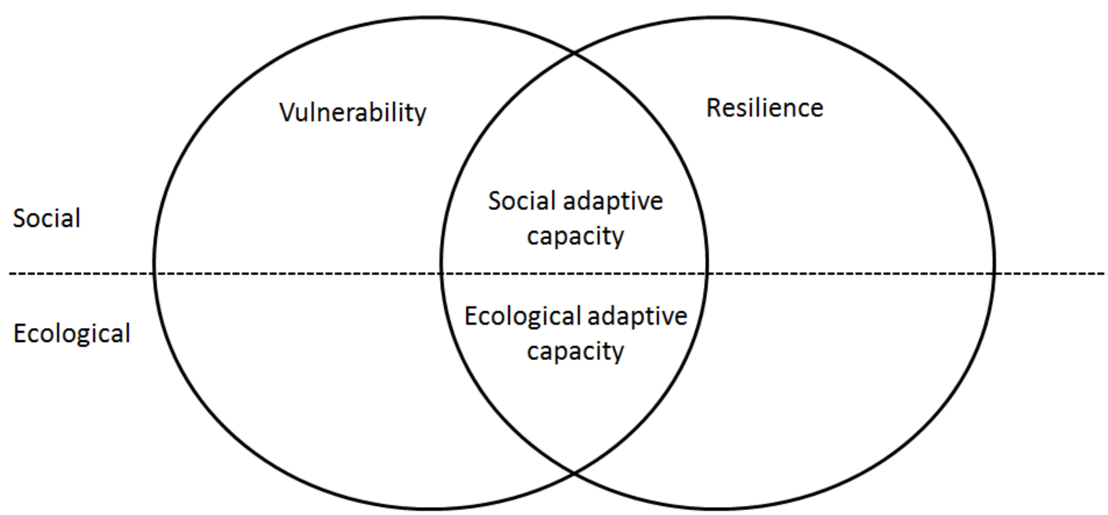


Figure 5.3. Adaptive capacity as the common component of resilience and vulnerability; Modified from (Engle, 2011)

The effective implementation of management actions depends on both types of adaptive capacities: ecological capacity and social capacity (Figure 5.4.). Social capacity reflects the socio-economic and institutional attributes that either limit the implementation of management (barriers) or are required in order to advance adaptation to climate change in the UNFCCC sense (effectiveness). The limits of social adaptive capacity have started to be studied (Barnett et al., 2015; Evans et al., 2016). These social limits arise from the way people "perceive, experience, and respond to climate change". Assessing these social limits can improve the planning of adaptation to climate change. Similarly, assessing ecological limits define by ecological adaptive capacity should improve the planning of management strategies to tackle climate change in SES.

Evaluating relative appropriateness of management actions is not possible using RBM or vulnerability frameworks alone. While RBM is useful to identify where GEC may exceed the tipping point for coral reefs, it does not take into account the human dimensions that affect where to focus management effort - namely where management can yield ES benefits (Mumby et al., 2014b). As a result, RBM tends to focus on ecological management options (mostly protection and repair) while vulnerability approaches often focus on human-oriented management actions (mostly adaptation). A synthetic analytical framework that combines elements of both vulnerability and resilience approaches can bridge this gap and will better illuminate the role of ecological limits to GEC the prioritization of local management actions.

3. Operationalizing Ecological Adaptive Capacity: Incorporating ecological limits in management

a. Definition of the concept of ecological adaptive capacity

We propose the concept of "ecological adaptive capacity (EAC)" that defines the maximum potential ecological state of a reef in the absence of local environmental stress. EAC describes a boundary condition that sets an upper-limit to the expected outcomes from proposed management actions which seek an improvement or change from some baseline (e.g. business as usual). EAC sets the upper bound for the expected benefits of different management strategies.

Measuring the potential change in ecological state is function of the current state of coral reef and associated ecosystems, the extent of their past and current degradation, and the ecosystem properties that will limit their potential recovery in the context of future global environmental change. Information on these parameters sets a baseline to measure the potential benefits of management action.

For instance, some reefs are already too damaged to recover and may never support the same ecological function as in the past. Other reefs may be near their ecological limits and will not be able to recover from global environmental change, regardless of how well they are managed. Clearly, further investment in protection may not be the best management approach for these reefs. Other reefs may thrive in the face of climate change due to their given evolutionary, genetic, or ecological properties. These reefs may be good candidates for protection and could serve as important refugia. Other reef ecosystems may be good candidates for restoration or mitigation to increase resilience and ecological function that will stave off the effects of global environmental change. Identifying the EAC of a reef helps to prioritize the potential for improved (i) resilience, (ii) recovery, (iii) ability to avoid losses of ecosystem services (which can require human adaption) (Figure 5.4.).

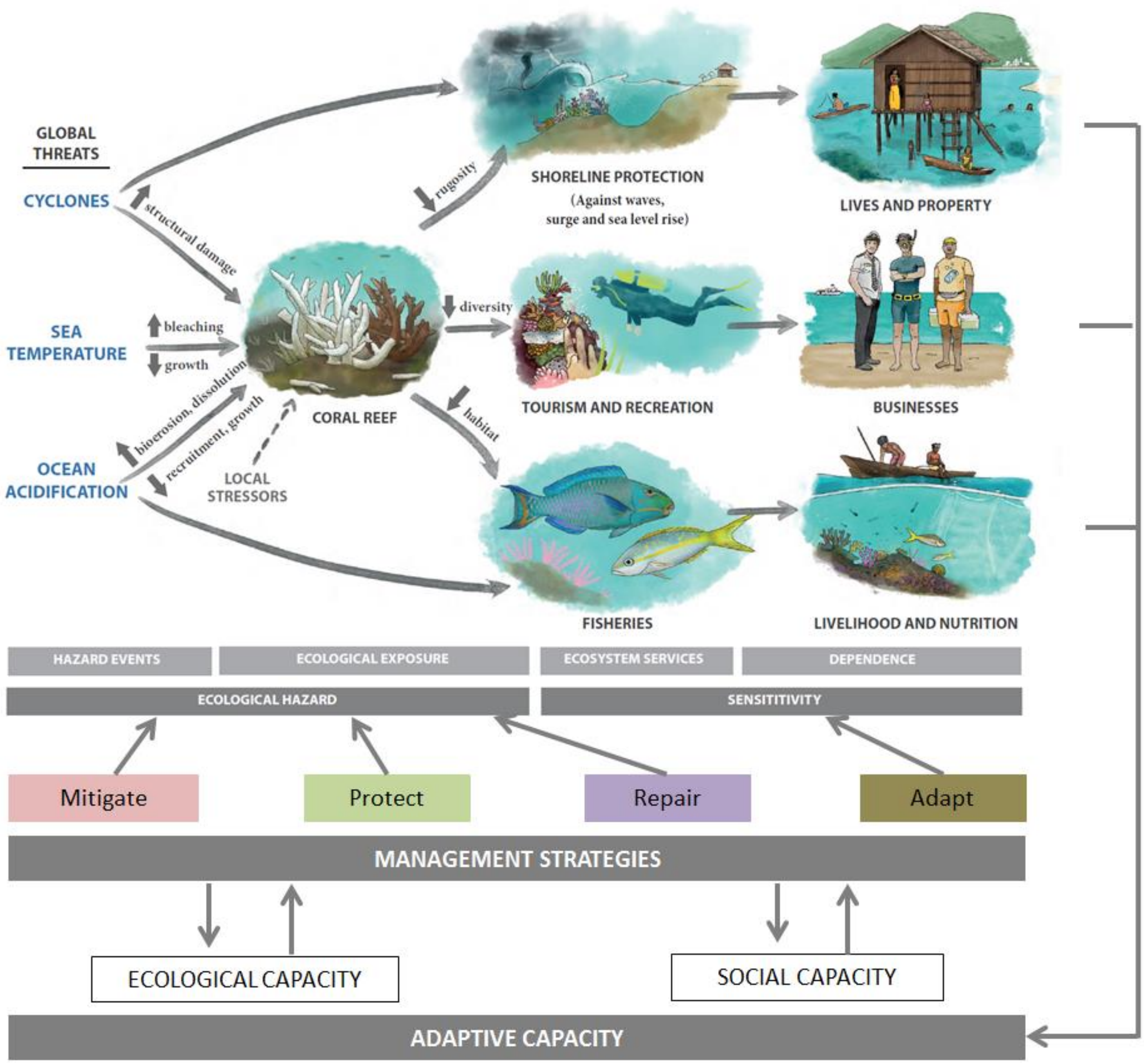


Figure 5.4. Chain of impacts of GEC on CR SES, management, and adaptive capacity

b. Incorporating ecological adaptive capacity in management

Knowing the potential upper limit for the supply of ecosystem functions and services that could be achieved in the absence of other stressors sets an upper bound on the potential benefits of management actions and helps the manager understand whether the potential costs of management may exceed the potential benefits (Figure 5.5.). Management effort is intended to improve the ecological state of a reef from some initial point 0, that represents the current state of a coral reefs or the state of a reef after a disturbance such as a bleaching event or a cyclone. The more effort invested in management (e.g. including establishing marine protected areas, regulating fishing and other human activities to help a reef recover or increase its resilience), the more the cost of management. However, the outcome of management will differ depending on the EAC of the reefs (outcomes can include different dimensions of ecological state include coral cover, diversity of coral species, diversity and abundance of fish functional groups). If the upper limit is close to the current state of the system, meaning that not much more ecological function can be provided, then it may not be worthwhile to invest in protection or mitigation measures. However, if the limit is very high (such as ecological refugia for example), even if the reef is providing very few ES in current conditions, management may be warranted.

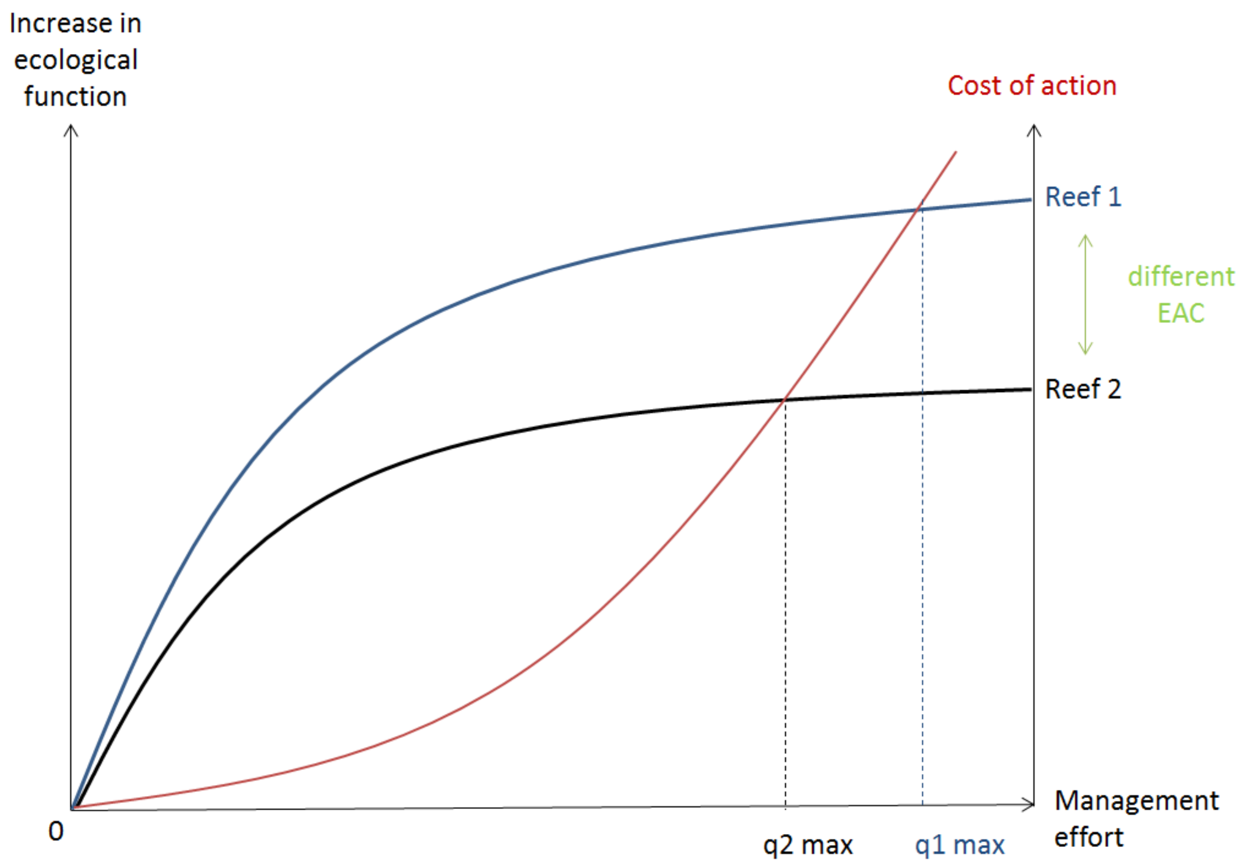


Figure 5.5. Theoretical representation of ecological adaptive capacity determining the expected benefits of management effort. Cost of action will exceed expected benefits at q1 max for Reef 1. Cost of action will exceed expected benefits at q2 max for Reef 2.

Conceptualizing the potential change in ecosystem state under management can also be thought of as the relative difference between current state (C) and the maximum potential (Pm) state of a system in the absence of global environmental change (Figure 5.6.). The managers' choice is to determine the desired state (D) which will depend on the objectives of management, for example reaching a "good ecological health status", the costs and the benefits of more management effort. GEC reduces the maximum potential state of a reef, setting an upper-bound on the realizable potential (Pr) – determined by how much ecological function can be expected in the absence of local stressors. To illustrate the role of EAC in guiding the choice of management options and effort, consider four different outcomes of GEC on a reef system. In case (1), GEC only moderately lowers maximum ecological state and the manager chooses mitigation, protection or restoration, but only up to the point where net benefits are maximized (or at least costs of investment don't exceed perceived benefits: C<D<Pr). In case (2), the effect of GEC on the reef system is such that the desired state of the system cannot be reached, but local management can still improve ecological state: C<Pr<D. Maladaptation can start to occur if the objectives of management are not revised and actions still attempt to reach desired state. In case (3), management can still maintain current conditions but GEC will prevent any improvement in ecological state: C=Pr. The focus of management should start to switch towards adaptation measures at this point to prevent impacts due to the loss of ecosystem services. In case (4), the onset of GEC will continue to degrade reef systems regardless of local management, and adaptation will be necessary: Pr<C.

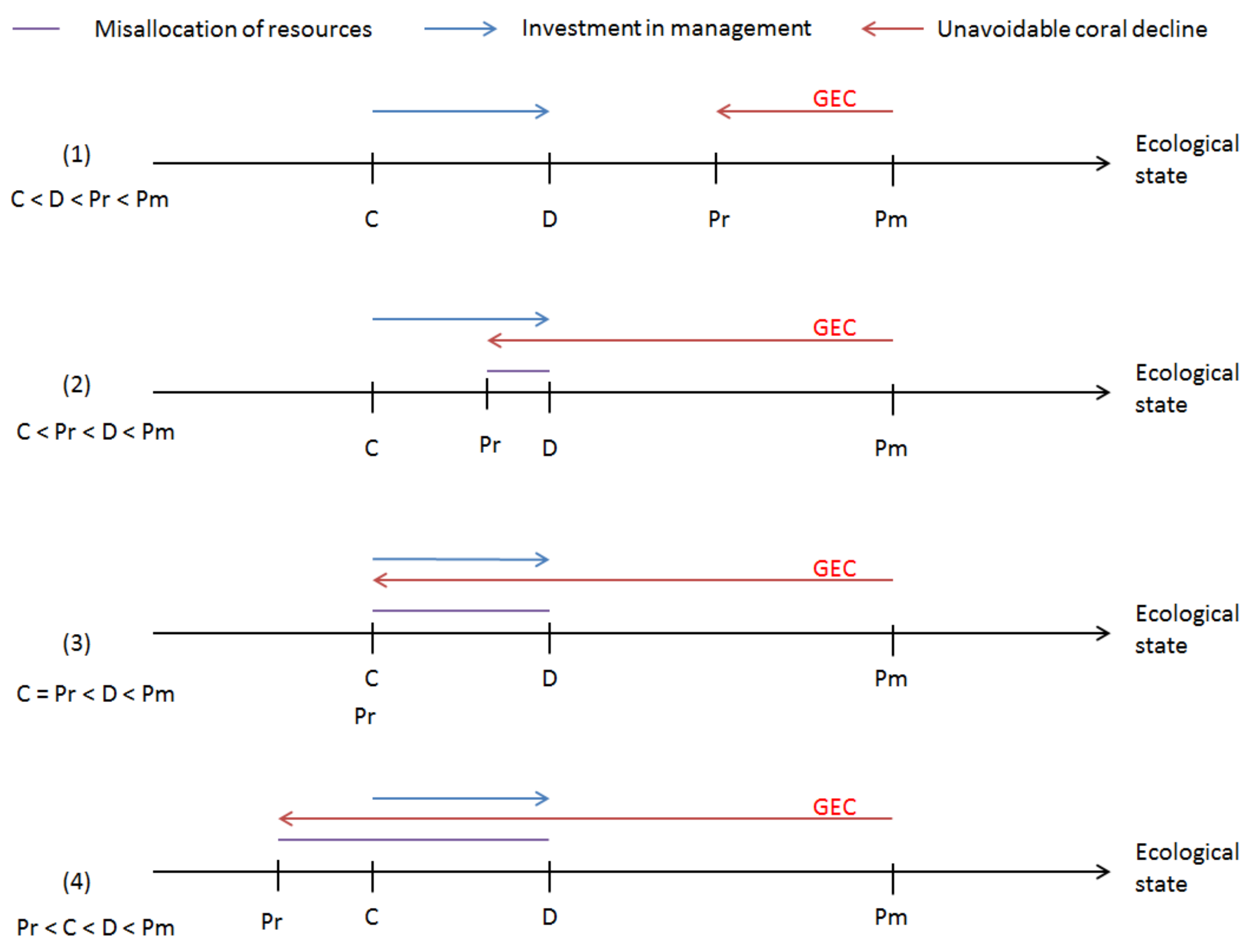


Figure 5.6. Different situations where incorporating GEC could limit misallocation of resources by investing in management strategies where they can be effective.

4. Measuring Ecological Adaptive Capacity and creating typologies to prioritize action

a. Metrics of EAC

The notion of ecological adaptive capacity is very much tied to resilience, and resilience-based indicators to prioritize strategies are important building blocks (Table 5.1.). To go from theoretical thinking towards operational assessments of EAC and integration of vulnerability and resilience thinking, we first attempt to formalize the relationships between the components identified by these two fields by identifying the factors that influence key elements of EAC and ecological states. We build on ecological limits reviewed by Markham (1996) to link future threats and ecological adaptive capacity:

1) Managed reef state = fn(current state, net local environmental stress, global environmental stress, EAC)
2) Net local environmental stress = fn(management) = fn(mitigation, protection)
3) Global environmental stress = fn (absolute level of stress, rate of change in stress)
4) EAC = fn(evolutionary and ecological history, restoration)
5) Restoration includes direct restoration and restoration of associated ecosystems (mangroves and seagrasses).

The framework applies to the management of reefs, or managed reef state 1), which is characterized by the current conditions of the system, the current local stresses in the environment that can be managed, the onset of global environmental stresses, and the capacity of the ecosystem to adapt to GEC. Net local environmental stress 2), includes pollution, fishing species that provide ecosystem functions, physical disturbances, and biological disturbances that can be managed locally through mitigation and protection measures. Global environmental stress 3) linked to climate change and ocean acidification, is a function of the level of the stress but also of the rate of change and mostly cannot be managed locally. The capacity of the system to adapt to GEC 4) depends on ecosystem characteristics linked to its evolutionary and ecological history and can potentially be improved through restoration 5). Management strategies are discussed in more depth in Annex C.

We surveyed the literature to find indicators that can be used to measure EAC. We extracted the indicators that are proposed in seven research articles that all attempt to guide management of coral reefs under future conditions (Table 5.1.). We then categorized the indicators proposed in the literature based on the components of SES vulnerability they best describe or influence: ecological exposure (net local environmental stress, global environmental stress), ecological sensitivity (current state), or EAC. We then repeated this exercise using a dataset of resilience indicators published recently (Lam et al., 2017) (Table 5.2). The indicators most used in the literature are not proxies for EAC but measure either local or global stressors or ecological sensitivity that represents physical characteristics of the reef systems.

Table 5.1. Resilience indicators found in selected publications used to inform management of coral reefs in the context of GEC and reclassification in the combined assessment framework: Net local environmental stress (L), Global environmental stress (G), current state (S), ecological adaptive capacity (EAC)

Ecological indicator	Baskett et al., 2010	McClanahan et al., 2012; Knudby et al., 2013	Edmunds et al., 2014	Maynard et al., 2015	Graham et al., 2015	Davies et al., 2016	Harris et al., 2017	**L**	**G**	**S**	**EAC**
Resistant Coral Species	X	X	X	X		X	X				X
Herbivore Biomass	X	X		X	X	X	X				X
Coral Diversity	X	X		X		X	X				X
Macroalgae	X	X		X		X	X				X
Temperature Variability		X		X		X	X				X
Coral Disease		X		X		X					X
Connectivity	X			X		X					X
Herbivore diversity				X		X					X
Juvenile coral density					X						X
Recruitment/substrate availability		X		X		X	X			X	
Depth/Light	X				X	X				X	
Structural complexity					X	X				X	

Live coral cover						X	X			X	
Salinity	X									X	
Mangroves										X	
Seagrasses										X	
Future thermal stress	X								X		
Future OA									X		
Nutrients/pollution	X	X		X	X	X		X			
Sedimentation	X	X		X		X		X			
Fishing Pressure	X	X		X		X		X			
Physical Human Impacts		X		X		X		X			

Table 5.2. Resilience indicators found in (Lam et al., 2017) used to inform management of coral reefs in the face of climate change and reclassification in the vulnerability assessments framework

Lam et al. 2017 indicators of resilience	% studies that use this indicator	**L**	**G**	**S**	**EAC**
Coral Cover	75-100%			X	
Anthropogenic Disturbance	75-100%	X			
Location and geomorphology	75-100%			X	
Physical characteristics	75-100%			X	
Substrate	75-100%			X	
Coral Community	75%				X
Physiological disturbance	75%		X		
Herbivory	75%				X
Algal Cover	50-75%				X
Recruitment	50-75%				X
Fish community	25-50%				X
Other invertebrates	25-50%				X
Biological Disturbance	25-50%				X
Physical Disturbance	25-50%	X			
Connectivity	25-50%				X
Mortality	25-50%				X
Management Status	25-50%	X			
Fish abundance	25%				X
Fish size	25%				X
Fish biomass	25%				X
Harmful organisms	25%	X			
Competition	25%				X
Reproduction	25%				X
Unharmful organisms	0-25%				
Growth	0-25%				X

Because many indicators found in the literature are difficult to measure, proxies will be needed to assess potential conditions. One possibility is to use known past ecological state. However, it is hard to define what "states" we are talking about and how these influence EAC. Geological studies show periods of "turn off" and "turn on" off reef accretion due to changes in sea level and sedimentation (Perry and Smithers, 2011) that could be used as indicators for potential conditions. "Coral regeneration potential" have been estimated for the Indo-Pacific using SST and chlorophyll-a (Riegl et al., 2015). Time series of coral cover change are available for the French overseas territories (IFRECOR, 2016), for the Hawaiian Islands (Rodgers et al 2014) and rates of recoveries are available for the Great Barrier Reef (Johns et al., 2014). One dimension that reflects EAC is the notion of pristineness found in McClanahan et al. (2009) which includes elements of current state and EAC. There, pristineness was calculated as a weighted index of coral bleaching susceptibility, coral cover, fish species richness and fish biomass.

5. Decision framework of EAC to guide prioritize management strategies

Using the typology of management strategies developed in the Chapter five of this thesis, we are able to relate how actions influence the components of social-ecological vulnerability, including EAC (Figure 5.7.). Mitigation actions are directed towards reducing hazard or ecological exposure. Protection and repair actions are targeted to improve ecosystem state and resilience, therefore influencing both the coral reefs sensitivity to GEC and their ecological adaptive capacity. Repair measures including assisting evolution and coral transplantation could be able to push back ecological limits and thus improve EAC. Repair measures are still in early stage of research. Adaptation actions influence the social dependence on ecosystem services provided by coral reefs, and indirect measures, including research and monitoring and building capacity aim at improving social adaptive capacity. Actions that target social dependence and adaptive capacity could reduce local environment stresses if they lead to behavior change that reduces the pressures that create these stresses.

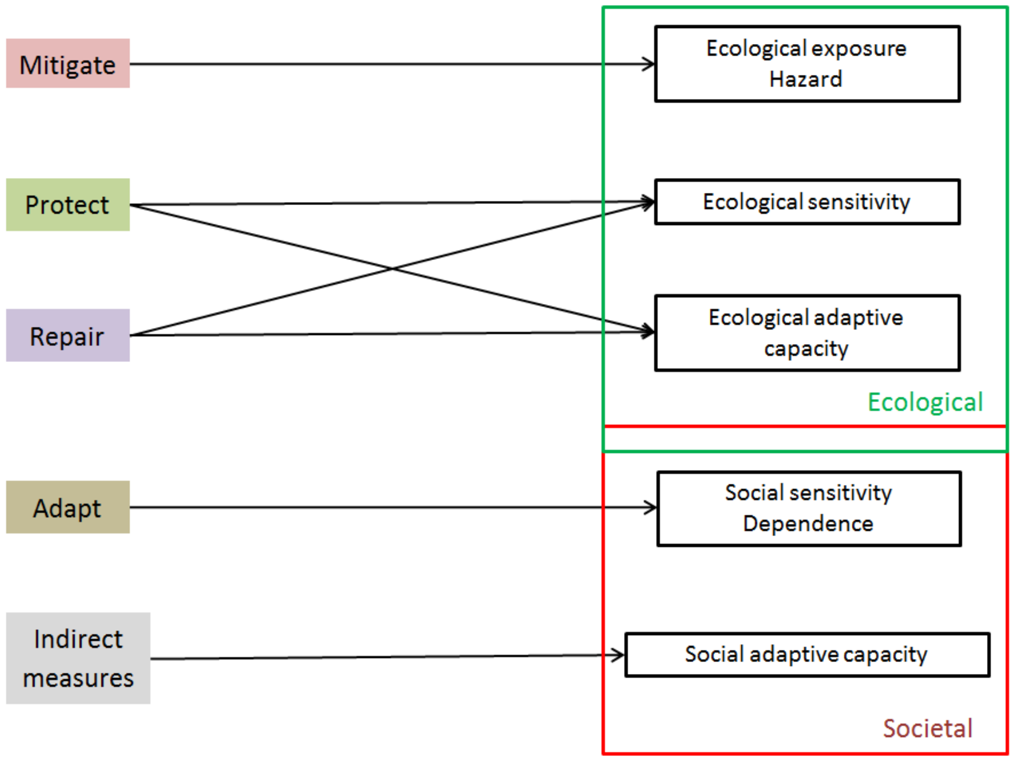


Figure 5.7. Influence of the categories of management strategies on the different components of socio-ecological vulnerability

From this diagnostic, four typologies emerges: reefs SES with high threats and high degree of management (i), reefs SES with high threats and low degree of management (ii), reefs SES with low threats and high degree of management (iii), and reefs SES with low threats and low degree of management (iv). Reefs SES in group (i) have headway to engage in more management and protection to combat environmental change and maintain an acceptable level of ecosystem services provision. Reefs SES in group (ii) have to adapt their economy to the risk of lower provision of ecosystem services. Reefs SES in group (iii) have the potential to ensure refugia for the preservation of coral reefs and management should be preserved and possibly bettered (through networks of MPAs) to be a source of ecosystem services and a source of protection for reefs endangered elsewhere. Reefs SES in group (iv) should prepare for future threats and plan for future management and protection, including processes such as co-construction of rules and MPAs with stakeholders.

6. Case study: do global level indicators of EAC exist?

We have argued that it is important that vulnerability assessments be expanded to include EAC in the composite indicators. We have not shown, though, whether to do so would be feasible for coral reef vulnerability to climate change. One important such assessment is "Reefs at Risk Revisited" (Burke et al., 2011). This assessment does not include measures of EAC. We attempt to add such EAC relevant indicators to better understand the effect of including them in global vulnerability assessments for coral reefs (Table 5.3.).

The first challenge in finding EAC indicators for such a global scale assessment is that ecological adaptive capacity is context-dependent. For instance, it seems that herbivore fishes have a more important ecological function for resilience in the Caribbean than in the Indo-Pacific (Côté et al., 2005). The other issue when compiling global datasets of EAC will be the mismatch in spatial resolution. Reefs at Risk Revisited and van Hooidonk et al., (2016) have data at high spatial resolution on reefs locations. Maina et al., and Henson et al., have data at relatively high spatial resolution for the entire extent of the ocean. Veron et al., has low spatial resolution (scale of ecoregions), Parravicini et al., also has low spatial resolution data.

Table 5.3. Potential locations of global datasets for prioritizing managed reefs locations

Category	Criteria	Source
Coral reefs cover	Reefs location	UNEP-WCMC
Global threats	Temperature	van Hooidonk et al., 2016; Henson et al., 2017; Chapter 3
	Ocean acidification	Pendleton et al 2016, Henson et al 2017
	Cyclones	UNEP
	Oxygen	Altieri et al., 2017; Henson et al 2017
	Combinations	Maina et al., 2011; Chapter 3; Henson et al 2017
Local threats	Fishing	Reefs at Risk Revisited
	Watershed Pollution	Reefs at Risk Revisited
	Physical damages	
	Marine pollution	Reefs at Risk Revisited
	MPAs	Reefs at Risk Revisited; MPA Atlas
	Reef fisheries regulations	Mora et al., 2009, Newton et al.,

		2007
Human dependence	Fishing	Chapter 3
	Coastal Protection	Chapter 3
	Tourism	Spalding et al., 2017
EAC and resilience	Species richness	Parravicini et al., 2014, 2013(fish); Veron et al., 2015 (corals)
	Tolerance to warming	Edmunds et al 2014; Finnegan et al 2015
	Connectivity	Andrello et al., 2017
	Genetic diversity	Veron et al., 2015
	Historical recovery rate	GCRMN
	Potential recovery rate	Riegl et al., 2015
	Herbivores density/diversity	Parravicini et al. 2013
	Diseases	Maynard et al., 2015
Associated ecosystems	Mangroves	Spalding, 2010
	Seagrasses	

7. Discussion

a. Linking ecological adaptive capacity to resilience thinking

One of the two definitions of resilience proposes that resilience be measured as a threshold of environmental disturbance beyond which as system is not able to recover and shifts to a different phase (Folke et al., 2004). Management strategies have been proposed to reverse phase shifts in coral reefs ecosystems (Graham et al., 2013). These strategies could lead to maladaptation since they do not take into account unmanageable environmental changes. Climate change and ocean acidification are expected to lower the resilience of coral reefs, and may either make these systems shift into macro-algae dominated phase, or keep them in this unwanted phase despite management actions (Figure 5.8.).

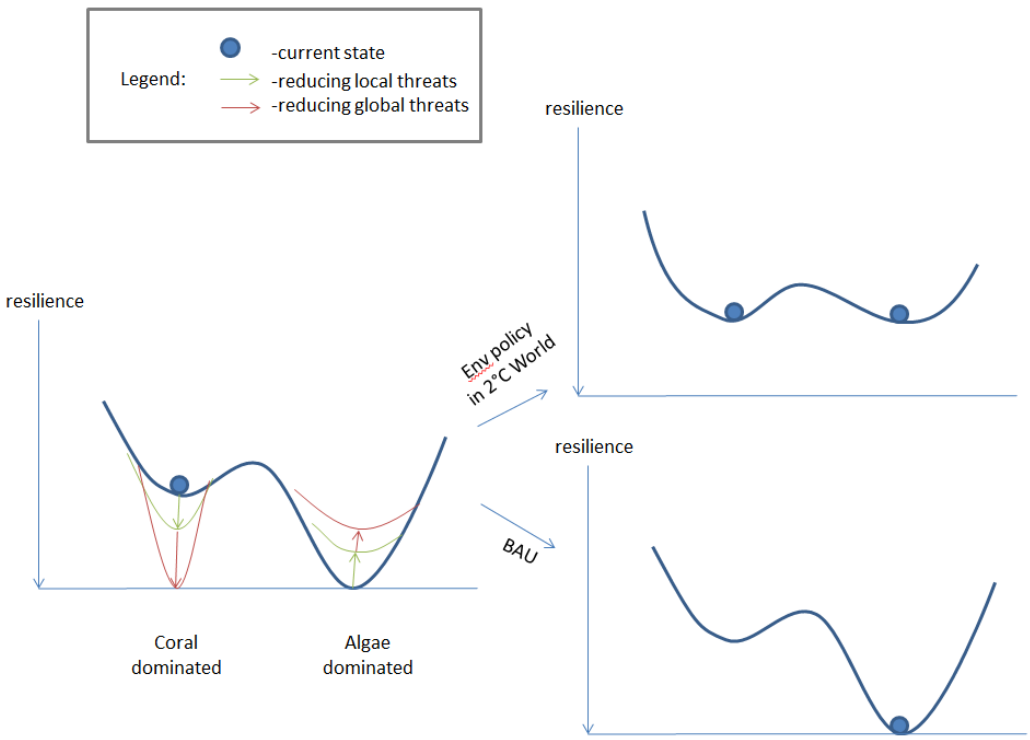


Figure 5.8. Management effects on phase shifts in a 2°C world; re-drawn from Graham et al 2013. In a 2°C world, it is not certain that good environmental policy will keep SES in a coral-dominated state.

This is especially problematic for coral reefs ecosystems where their mass bleaching may be expected at low levels of CO_2 and warming (Hoegh-Guldberg et al., 2007; van Hooidonk et al., 2016). In this case, resilience thinking is useful to estimate thresholds, but is not useful to assess action once these thresholds are inevitable. Because coral resilience is not a major determinant of climate mitigation policies, new tools have to be developed to deal with the management of coral reefs socio-ecosystems beyond these thresholds.

The seven principles put forward to manage for resilience are nonetheless important to guide management of SES (R. Biggs et al., 2015). Some of these principles are reflected in the operationalization of EAC. The first principle, maintaining diversity and redundancy, is linked to the processes of recovery of reefs. Diversity of species of corals and fish will allow the maintenance of important functional groups like herbivores that drive recovery of reefs even if some species are affected by GEC. The second principle, manage connectivity, is linked to the supply of new individuals to reef systems to help them recover after disturbances. The third principle, managing slow variables and feedbacks refers to the explicit account for global changes effects including ocean warming and acidification in the EAC framework. The inclusion of EAC in a vulnerability framework and emphasizing the process of adaptive management that accounts for complexity and uncertainty resonates with principle five, complex adaptive thinking. Assessing ecological adaptive capacity will confront the gaps in knowledge and the data collection required to better estimate the capacity of coral reefs to adapt to GEC. This sixth principle of resilience, to encourage knowledge, follows this philosophy of improving knowledge on SES. The seventh principle of resilience is encouraging polycentric governance, or broadening participation in decision-making. The variety of management strategies that we discuss here and that we attempt to link to EAC builds on this principle since different stakeholders are responsible for the implementation of the management strategies we identify and therefore need to be included in decision-making.

b. Linking ecological capacity to vulnerability assessments

While the concept of ecological adaptive capacity is linked to the ecological components of SES vulnerability assessments developed by Marshall et al., it goes further to make explicit the limitations to reducing ecological vulnerability. It also incorporates resilience metrics, and potential conditions that feed into future socio-economic sensitivity (i.e. future provision of ecosystem services). We therefore modify the framework developed by Marshall et al. adding a directional link between ecological adaptive capacity and the other two components of the sub-systems, ecological exposure and sensitivity (Figure 5.9.). Indeed, adaptive capacity (both ecological and social) will drive future exposure and future sensitivity.

The evaluation of ecological capacity should improve vulnerability assessments by identifying the ecologically vulnerability of coral reefs. While the measure of social adaptive capacity is designed to target places and people that do not have the resources to adapt to the adverse effects of climate change, ecological adaptive capacity also can be used to identify places were management solutions may fail to improve ecosystem state and thus the maintenance of function and services. Thus, it will help identify (i) places where management action could provide more ecosystem services and biodiversity, or places that will need to adapt reduce their sensitivity because loss of ecosystem services will be hard to prevent.

The success or failure of implementing management strategies depends in part on the ecological adaptive capacity of the system. Incorporating ecological adaptive capacity in vulnerability assessments is an important step to guide possible action. Creating a typology of situations of ecological capacity could further help to prioritize between the different strategies available. EAC allows the creation of a typology of ecological conditions that influence and possibly limit the success and outcomes of management options. Several options could be pursued to develop a framework to prioritize these options using EAC. Simple decision frameworks are found in most RBM studies (Magris et al., 2015; Maynard et al., 2015a; McClanahan et al., 2009; Mumby and Anthony, 2015).

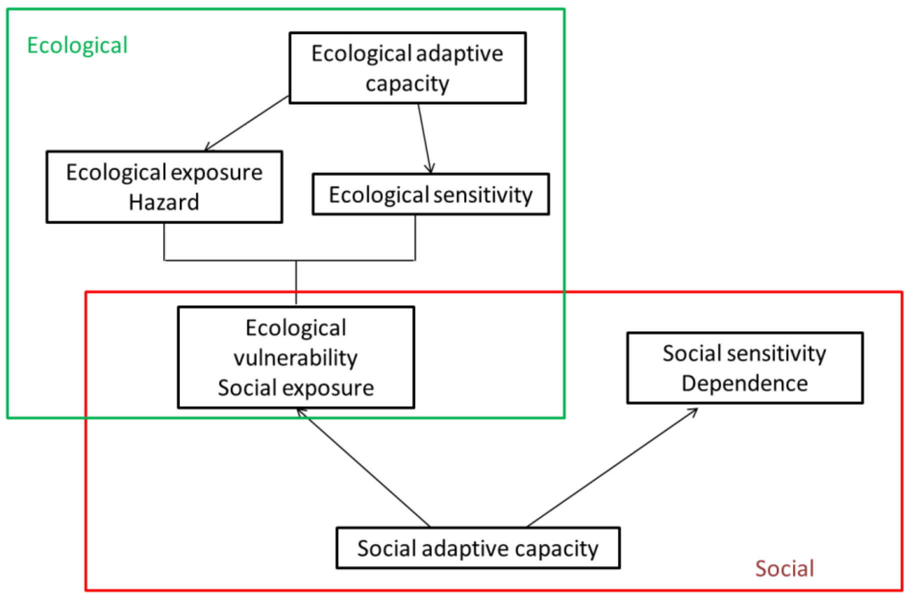


Figure 5.9. Vulnerability framework adapted from Marshall et al 2013 to incorporate EAC and to represent the influence of adaptive capacity on exposure and sensitivity

c. Gaps and next steps

The operationalization of EAC needs to be tailored locally. The identification of thresholds in RBM cannot be generalized because the health of different reefs ecosystems is shaped by their local environmental context (Norström et al., 2016). This shortcoming is partly resolved in the ecological capacity framework since it explicitly takes into account local environmental conditions.

Global list and review of indicators proposed in the literature help identify what kind of data is missing to understand what parameters affect the adaptive capacity of the ecosystem and which indicators have to be monitored through time to help management in an adaptive management framework. Our attempt to scan the existing literature to find indicators to measure EAC is a very first step that should be improved on at the scale appropriate for management. These indicators should be tailored at the local scale and therefore other methods of selecting indicators should be used at this scale. Expert opinion gathering scientists that are familiar with a particular reefs system could be gathered to identify important indicators for that particular system.

Finally, after indicators to measure EAC are selected, values will need to be assigned to measure the potential gains in ecological functions and states that could be gained by improving EAC, and what values could mean the failure of management strategies. This thinking assumes an explicit link between coral cover and provision of ecosystem services, which may not be true in every case. For instance, changes in coral cover may not influence the abundance of reef fishes until a low threshold of coral cover is reached (Chabanet et al., 1997).

Empirical and experimental studies are essential to better understand the factors that influence the recovery and maintenance of coral reefs under local and global environmental changes (including “pulse” types events like bleaching and crown-of-thorns starfish outbreaks and “presses” types events like OA) and improve the selection and measurement of indicators of EAC. Many unknowns remain about the capacity of coral species to acclimate and adapt to future environmental conditions for instance or what combination of factors provoke phase shifts towards undesired states and this can only be resolved by empirical studies and experiments (Chapter 2). In addition, studies on the effectiveness of management strategies to improve EAC need to be pursued. Studies so far focus on the effectiveness of MPAs to improve recovery (ex: Mellin et al., 2016) but the effect of other management strategies such as mangrove restoration or coral restoration need to be assessed.

Multiple spatial scales have to be taken into account since climate change and ocean acidification are global phenomena, but responses the impacts specific to coral reefs and to people who depend upon them are going to be felt at the local level. Institutional responses may be undertaken by international organizations, regional organizations (by region we mean groups of countries), national governments, sub-national administrations, or local authorities, with the help of researchers and NGOs at every level of decision-making. The identification of appropriate strategies to help corals and coral-dependent human communities deal will climate change will depend on the objectives set by the institutions. These objectives change across scale, and across institutions (Table 5.4.). At the global scale, objectives may be broad and targeted towards the maintenance of biodiversity and reduction of poverty, such as dictated by the SDGs or the Aichi targets. At national scales, objectives may include green growth targets such as job creation and optimization of ecosystem services. However, the response strategies are influenced by decisions across scales (Adger et al., 2005). The identification of appropriate strategies also depends on factors that are both socio-economic and environmental in nature, because both dimensions of the socio-ecological system are important for the ecosystem to function and to supply services to human populations.

Table 5.4. Examples of issues, institutions, objectives, and strategies across spatial scales

Scale	Issues	Institutions	Protect	Mitigate	Repair	Adapt
Global	GEC	UNFCCC, CBD, WB, TNC, CI, WWF, Nations	Refugia, International Aid, Aichi Targets, SDGs	International Aid, SDGs, GHG target (1.5-2°C)	International Aid Aichi targets SDGs	International Aid Aichi targets SDGs
Regional	GEC Fishing	Reg. dev. Banks Cooperation agencies (OECD, ASEAN, COI, SPC,…)	MSP, MPA networks	International Aid, SDGs, GHG target (1.5-2°C)	International Aid Aichi Targets SDGs	International Aid Aichi Targets SDGs
National/ State	GEC Fishing Tourism Pollution	Nations States	MPA network Fishing Land-use	Marine pollution	No net loss	NAP Insurance policy
Local	Fishing Pollution Destructive use Tourism	Regions Municipalities Management agencies NGOs	MPA Zoning Land-use	Transportation	Compensation of local development	Diversification Zoning

There are remaining challenges to the use of EAC to guide action : (i) simply adding ecological adaptive capacity to other types of assessment is not enough to prioritize the full range of options because it does not assess the adaptive capacity of the society to respond to GEC, (ii) we did not relate EAC to the decision frameworks used to prioritize options and plan for adaptation, notably multi-critieria assessments, co-benefits, no-regret, and maladaptation (Hallegatte, 2009;

Magnan et al., 2016), (iii) a case study is needed to understand the potential use and shortcomings of this concept.

8. Conclusion

Building on vulnerability assessments and resilience-based management, the concept of ecological adaptive capacity is developed. Ecological adaptive capacity fills two gaps in the literature: it brings a missing dimension to the assessment of vulnerability and resilience of social-ecological systems, and it provides a tool to prioritize management strategies to deal with potential impacts of global environmental change.

This concept is designed to be a useful tool for decision-makers dealing with the threats that global environmental change poses on coral reefs and people who depend upon them. The framework explicitly integrates limits of ecosystem recovery and provision of functions and services. It allows for the assessment of available actions in the framework, so that prioritization can explicitly account for trade-offs between options. This also permits the integration of ecological and human components of action, effectively socio-ecological systems management. The definition and measurements of limits to ecological capacity renders the concept dynamic and helps prevent maladaptation and misallocation of resources.

This tool has been operationalized for coral reefs because this ecosystem and the people who depend on them will be some of the first impacted at a massive scale by climate change, and where a new management paradigm is needed. The framework can be more broadly applied to other socio-ecological systems at risk from the impacts of global environmental change.

Discussion générale

Cette discussion générale compte cinq sections. Les résultats des chapitres de thèse sont d'abord récapitulés. La deuxième section discute des résultats en se focalisant sur les apports pour la recherche, suivi des apports de la thèse pour la gestion dans la troisième section. Les limites de la thèse sont développées dans la quatrième section. Enfin, des pistes de recherche future sont présentées dans la cinquième section.

1 Résultats importants

Les cinq chapitres proposés dans cette thèse sont autant de contributions à l'étude des effets des CEG sur les systèmes socio-écologiques marins et à l'étude des stratégies possibles pour y répondre à des échelles spatiales multiples. Cette première section effectue une synthèse de ces contributions en ce qu'elles éclairent la problématique posée en introduction.

Le premier chapitre montre qu'à l'échelle globale il est préférable d'utiliser des évaluations des impacts potentiels plutôt que de la vulnérabilité, la capacité d'adaptation dépendant de facteurs locaux difficilement mesurables à l'échelle globale. Ces études globales peuvent ensuite guider la planification d'évaluations locales ancrées dans des contextes spécifiques et donc mieux à même d'évaluer la capacité d'adaptation, et donc la vulnérabilité, des systèmes étudiés. Ce cadre analytique « *2-tier approach* » est une réponse à la difficile prise en compte d'échelles spatiales multiples pour l'étude et la gestion des systèmes socio-écologiques face aux CEG.

La revue de la littérature proposée dans le deuxième chapitre montre que de nombreux processus lient les CEG aux récifs coralliens, puis aux services qu'ils produisent pour l'homme. Les effets des CEG les plus déterminants sur les espèces de coraux, qui forment la base de ces écosystèmes, et sur les autres espèces présentes dans ces écosystèmes sont l'augmentation de la température de l'eau et l'acidification de l'océan. Il se pourrait que la combinaison de ces deux effets soit synergétique et affecte de nombreux paramètres sub-létaux. Nous recommandons donc de développer la recherche expérimentale sur des effets multiples dans des mésocosmes. De plus, nous proposons que les interactions entre ces CEG soient prises en compte pour déterminer les impacts potentiels sur les récifs coralliens et les services qu'ils produisent pour les populations humaines.

Le deuxième chapitre met en avant un besoin de repenser les études scientifiques pour évaluer ces impacts. D'une approche scientifique disciplinaire concentrée sur l'étude des effets de menaces uniques sur des espèces uniques, la recherche future doit passer à la prise en compte de multiples espèces et de multiples menaces du fait de l'importance des interactions dans ce système complexe. Il faut également développer une dimension interdisciplinaire en incorporant des études en sciences économiques et sociales afin d'évaluer la dépendance des populations humaines face à ces changements écosystémiques et les réponses des sociétés à ces changements.

La construction de nouveaux indicateurs composites dans le troisième chapitre permet de cartographier la distribution spatiale de l'exposition des récifs coralliens aux CEG face à la dépendance des sociétés aux services produits par les récifs. La côte ouest du Mexique, la Micronésie, l'Indonésie et l'Australie présentent une forte dépendance et seront vraisemblablement affectés en premier par la dégradation des récifs coralliens. L'Asie du Sud-Est est la région qui possède le plus haut niveau de menace face aux CEG et la plus forte dépendance aux récifs coralliens. Cette étude montre également que de nombreuses régions côtières parmi les plus affectées, et notamment en Asie du Sud-Est, ne possèdent pas de données robustes qui permettent de prévoir l'évolution future de l'acidification de l'océan. Ces pays doivent répondre en priorité aux effets négatifs des CEG sur les récifs coralliens en développant des études scientifiques pour mieux comprendre ces effets et des plans d'action pour y répondre. Cependant, tous les pays ayant des récifs coralliens doivent également se pencher sur la question pour plusieurs raisons. Premièrement, les indicateurs relatifs mobilisés dans le chapitre trois montrent quels pays sont les plus à risque. Ceci étant, tous les pays vont subir des niveaux de menaces élevés sur leurs récifs coralliens d'ici à la fin du siècle selon le scénario *« business-as-usual »* du GIEC. Dans les quelques cas où les menaces sont faibles et où les récifs vont continuer à prospérer et à fournir de nombreux services, notamment en servant de refuge à une biodiversité menacée, il est d'autant plus important d'initier des mesures de gestion pour les protéger.

Dans le quatrième chapitre, nous améliorons une typologie développée par Gattuso et al. (2015) afin de classifier les stratégies de gestion disponibles pour lutter contre les effets des CEG sur les récifs coralliens et les populations humaines qui en dépendent. Cette typologie se divise en quatre grands types de mesures : l'atténuation, la protection, la restauration, et l'adaptation. L'atténuation comprend des mesures qui réduisent la concentration de GES, le CO_2 étant particulièrement important pour les récifs coralliens. L'atténuation regroupe également les mesures qui limitent la pollution de l'eau et la sédimentation, ces facteurs interagissant avec le pH et la température de l'eau ainsi que d'autres caractéristiques du milieu dont dépend la santé des récifs. La catégorie protection comprend les mesures qui limitent les activités anthropiques impactant directement les récifs coralliens et diminuant leur résilience, comme la surpêche. Ces mesures incluent l'établissement d'aires marines protégées et de réseaux d'aires marines protégées, les politiques de gestion des pêches, et la gestion marine spatiale. La restauration comprend des mesures de restauration d'écosystèmes dégradés, l'ingénierie locale pour compenser les changements environnementaux à une échelle très locale, et l'évolution assistée des espèces pour leur permettre de s'acclimater et de s'adapter aux conditions environnementales futures. Enfin, l'adaptation regroupe des mesures qui visent à limiter les effets de la dégradation des récifs coralliens sur les populations humaines, par exemple en réduisant les activités économiques qui dépendent des récifs coralliens ou en modifiant des pratiques comme la pêche.

Le quatrième chapitre effectue une revue des stratégies identifiées par la communauté scientifique pour gérer les récifs coralliens dans le contexte des CEG. Ce chapitre donne une vision globale des efforts de recherche afin d'identifier les champs de recherche et les régions du monde qui sont peu étudiés. Le nombre de publications sur les mesures de gestion des récifs coralliens pour faire face aux CEG est en croissance depuis la deuxième moitié des années 2000, tendance qui suit l'accroissement des études sur les CEG en général. Cette recherche est concentrée dans les pays développés et particulièrement en Australie et aux Etats-Unis. Elle se focalise particulièrement sur les stratégies de protection, qui incluent la mise en place d'aires marines protégées et la gestion des pêches. A l'échelle régionale, c'est la Grande Barrière de Corail qui fait l'objet du plus grand nombre d'articles scientifiques, suivi de la région Caraïbe et de l'ouest de l'Océan Indien. Trois régions sont sous-étudiées par rapport à la dépendance des populations aux services écosystémiques : l'Asie du Sud-Est, le Moyen Orient, et le Brésil.

Des outils analytiques ont été développés par la communauté scientifique pour aider les gestionnaires et les décideurs à prioriser les réponses aux effets des CEG sur les récifs coralliens. Ces outils, à l'image de l'évaluation de la vulnérabilité et de la gestion basée sur la résilience, n'ont jusqu'à présent pas réussi à expliciter la notion de capacité d'adaptation écologique (CAE). Nous proposons deux nouveaux apports conceptuels pour opérationnaliser cette CAE : la prise en compte des limites écologiques des récifs coralliens face aux CEG, et l'intégration des cadres analytiques de vulnérabilité et de résilience pour identifier des indicateurs afin de mesurer la CAE. Le nouveau cadre proposé pourrait être appliqué pour analyser le potentiel de stratégies de gestion locale alternatives.

Les évaluations théorisées dans le chapitre premier et appliquées aux récifs coralliens dans les chapitres suivants, montrent que des indicateurs simples peuvent apporter des informations précieuses pour guider la recherche et l'action face aux CEG. Les indicateurs du chapitre trois montrent où les impacts cumulés des CEG sur les récifs coralliens et la dépendance des pays à leurs services écosystémiques sont les plus forts. Ces indicateurs peuvent aider à prioriser les endroits où les impacts seront le plus important, et où la recherche peut améliorer la compréhension des impacts. Dans le quatrième chapitre, nous montrons dans quels pays les études sur les solutions ont été menées. Dans ce cas, l'utilisation d'indicateurs peut permettre d'aider à formuler des stratégies de recherche visant des régions particulières. Les indicateurs développés dans cette thèse apportent donc des informations mais ne doivent pas être utilisés de manière exclusive. De nombreuses dimensions ne sont pas prises en compte comme les aspects socio-culturels qui sont difficilement quantifiables. Très récemment, de nouvelles approches émergent dans le cadre d'évaluation des SES pour définir et mesurer des indicateurs culturels, c'est le cas par exemple de l'approche bio-culturelle (Sterling et al., 2017). Par ailleurs, nous ne disposons pas de séries temporelles pour pouvoir construire des indicateurs pour suivre l'évolution de la dépendance aux services écosystémiques dans le temps, ce qui constitue une étape importante pour pouvoir mettre en place une gestion adaptative.

2. Contributions méthodologiques et épistémologiques

Les chapitres développés dans cette thèse contribue à trois axes de recherche : (i) des avancements théoriques et méthodologiques pour évaluer les impacts, la vulnérabilité, et l'adaptation face aux CEG, (ii) le développement d'approches interdisciplinaires sur les systèmes socio-écologiques, l'évaluation des services écosystémiques et de leur dégradation dans le cas particulier des récifs coralliens, et (iii) l'émergence d'une science des solutions pour répondre à ces enjeux globaux.

L'articulation des chapitres développés dans cette thèse contribuent à la conceptualisation et à l'amélioration des cadres analytiques des impacts, de la vulnérabilité, et de l'adaptation aux CEG. Dans le premier chapitre, nous proposons une nouvelle manière d'utiliser les études d'impacts et les études de vulnérabilité pour améliorer la priorisation de la recherche et de l'action. Cette étude part du postulat que l'évaluation de la vulnérabilité ne peut se faire qu'à l'échelle locale (Hinkel, 2011). Il apparait que ce postulat ne fait pas consensus puisque des efforts continuent d'être fournis par la communauté scientifique pour améliorer les évaluations de la vulnérabilité globale dans le milieu marin (Blasiak et al., 2017; Monnereau et al., 2017). Ces efforts proviennent-ils d'une demande des pouvoirs publiques et des instances internationales ? Il est possible que ces efforts découlent de la prise en compte tardive du milieu marin dans l'étude des effets des CEG. Il semble néanmoins que la vulnérabilité soit un champ d'étude en perte de vitesse, au profit de l'étude de l'adaptation (Figure DG.1).

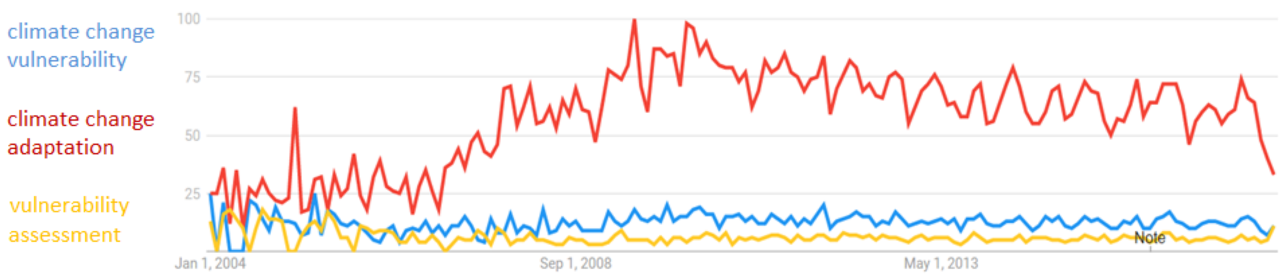


Figure DG.1. Résultats Google en pourcentage pour la fréquence de recherche sur le web dans le monde et dans la catégorie science des termes vulnérabilité (bleue et jaune) et adaptation (rouge) entre 2004 et 2017

L'articulation des chapitres développés dans cette thèse nous amène à nous demander si une modification du cadre de la gestion adaptative n'est pas envisageable pour aider à la mise en œuvre des politiques d'adaptation. L'enchainement des chapitres de ce manuscrit est différent du cycle proposé par le cadre analytique couramment appliqué de la gestion adaptative. En effet, celui-ci propose 1) de définir le système étudié ou qui a besoin d'être géré, 2) d'évaluer la vulnérabilité du système, 3) d'identifier les solutions et de les évaluer pour réduire la vulnérabilité, 4) d'implémenter ces solutions, 5) d'évaluer leur succès et de retourner à l'étape 1). Pour ce qui est des étapes 1 à 3, notre démarche se focalise plus sur la notion d'adaptation que celle de vulnérabilité en partant du problème, partant du fait que les politiques d'adaptation ont pour but premier de réduire la vulnérabilité. Après avoir identifié le problème à traiter, nous avons analysé les impacts potentiels, identifié les solutions disponibles, et enfin évalué la capacité d'adaptation pour étudier la faisabilité de ces solutions. Cette modification du cadre de la gestion adaptative pourrait avoir des répercussions sur l'évaluation des politiques publiques de réponse aux CEG. Les études d'évaluation de la vulnérabilité ne permettent pas d'identifier la gamme d'actions disponibles pour gérer les effets des CEG sur les systèmes socio-écologiques (Burton et al., 2002). Se limiter à gérer les indicateurs de vulnérabilité (exposition, sensibilité et capacité d'adaptation), comme suggéré dans de nombreuses études (Johnson et al., 2016), peut entrainer des situations de maladaptation. Par exemple, une étude récente propose, pour réduire la sensibilité des nations aux effets des CEG sur la pêche marine, de réduire le nombre de pêcheurs et de réduire la quantité de poisson pêchée tout en augmentant la part de pêche industrielle par rapport à la pêche artisanale (Blasiak et al., 2017). Ces propositions vont à l'encontre d'autres recommandations scientifiques sur l'adaptation des pêcheries (Bell et al., 2017). Se baser sur les études de vulnérabilité pour formuler des politiques d'adaptation peut également empêcher d'identifier des mesures alternatives qui pourraient être efficaces. Dans le quatrième chapitre, nous avons vu qu'une des quatre catégories de réponse aux effets des CEG sur les systèmes socio-écologiques coralliens est la restauration. Aucune étude n'a jusqu'à présent pris en compte la restauration comme paramètre d'analyse de la vulnérabilité. Nous pensons donc que l'identification de stratégies de gestion doit se faire en parallèle des évaluations de vulnérabilité et non a postériori. Par ailleurs, l'étape 5) d'évaluation et de suivi pose des problèmes importants à prendre en compte pour des recherches futures, notamment l'échelle temporelle et la disponibilité d'indicateurs nécessaires pour mesurer les effets des solutions sur les systèmes étudiés.

L'identification des stratégies disponibles en amont permet également de renforcer la création d'indicateurs liés à la capacité d'adaptation. Si la capacité d'adaptation est définie comme l'ensemble des facteurs qui permettent au système de s'adapter, et donc de réduire sa vulnérabilité, c'est donc que la capacité d'adaptation représente la capacité d'implémenter des mesures qui vont réduire l'exposition et la sensibilité du système (Figure 5.9. ; (Engle, 2011). Dans ce cas, il semble plus cohérent d'identifier d'abord les mesures qui réduisent l'exposition et la sensibilité du système pour ensuite évaluer la capacité d'implémenter ces mesures. Par ailleurs, ce cadre analytique pourrait permettre de mesurer la capacité d'adaptation de manière empirique. Plutôt que d'exprimer la capacité d'adaptation comme un indicateur composite général contenant le capital social, le capital économique, le capital naturel, ou l'efficacité des institutions (Brooks et al., 2005), notre démarche rattache l'évaluation de la capacité d'adaptation à la capacité de mettre en place des mesures concrètes par des acteurs identifiés. Nous pensons donc que cette nouvelle version du cycle de gestion adaptative permettra d'améliorer l'étude de la capacité d'adaptation, de la vulnérabilité, et donc d'améliorer la priorisation et l'efficacité des politiques publiques d'adaptation aux CEG.

SSE et interdisciplinarité

Nos analysent contribuent au développement d'approches interdisciplinaires sur les systèmes socio-écologiques, et l'évaluation des services écosystémiques et de leur dégradation dans le cas des récifs coralliens. De nombreuses inconnues subsistent quant à l'hétérogénéité de la réponse des récifs coralliens aux CEG (Pandolfi et al., 2011). Les deuxième et troisième chapitres contribuent à améliorer notre compréhension de cette hétérogénéité spatiale, du moins en ce qui concerne l'exposition aux CEG et la dépendance aux services écosystémiques. L'importance donnée dans ces chapitres aux effets de l'acidification et de l'augmentation de la température peut poser question. En effet, un débat dans la communauté scientifique est de savoir si ces menaces sont plus ou moins pressantes que les menaces locales déjà existantes et en expansions liées au développement économique des populations côtières, notamment la pêche, la pollution du milieu marin et la prolifération de prédateurs telle l'étoile de mer *acanthaster*. S'il est clair que ces menaces locales ont eu un rôle dominant dans la destruction des récifs par le passé (De'ath et al., 2012), c'est aujourd'hui les CEG qui sont la menace dominante. L'épisode de blanchissement de 2015-2016 a touché plus de 90% des coraux de la partie nord de la Grande Barrière de Corail (GBC), ce qu'aucune combinaison de menaces locales n'a faite jusqu'à présent (Hughes et al., 2017). Par ailleurs, l'hypothèse d'une adaptation possible des récifs aux changements futurs, bien qu'anticipée par des études théoriques (Pandolfi et al., 2011) et étayée par certaines études locales (Fine et al., 2013; van Oppen et al., 2015), s'avère pour l'instant contredite à une échelle spatiale plus large par une étude empirique récente qui montre que les récifs ne s'acclimatent pas aux évènements répétés de blanchissement (Hughes et al., 2017). Il semble clair que seule une combinaison de réponses locales et globales puisse véritablement être efficace (Kennedy et al., 2013).

La cartographie de la distribution spatiale à l'échelle globale de deux menaces globales, l'augmentation de la température et l'acidification de l'océan, est une contribution importante à la recherche sur les effets des CEG sur les récifs coralliens. La majeure partie des études menées à l'échelle globale cartographie une seule des menaces liées aux CEG qui vont affecter les récifs coralliens. Des modèles développés notamment par la *National Oceanic and Atmospheric Administration* (NOAA) américaine sont de plus en plus performants pour cartographier et prédire le risque de blanchissement lié aux effets de l'augmentation de la température (Heron et al., 2016; van Hooidonk and Huber, 2009). Quelques études globales ont cartographié l'exposition des récifs aux CEG (Burke et al., 2011; Maina et al., 2011). Aucune de ces études cartographiant la distribution spatiale de l'exposition aux CEG n'a intégré des projections de l'acidification de l'océan jusqu'à présent. D'autres études commencent à la cartographier, sans pour autant s'intéresser spécifiquement aux récifs coralliens (Jiang et al., 2015). En ce sens, la cartographie de l'exposition des récifs coralliens à l'acidification et à la montée de la température de l'océan effectuée dans le troisième chapitre est une contribution originale à la recherche.

La place des facteurs socio-économiques pour mesurer l'efficacité des mesures de gestions des écosystèmes est de plus en plus étudiée (Cinner et al., 2013; Cinner et al., 2009; Leenhardt et al., 2016; Stephanson and Mascia, 2014). Le troisième chapitre participe également au développement d'indicateurs pour mesurer ces facteurs socio-économiques, à savoir la dépendance à des bouquets de services écosystémiques délivrés par les récifs coralliens. Une des raisons qui nous a poussé à étudier la dépendance actuelle aux services écosystémiques est la difficulté d'évaluer le coût économique des CEG. Nous aurions besoin de connaître et de modéliser les activités socio-économiques sans les CEG et avec les CEG pour pouvoir évaluer la différence. Cette réponse des activités humaines aux CEG dépend de leur capacité d'adaptation et de leur vulnérabilité mais également des options socio-économiques et des conditions sociétales au-delà des simples activités liées aux récifs coralliens. De nombreux autres facteurs de risque comme les évolutions politiques, géopolitiques et juridiques jouent un rôle important à moyen/long terme (Guillotreau et al., 2012). Ces facteurs n'ont pas été pris en compte ici.

Pour une science des solutions

La contribution scientifique de cette thèse est également de tenter de coordonner les efforts de recherche sur les impacts et sur les solutions. Nous avons montré dans le quatrième chapitre que de plus en plus d'études se focalisent sur la gestion des CEG et de ses impacts sur les récifs coralliens et les populations qui en dépendent, sans pour autant que soient coordonnées les priorités à donner à la recherche. Nous proposons donc des pistes pour la recherche future. Nous montrons que les études scientifiques se focalisent pour la plupart sur un seul type de solution. Ceci pose problème car des trade-offs et des synergies entre différents types de solutions sont rarement explicités (Hicks et al., 2009). Les mesures de protection, qui sont les plus étudiées, ne sont potentiellement pas efficaces si elles ne sont pas replacées dans leur contexte socio-écologique (Cinner et al., 2009). Les mesures de protection comme l'instauration d'aires marines protégées, ne sont pas efficaces si le contexte socio-économique des populations à proximité de ces AMP n'est pas pris en compte, la pauvreté poussant les populations à surexploiter les ressources naturelles (Gurney et al., 2014).

L'émergence d'une science des solutions, décrite et analysée dans ce manuscrit, est importante pour plusieurs raisons. D'abord, la diffusion des connaissances scientifiques dans la société améliore la participation de la société civile à la discussion générale sur les CEG (Geiger et al., 2017). Ce nouveau paradigme commence à être institutionnalisé dans les instances scientifiques internationales. Après s'être concentré sur l'attribution des changements et l'évaluation des impacts, le GIEC souhaite désormais se concentrer sur les solutions (Tollefson, 2015). Nous espérons donc que nos travaux de synthèse de la production scientifique contribueront à diffuser les connaissances dans la société, auprès de la communauté scientifique, des décideurs et des gestionnaires.

La science a une responsabilité envers la société en informant les décideurs et les gestionnaires sur les progrès scientifiques dans le domaine des impacts et des solutions aux CEG (Stilgoe et al., 2013). Il est donc important d'avoir une réflexion sur les solutions proposées par la science, d'améliorer la communication entre la recherche scientifique et les sociétés, et d'éliciter les tensions qui pourraient exister à promouvoir certaines solutions. Par exemple, le développement du scénario RCP2.6 du GIEC qui montre une possibilité de limiter le réchauffement à 2°C en 2100 cache une utilisation de technologies de capture du CO_2 qui est controversée (Hulme et al., 2011; Peters, 2016). Dans le cas des récifs coralliens, une surreprésentation des mesures de protection dans les discussions scientifiques pourraient mener à une maladaptation liée 1) aux problèmes d'efficacité et de mise en œuvre des aires marines protégées (Hilborn, 2016) et 2) un manque de discussion sur d'autres types de solutions qui doivent faire l'objet de débats scientifiques et sociétaux avant leur mise en œuvre, comme le développement de l'aquaculture ou l'adaptation des activités humaines à une perte de services écosystémiques.

Il est également important de confronter l'hétérogénéité géographique des efforts scientifiques. Les pays développés et particulièrement l'Australie et les Etats-Unis sont surreprésentés dans la littérature. Les scientifiques provenant de ces pays ont une vision du monde qui peut être différente d'autres cultures (Morandi et al., n.d.). Des régions du monde peu étudiées pourraient contenir des solutions écologiques ou sociales innovantes qu'il nous reste à découvrir. Par exemple, la pratique du *Rahui* en Polynésie française pourrait aider à la diminution des pressions anthropiques locales en améliorant les systèmes de gouvernance des aires marines protégées (Gaspar and Bambridge, 2008). Des savoirs traditionnels sur les méthodes et le choix des terrains pour la construction d'infrastructure pourraient également limiter la sensibilité des populations aux risques côtiers (Aswani, 2014; McMillen et al., 2014). En termes biologiques, certaines espèces de coraux, qui résistent aux phénomènes de blanchissement et à l'acidification ont été étudiés, mais seulement dans quelques régions du monde : les Palaos et les sources volcaniques pour la tolérance à l'acidification (Barkley et al., 2015; Golbuu et al., 2007) et la Mer rouge pour la tolérance au stress thermique (Fine et al., 2013).

Le déclin des récifs coralliens et leur dégradation liée à des menaces locales et globales est documentée et connue depuis plusieurs décennies (Côté et al., 2005; Hoegh-Guldberg and Smith, 1989; Smith and Buddemeier, 1992). Si cette situation perdure, c'est d'abord parce que le modèle de développement humain focalisé sur la croissance du PIB et le développement des activités polluantes a plus de poids que leurs effets négatifs sur l'environnement. C'est peut-être également parce que la focalisation des études scientifiques sur les impacts et la vulnérabilité et non sur les solutions n'est pas un levier qui entraine un changement structurel. Des études psychologiques montrent que des messages négatifs ont peu d'influence sur l'action, tandis que des messages positifs, orientés sur des solutions, sont plus enclins à modifier les comportements. Bien que d'autres arguments psychologiques en faveur d'un certain niveau de pessimisme existent (Sweeny and Dooley, 2017), le nouveau paradigme scientifique qui se focalise sur les solutions, par exemple sur les *« bright spots »* (Bennett et al., 2016; Cinner et al., 2016a), est peut-être porteur de plus grandes transformations sociétales.

3. Implications pour la gestion et les politiques climatiques et environnementales

Dans le chapitre premier, nous concluons que les études d'évaluation de la vulnérabilité globale, pourtant de plus en plus nombreuses, ne sont pas adéquates pour prioriser les investissements et l'aide aux politiques d'adaptation, car les facteurs qui influencent la vulnérabilité, et notamment la capacité d'adaptation, sont complexes et spécifiques aux contextes sociaux, politiques, économiques, et écologiques locaux. Nous proposons donc aux instances politiques internationales de se baser sur des études d'impacts potentiels globales comme première étape pour l'attribution de moyens en vue d'aider les politiques locales d'adaptation. L'utilisation de ces études pourrait permettre de se concentrer sur les enjeux spécifiques au climat plutôt que sur les politiques de développement générales. Cette distinction entre enjeux climatiques et enjeux de développement pourrait permettre de mieux flécher les fonds climatiques tout en laissant ouverte la possibilité de comparer les besoins liés aux CEG et les besoins de développement. Cette distinction fait donc écho au besoin de traçabilité des fonds climat promis dans le cadre des négociations internationales, fonds qui doivent être réellement additionnels aux flux financiers déjà existants.

Nos études sont un premier pas vers l'évaluation des effets des CEG sur les récifs coralliens et les services écosystémiques qui y sont associés. Dans la plupart des pays à récifs coralliens, très peu d'indicateurs sont suivis à l'heure actuelle pour mesurer les évolutions des paramètres physico-chimiques, écologiques et socio-économiques au niveau global et national. Au niveau international, le *Global Coral Reef Monitoring Network* (GCRMN) coordonne les réseaux d'évaluation de l'état de santé des récifs coralliens. Dans ce cadre, des rapports globaux (Wilkinson, 2008) et régionaux (Jackson et al., 2014) sur l'état de santé des récifs sont publiés.

Ces rapports reposent sur des indicateurs écologiques (principalement couverture corallienne, parfois menaces locales comme les *acanthasters* et la pêche) mais ne reposent ni sur des indicateurs physico-chimiques liés aux effets des CEG (température, salinité, pH par exemple) ni sur des indicateurs socio-économiques d'usage et de dépendance aux services écosystémiques. Des protocoles GCRMN de suivi des usages socio-économiques liés aux récifs ont été développés (SocMon) mais ne sont pas implémentés ni suivis sur le long terme (Pendleton and Edwards 2017). Le manque de données socio-économiques à des échelles pertinentes et le manque de données de référence pour évaluer les bénéfices des politiques publiques est un problème récurrent pour la gestion de l'environnement marin (Alban et al., 2011). La collecte d'informations socio-économiques basiques sur le long terme est donc un prérequis pour guider les politiques climatiques. Le suivi des récifs coralliens est également inscrit comme une des mesures de l'objectif 14 des ODD.

Au niveau national, ces suivis dépendent de différentes instances. En France, l'Initiative Française pour les Récifs Coralliens (IFRECOR) effectue une coordination des réseaux de suivi de tous les récifs présents dans les Territoires d'Outre-Mer et produit un état de santé (IFRECOR, 2016). Notre démarche pourrait donc servir à intégrer les indicateurs physico-chimiques, écologiques et socio-économiques disponibles et à en créer de nouveaux pour pouvoir appréhender les effets des CEG sur les récifs coralliens, mais également sur les services écosystémiques associés et donc sur les populations humaines qui en dépendent. En effet, comme à l'échelle globale, les suivis de l'état des récifs se concentrent sur la mesure de paramètres écologiques, mais peu de suivis de long terme des effets des CEG et de suivis socio-économiques existent (Pendleton and Edwards, 2017). Ces suivis socio-économiques à long terme seraient essentiels pour mieux comprendre les phénomènes d'adaptation des populations locales et donc pour anticiper les besoins de gestion et de gouvernance de ces socio-écosystèmes.

Nous espérons également que la production d'une typologie des stratégies disponibles pour gérer les récifs coralliens et les populations dans un contexte de CEG recensées dans la littérature pourra servir directement la mise en œuvre de politiques publiques. Cette typologie de stratégies de gestion donne accès à une synthèse de la littérature scientifique aux gestionnaires locaux qui sont potentiellement demandeurs de connaissances sur les actions disponibles. Cette typologie de stratégies de gestion dépasse le périmètre du mandat de la plupart des instances de gestion nationales et locales. Plusieurs solutions sont possibles : renforcer la concertation entre les services responsables (bassins versant, AMP, pêche,…), modifier le périmètre des agences ou porter ces stratégies à de plus hautes échelles de décision (Premier Ministre par exemple pour le premier PNACC en France).

Nous pensons que ce premier pas pourrait servir de socle à l'évaluation et à la priorisation de mesures par les gestionnaires et les décideurs locaux, nationaux, et régionaux afin de limiter les effets négatifs des CEG. Le blanchissement et les épisodes de cyclones ou d'*acanthasters* sur les récifs coralliens ne seront pas linéaires, et leur multiplication va forcer les politiques publiques à prendre des mesures dans l'urgence. C'est déjà le cas de l'instance de gestion de l'AMP de la Grande Barrière de Corail qui est en train de développer une stratégie d'urgence suite aux épisodes de blanchissement massifs sur la période 2015-2017[1]. Il faut donc que la communauté scientifique discute des solutions disponibles dès à présent et propose une série de mesures efficaces quand ce moment surviendra.

4. Limites de l'analyse

Les limites inhérentes à tout travail de recherche de ce type, doivent être explicitées pour mieux appréhender ses conclusions. Ces limites, de différentes natures, sont détaillées ci-dessous. Premièrement, la conceptualisation des différents chapitres de cette thèse repose sur des hypothèses de travail qui relèvent du parcours et de la vision du monde du chercheur et ne sont donc pas nécessairement universelles. Deuxièmement, il existe des limites inhérentes à la construction d'indicateurs. Enfin, le manque d'études empiriques à l'échelle locale laisse un certain nombre de questions de recherche ouvertes.

Hypothèses de travail

L'état des lieux présenté en introduction nous amène à formuler l'hypothèse que l'un des problèmes limitant l'action et la recherche face aux CEG est le manque d'information sur les méthodologies d'évaluation de la vulnérabilité, les stratégies de gestion disponibles et les outils pour prioriser les stratégies à mettre en place. Cette hypothèse n'a pas été testée. Il est en effet possible que le manque d'action provienne d'autres enjeux politiques, sociétaux, financiers ou culturels. Dans la mesure où l'action politique ne peut que s'accroitre avec l'augmentation des effets visibles des CEG, il sera de plus en plus important d'informer les politiques publiques avec des outils dont ils peuvent se saisir. Le développement d'indicateurs et de cadres analytiques nous semble donc pertinent pour guider la recherche et l'action publique.

[1] http://www.gbrmpa.gov.au/managing-the-reef/reef-2050

La problématique de l'évaluation de la capacité d'adaptation nous est apparue comme un enjeu central. Ceci ne disqualifie pas pour autant les approches par évaluation de la vulnérabilité. L'identification de cet enjeu provient d'une analyse sur un nombre restreint d'études (Chapitre 1) mais également en partie de communications personnelles avec des chercheurs spécialistes du sujet (E. Allison, H-M Füssel), ce qui ne reflète pas nécessairement la mise en œuvre effective des politiques publiques climatiques. A ce stade, il s'agit plus d'une hypothèse nécessitant de plus amples investigations.

Dans cette thèse, nous nous sommes focalisés sur la vulnérabilité et l'adaptation aux CEG. L'hypothèse selon laquelle l'évaluation de l'exposition aux CEG seuls permettra de réduire la vulnérabilité des systèmes socio-écologiques concernés n'est pas universellement admise. Une deuxième vision de la vulnérabilité, dite vulnérabilité contextuelle (O'Brien et al., 2004) postule que les caractéristiques intrinsèques du système socio-écologique lui-même le rendent vulnérable, et non pas les aléas exogènes auxquels le système est exposé. Certains argumentent que l'amélioration de la capacité d'adaptation générale tel l'accès à l'éducation (Bennett et al., 2014a; Folke et al., 2003) ou l'engagement dans des activités non-sectorielles comme l'assainissement (Mills et al., 2011) sont les approches les plus efficaces pour réduire la vulnérabilité.

Limites liées à l'utilisation d'indicateurs

Le choix de développer des indicateurs dans les troisième et quatrième chapitres ne va pas de soi. D'une part, les indicateurs sont un bon moyen d'intégrer des aspects physiques, écologiques et socio-économiques, de gérer le manque de données, et de faciliter la communication de résultats complexes à des gestionnaires, décideurs, et chercheurs (Levrel, 2007; OECD, 2008).

D'autre part, l'utilisation d'indicateurs impose des limites analytiques. La construction d'indicateurs ne permet pas d'expliciter des interactions complexes comme il serait possible de le faire au sein d'un modèle. En effet, le cadre analytique développé dans les troisième et quatrième chapitres (Figure 3.1. ; Figure 4.2. ; Figure 5.4.) suppose des relations linéaires entre les parties du système, ce qui permet de les isoler et de créer des indicateurs pour les mesurer. En réalité, des réponses complexes et des boucles de rétroactions existent dans les systèmes socio-écologiques coralliens et doivent être prises en compte pour comprendre leur trajectoire d'évolution (Kittinger et al., 2012). Par exemple, la sollicitation de services écosystémiques peut avoir des conséquences négatives sur les récifs coralliens. Le tourisme peut générer une dégradation directe liée à des mauvaises pratiques de plongée ou une dégradation indirecte liée à la pollution de l'eau générée par le développement d'infrastructures touristiques (Albuquerque et al., 2014; Lamb et al., 2014). A l'inverse, le tourisme peut limiter les impacts d'autres activités comme la pêche en sensibilisant les acteurs et en promouvant la conservation (Dearden et al., 2007). De même, les impacts des CEG sur les populations humaines comme les cyclones et la montée des eaux peuvent diminuer l'activité humaine et donc la pression de pêche (Cinner et al., 2016b).

Une deuxième question portant également sur l'utilisation d'indicateurs socio-économiques à une échelle globale concerne l'utilisation de valeurs nominales ou de valeurs pondérées par la population. Pour mesurer la dépendance des nations aux services produits par les récifs coralliens, nous utilisons des valeurs nominales. Avec cette méthode de calcul, ce sont les plus gros pays qui apparaissent comme étant les plus dépendants. Si nous avions utilisé des valeurs pondérées par le nombre d'habitants, par exemple en utilisant le pourcentage de la population protégée par les récifs coralliens plutôt que la population totale, les résultats seraient totalement différents (Figure DG.2.). Cette méthodologie pose donc la question de la définition de la sensibilité/dépendance. La sensibilité, aussi appelée susceptibilité ou dépendance, est un concept inclus dans la vulnérabilité et est définie comme le degré avec lequel un système exposé aux CEG pourrait être affecté (Adger, 2006). La proportion du système exposé plutôt que sa taille peut être un facteur limitant sa capacité d'adaptation plutôt que sa dépendance. Pour prendre un cas hypothétique, il est plus difficile de s'adapter si une plus grosse proportion de la population doit être relocalisée dans un pays comme Les Palaos, plutôt que si un grand nombre de gens représentant un faible pourcentage de la population doit être relocalisé dans un pays comme la Chine. Dans ce cas, les valeurs nominales mesureraient bien la sensibilité, tandis que les valeurs pondérées par habitant mesureraient une facette de la capacité d'adaptation.

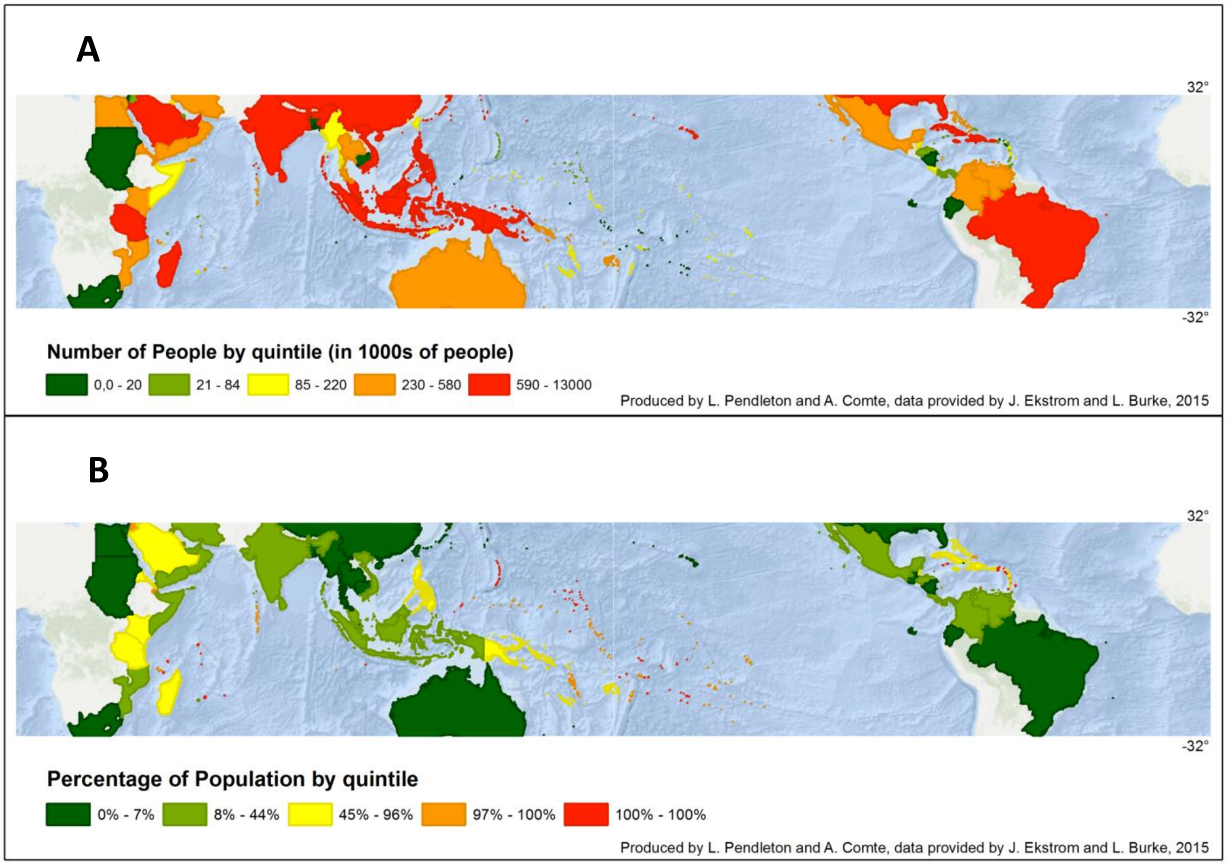


Figure DG.2. Utilisation de valeurs nominales (A) ou de valeurs pondérées par habitant (B) pour représenter la dépendance des Etats et des territoires au service de protection des côtes produit par les récifs coralliens

Une troisième problématique liée à l'utilisation d'indicateurs est leur agrégation et leur pondération dans des indicateurs composites. Il n'existe pas de méthode commune pour l'agrégation et la pondération dans les études de vulnérabilité utilisant des indicateurs (Tonmoy et al., 2014). Plusieurs méthodes existent, comme l'utilisation d'analyses statistiques incluant les analyses en composantes principales (ACP), ou l'utilisation de panels d'opinion d'experts. Dans le cas du chapitre trois, deux indicateurs composites ont été développés, un pour l'exposition aux CEG et l'autre pour la dépendance aux services écosystémiques. Pour l'exposition, les deux effets des CEG pris en compte, l'augmentation de la température de l'eau et l'acidification de l'océan, ont été pondérés de manière égale, puis additionnés. Une pondération égale suppose que l'acidification de l'océan ait un effet aussi important sur les récifs coralliens que l'augmentation de la température, ce qui n'a pas été démontré. Cette solution « par défaut » a été utilisée faute de ratio déterminé dans la littérature ou par des experts. Une agrégation par addition suppose que les deux effets (température et acidification) sont additifs, tandis que la littérature ne s'est pas encore prononcée sur la nature exacte des interactions de ces deux paramètres, qui pourrait donc également être synergétique ou antagoniste. De même, pour la création d'un indicateur composite de dépendance aux services écosystémiques, aucune pondération n'a été employée et les différents indicateurs ont été additionnés pour obtenir un indicateur composite. Le service de pêche a donc ici le même poids que le service de protection des côtes. On pourrait faire des hypothèses différentes, étant donné que la protection des côtes implique potentiellement la mise en danger de la vie humaine tandis que la pêche est pour certaines populations un mode de vie ancestral et fournit des protéines essentielles.

Intégrations à des échelles spatiales

Les chapitres de la thèse se réfèrent à des échelles spatiales différentes. Le premier chapitre tente de faire le lien entre échelle globale et échelle locale. Le deuxième chapitre est conceptuel et propose des pistes de recherches pour la communauté scientifique en général. Le troisième chapitre s'applique à l'échelle des pays, avec une couverture globale. Le quatrième chapitre est général, mais l'analyse des efforts de recherche se fait à l'échelle des pays, avec une couverture globale. La typologie et la description des stratégies de gestion disponibles est multi-échelle, avec des solutions locales, nationales, régionales, et globales. Le cinquième chapitre est ancré au niveau local car l'évaluation de la capacité d'adaptation écologique dépend du contexte spécifique. Plusieurs échelles spatiales sont donc couvertes dans ce manuscrit, sans forcément articuler les conclusions entre différentes échelles. Nous proposons un cadre dans le chapitre premier *« top-down »*, de l'échelle globale à l'échelle locale, mais nous ne proposons pas explicitement de cadre « *bottom-up* » pour faire remonter des informations locales à des échelles plus larges.

5. Perspectives de recherche

L'importance des enjeux liés aux CEG, à leurs impacts sur les écosystèmes, les sociétés, et les solutions disponibles pour y répondre en font un sujet de recherche immense. Les réponses scientifiques proposées ici se focalisent sur une toute petite partie du problème, et amènent également de nouveaux questionnements. Les directions futures pour la recherche sont donc nombreuses. Nous avons déjà proposé des directions de recherche dans les différents chapitres de cette thèse. Ici, nous allons brièvement proposer d'autres pistes de recherche qui découlent des questions soulevés par nos résultats. Ces pistes de recherche sont classées par intérêt personnel du court terme au moyen terme.

a. Etude de cas pour évaluer la Capacité d'Adaptation Ecologique

La définition d'indicateurs pour opérationnaliser la capacité d'adaptation écologique localement n'a pas été testée empiriquement. Un projet futur a pour objectif d'évaluer la CAE en Polynésie française afin d'opérationnaliser ce cadre analytique et de participer à l'étude de la vulnérabilité et de l'adaptation des territoires français d'outre-mer. Cette étude, financée par le LabexMer et l'IFRECOR, repose sur l'organisation d'ateliers de travail et sur un travail d'enquête. Un panel d'experts locaux permettra de déterminer quels paramètres caractérisent la capacité d'adaptation des écosystèmes coralliens en Polynésie française et identifiera les données qui permettront d'évaluer cette capacité d'adaptation écologique et de l'intégrer dans une étude locale d'évaluation de la vulnérabilité socio-écologique aux CEG. Ce cadre pourra ensuite aider à la priorisation de stratégies de gestion et être transposé à d'autres territoires d'outre-mer.

De nombreux autres systèmes socio-écologiques font l'objet d'évaluation de la vulnérabilité sans que la CAE de ces systèmes soit prise en compte (Lee et al., 2017). La capacité d'adaptation écologique pourrait également être un outil intéressant dans d'autres systèmes socio-écologiques et pourrait donc être adaptée à d'autres contextes.

L'explicitation des limites écologiques et l'intégration des cadres de vulnérabilité et de résilience dans l'évaluation de la CAE posent de nouvelles questions. Bien que de nombreux chercheurs assimilent résilience et capacité d'adaptation (Angeon and Bates, 2015; Engle, 2011; Turner et al., 2003), il est en fait possible que l'augmentation de la résilience d'un système, et donc de sa stabilité, empêche l'adaptation d'un système si cette adaptation requiert une transformation (Folke et al., 2010). Il serait donc intéressant de savoir quels sont les processus transformatifs des systèmes socio-écologiques coralliens.

b. Créer de nouveaux indicateurs pour améliorer les projections des effets des CEG sur les récifs coralliens et les services écosystémiques associés

La cartographie des impacts potentiels des CEG sur les récifs coralliens et les populations qui en dépendent est un premier pas important, mais de nombreuses améliorations peuvent être apportées à cette étude.

En ce qui concerne l'exposition des récifs coralliens, il n'a pas été possible de définir une valeur seuil pour l'acidification des océans comme il a été possible de le faire pour l'effet de l'augmentation de la température de l'eau. Des recherches futures pourraient se concentrer sur l'estimation des valeurs seuil sur la biologie et l'écologie des récifs coralliens. Il est désormais admis que l'étude des impacts liés aux CEG sur les sociétés et les écosystèmes doivent intégrer des menaces multiples (Riebesell and Gattuso, 2015 ; Chapitre 2). Cependant, très peu d'études vont au-delà pour essayer d'identifier d'autres risques majeurs en dehors des CEG (Bennett et al., 2015). Le manque d'information sur la distribution des enjeux locaux pourrait freiner l'adoption de mesures par les gestionnaires locaux (Bennett et al., 2015; Brown et al., 2014). Les menaces locales sur les récifs coralliens à l'échelle globale sont néanmoins décrites dans Burke et al. (2011) et pourraient être utilisées pour prioriser certaines mesures de gestion.

L'indicateur composite qui mesure la dépendance aux services écosystémiques prend en compte deux services majeurs, la pêche et la protection des côtes, mais laisse de côté d'autres services produits par les récifs coralliens par manque de bases de données à l'échelle globale. Le troisième service majeur, le tourisme, dispose désormais d'une base de données globale publiée récemment (Spalding et al., 2017) qu'il serait intéressant d'intégrer à notre étude. Par ailleurs, contrairement aux indicateurs d'exposition qui sont projetés dans le futur, les indicateurs de dépendance socio-économiques utilisent des données actuelles (voire passées, les bases de données datant de 2007 et 2005). L'estimation de valeurs futures serait donc intéressante pour mieux appréhender les impacts potentiels futurs. Il n'existe pour l'instant pas de modèle pour expliquer quels facteurs (évolution démographique, amélioration du niveau de vie) influencent l'évolution de la dépendance aux services écosystémiques coralliens. Il serait donc intéressant d'explorer la disponibilité de données empiriques et le cas échéant de mettre en place des suivis temporels d'évolution de la demande en services écosystémiques pour tenter d'estimer l'évolution possible de cette demande.

c. Evaluer le coût de l'action

L'évaluation des coûts des mesures de gestion face aux effets des CEG sur les récifs coralliens et les populations qui en dépendent est une frontière de recherche (Leenhardt et al., 2015). Des estimations existent pour les coûts de restauration (Bayraktarov et al., 2016) ainsi que pour les coûts d'amélioration de la qualité de l'eau (Van Grieken et al., 2013). Le coût de nombreuses autres mesures de gestion n'étant pas chiffré, il n'est pour l'instant pas possible de faire la synthèse et de comparer le coût des différentes stratégies de gestion disponible. L'estimation de ces coûts est pourtant nécessaire pour prioriser les mesures à mettre en œuvre (Saunders et al., 2017), et pour évaluer les besoins de financement des communautés et des pays qui dépendent des récifs coralliens (Biagini et al., 2014). A l'échelle internationale, l'évaluation de ces coûts pourrait être utile dans le processus des négociations climatiques lié à l'attribution de financements et à la réparation des dommages liés aux changements climatiques. Aux échelles nationales et locales, le coût des mesures de gestion est un paramètre essentiel pour l'élaboration de plans de gestion et d'adaptation aux changements climatiques.

d. Comprendre l'influence des études de vulnérabilité globales

Le chapitre premier développé dans cette thèse montre que de nombreuses études d'évaluation de la vulnérabilité de l'environnement marin à l'échelle globale ont été menées. Il serait intéressant de comprendre de quelle manière ces études ont ou non influencé la distribution de fonds internationaux pour lutter contre les CEG. Une étude récente recense les projets en cours dans les pays en développement (Amerasinghe et al., 2017), permettant de comparer l'effort alloué à chaque pays avec leur niveau théorique de vulnérabilité.

Nous avons vu que l'évaluation de la capacité d'adaptation au niveau global est problématique. Il est néanmoins possible d'imaginer l'évaluation d'une capacité d'adaptation des gouvernements nationaux qui provienne entre autre de leur perception des enjeux, de la structuration des institutions, de leurs politiques en termes de gestion des risques, de gestion de l'environnement marin et de gestion intégrée. Dans le cas de l'aide internationale par exemple, il doit être possible d'établir des critères pour évaluer la capacité des pays à accéder aux fonds internationaux et à planifier efficacement des politiques climatiques et environnementales nationales pour la gestion des récifs coralliens et des populations qui en dépendent.

e. Identifier des indicateurs pour évaluer et suivre les progrès face aux effets des CEG sur les systèmes socio-écologiques coralliens

Le suivi de l'évolution des systèmes socio-écologiques est une étape importante dans un processus de gestion adaptative (Armitage et al., 2009). Les indicateurs développés dans le chapitre 3 sont des valeurs relatives pour déterminer quels pays sont le plus à risque face aux effets des CEG sur les récifs coralliens et la dépendance des nations aux services produits par ces récifs. L'utilisation d'indicateurs relatifs plutôt que d'indicateurs absolus se pose donc. Il n'existe pas de série temporelle sur les changements socio-économiques liés à la perte de services écosystémiques suite à la dégradation des récifs coralliens. La construction de séries temporelles devrait être un objectif de recherche (Pendleton and Edwards, 2017) ainsi qu'un objectif politique national et international qui devrait être porté auprès d'instances politiques internationales comme l'ICRI et l'ONU à travers les ODD.

f. Evaluer les impacts de la perte de services écosystémiques liés à la dégradation des récifs coralliens et d'autres écosystèmes sur la société

Il devrait être possible de mesurer les impacts des épisodes de blanchissement et de la perte de couverture corallienne sur les sociétés et l'économie, étant donné que la perte de couverture corallienne a été répertoriée dans plusieurs régions, notamment dans la GBC (De'ath et al., 2012). La perte de récifs devrait en effet entrainer une perte de services écosystémiques qui lui sont associés. Une première étude tentant d'estimer ce coût de l'inaction existe (Chen et al., 2015), mais les mécanismes qui lient la dégradation des récifs à une perte pour les sociétés ne fait pas encore l'objet d'études empiriques. Des questions précises pourraient être posées pour déterminer ces impacts : est-ce que des pêcheurs ont dû migrer ou changer de métier suite à la réduction de la couverture corallienne ? Est-ce que des clubs de plongée ont fermé ? Est-ce que des infrastructures ont été détruites ? Plus largement, est-ce que la perte de services écosystémiques est mesurée pour d'autres écosystèmes ?

Ces impacts donneront lieu à une redistribution des pertes et des gains à différentes échelles spatiales, notamment pour le tourisme où les sites résilients pourraient bénéficier d'un afflux de touristes (Hilmi et al., 2017). Les évaluations de la vulnérabilité ne sont pas équipées pour répondre à ce problème (Cheung et al., 2010), d'autres études doivent donc être menées. Il est important de comprendre les effets de cette redistribution pour évaluer son incidence sur les inégalités inter-Etats, intra-Etats, et intergénérationnelles. Attribuer la perte de services écosystémiques aux CEG pourrait également alimenter les négociations climatiques sur le « *loss and damage* », discussions qui portent sur les réparations des dégâts causés par les changements climatiques qui n'ont pas pu être évités par des mesures d'atténuation et d'adaptation (Thomas and Benjamin, 2017).

g. Explorer de nouvelles solutions

Compte-tenu de l'échelle du problème des CEG et de la dégradation des écosystèmes et des services qui y sont associés, de nombreuses innovations sociales, techniques, économiques ou organisationnelles vont nécessairement apparaître. Le Mexique par exemple explore un nouveau modèle d'assurance pour les récifs coralliens en partenariat avec *The Nature Conservancy* (TNC, 2017). Ce projet consiste à assurer les récifs coralliens qui protègent les infrastructures touristiques mexicaines à Cancun et Puerto Morelos. Les fonds récoltés servant d'autofinancement pour la protection et la restauration des récifs détruits par des évènements extrêmes. L'état des lieux des stratégies de gestion réalisé dans le quatrième chapitre permet d'explorer de nouvelles solutions et d'évaluer leur faisabilité et leurs impacts sur les systèmes socio-écologiques.

Annexes

Annex A. Methods for analyzing global threats to coral reefs and dependence of human populations; and results per country and per ocean province

Table A.1. files used for mapping

Data	Name	Attributes	Source
Reefs location	reef_500	grid	WRI
Bleaching	10x8DHW_corals	Year when 2x 8 DHW RCP 8.5	Van Hooidonk
Ocean Acidification	oa_2050	Omega aragonite in 2050 projections RCP8.5 gridded	Liqing Jiang
Countries' EEZ	World_EEZ_v8_2014_HR	Shapefile	web
Marine Ecoregions	meow_ecos	Shapefile	web

1 Creation of Ocean Provinces

Ocean provinces (OP) in Maina et al 2011 (Figure A.2.) come from Donner 2009 (Figure A.1.). Based on these, we created 12 ocean provinces by manually selecting ecoregions (MEOWs), creating ocean provinces (Figure A.3.). Note: Donner has 11 ocean provinces, and Maina adds a 12th one as the Brazilian province. This 12th province was kept here. This method was overall satisfactory to delineate ocean provinces. The frontier between Micronesia and Polynesia, however, is slightly different from Maina and Donner.

Note: West African coral reefs do not belong to any ocean province in this analysis.

We then merged MEOWs belonging to the same ocean province, removed some features, and converted it to lines to be able to remove the date line (file op_lines).

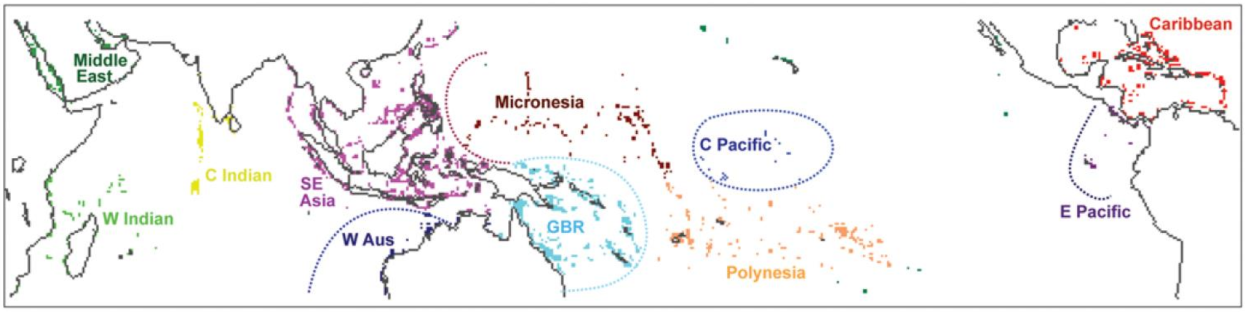


Figure A.1. Ocean provinces in Donner, 2009

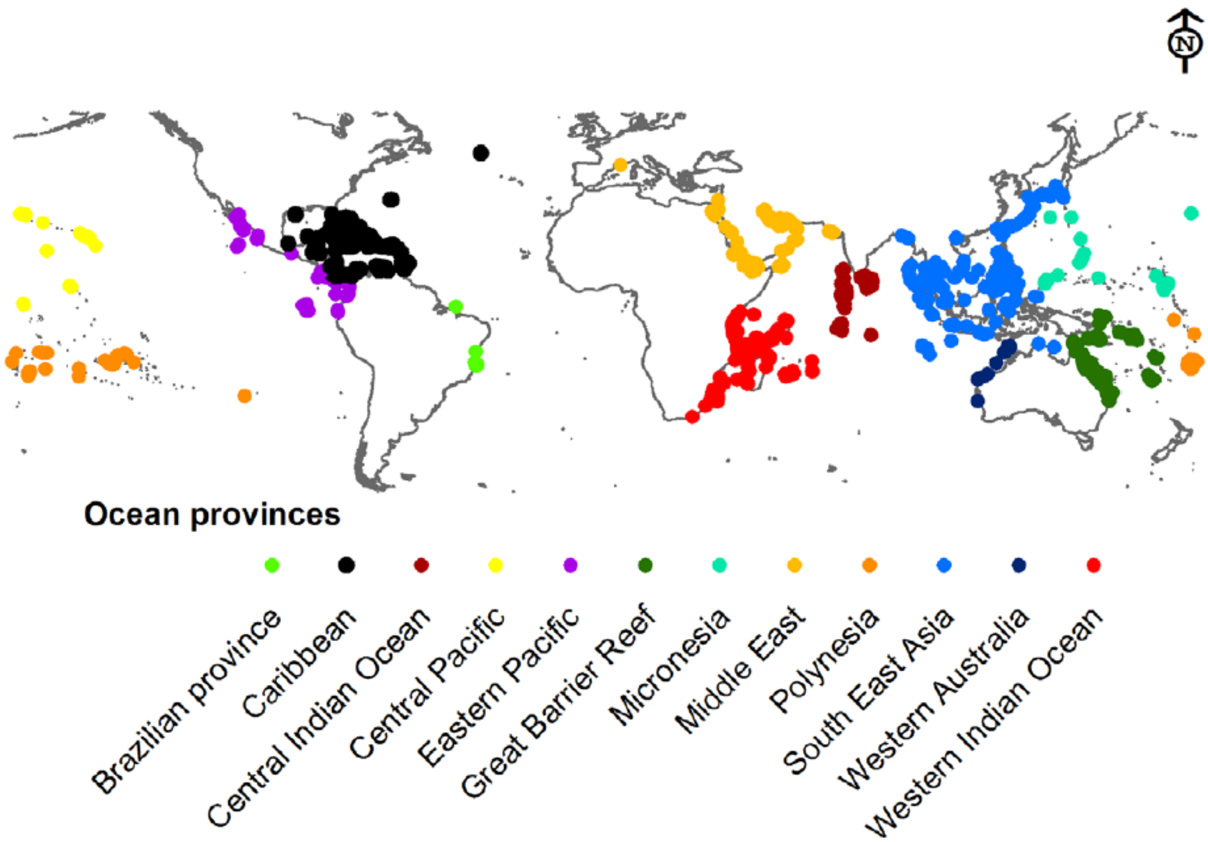


Figure A.2. Ocean provinces in Maina et al., 2011

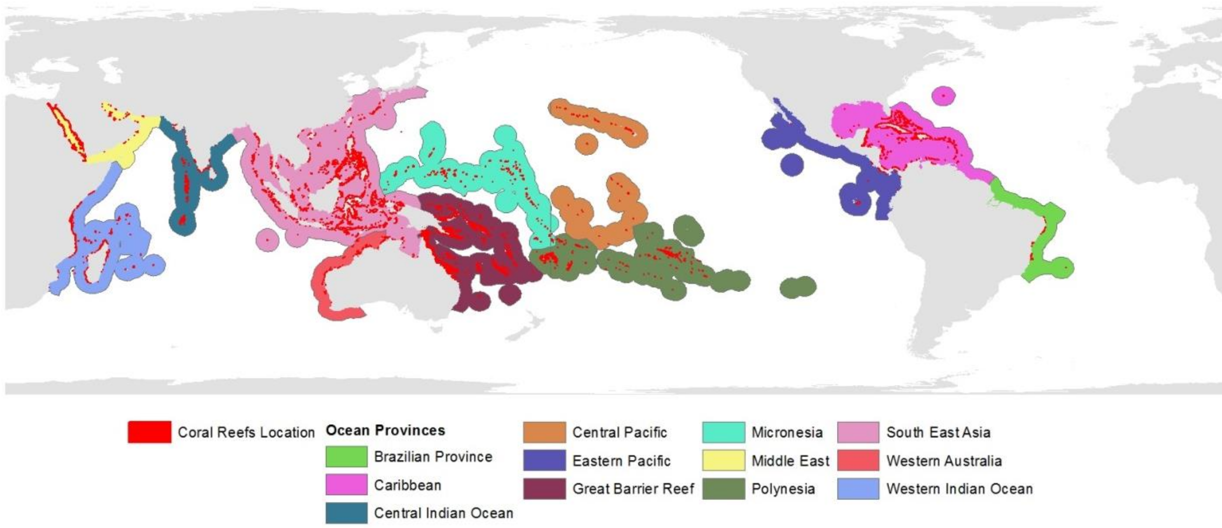


Figure A.3. Coral reefs location in 12 ocean provinces; manual ecoregions selected to make ocean provinces based on Maina et al., 2011 and Donner, 2009.

2. Dependence on ecosystem services (per country and per ocean province)

First, we map the ecosystem services (ES) dependence indicators per country. This indicator is calculated with the formula:

Average (P,max(F,V)) rescaled 0-10

with:

P: population protected by reefs (rescaled 0-1)

F: number of fishers (rescaled 0-1)

V: value of fish catch (rescaled 0-1)

Max(F,V) (rescaled 0-1)

Values were logged using the formula

$x = \log10(1+x)$

Z-scores were calculated to normalize the data for P, F, and V using the formula:

Zx= x-mean/std

To rescale, we use the formula:

A=min value, B=max value
a=0, b=10
$x' = a + (Zx-A)(b-a)/(B-A)$

Values of ES were then aggregated by ocean province. In order to do so, ES values per country had to match the zoning of ocean province. This was not the case for several countries (Figure A.4.). To identify which countries' EEZ contained more than one OP, *zonal tool* in ArcGIS was used. Twenty-four countries contained more than one OP in their EEZ (ASM, AUS, COK, COL, CRI, FJI, FSM, HND, IDN, IND, JPN, KIR, MEX, NIC, PAN, PLW, PNG, SOM, TLS, TUV, USA, WLF, WSM, YEM) based on this method. We then manually looked at each EEZ to see where coral reefs were located for these 24 EEZ (see Figure A.5. for an example in ASM). In some cases, coral reefs were effectively located in only 1 OP. In other cases, they were located in more than 1:

Colombia with reefs belonging to Colombia's EEZ located in 2 ocean provinces, reefs belonging to Costa Rica's EEZ located in 2 OP, reefs belonging to India's EEZ located in 2 OP, reefs belonging to Mexico's EEZ located in 2 OP, reefs belonging to Australia's EEZ located in 3 OP, reefs belonging to Panama's EEZ located in 2 OP, reefs belonging to the USA's EEZ located in 2 OP, reefs belonging to Fiji's EEZ located in 3 OP, reefs belonging to Kiribati's EEZ located in 3 OP, reefs belonging to Somalia's EEZ located in 2 OP, reefs belonging to Cook Islands' EEZ located in 2 OP, reefs belonging to Wallis and Futuna's EEZ located in 2 OP.

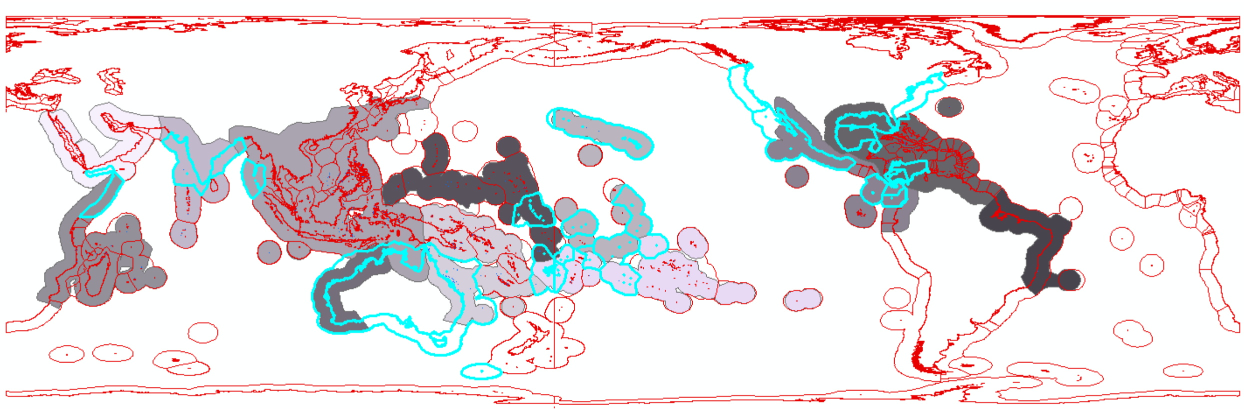


Figure A.4. Countries with coral reefs in more than one ocean provinces (represented in Turquoise); Grey= ocean provinces, Red= EEZs, Blue= coral reefs.

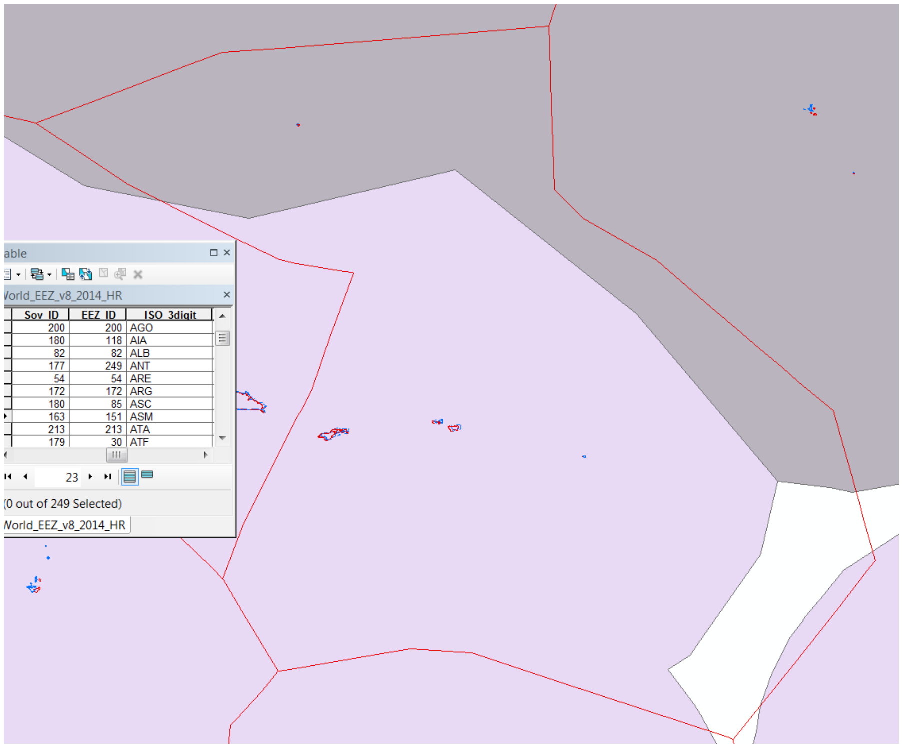
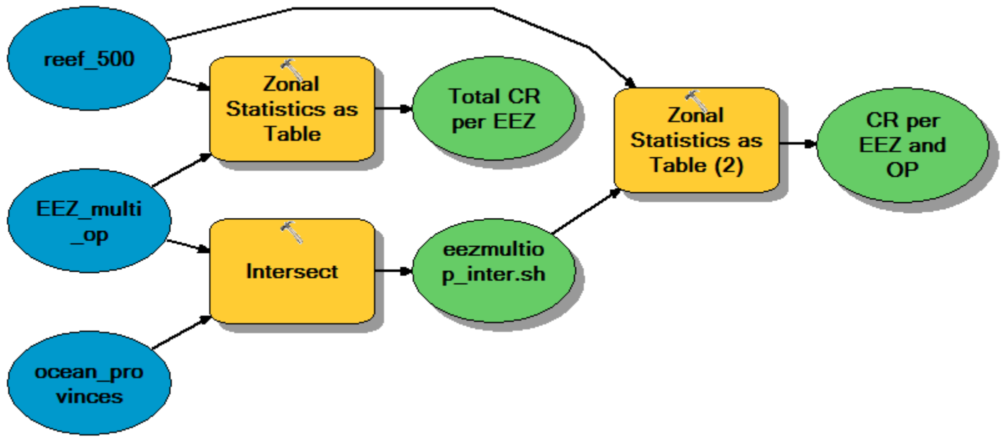


Figure A.5. ASM'EEZ contains 2 OP, and both contain coral reefs (blue dots).

We decided to estimate the ES provision in these countries for each Ocean Province by multiplying total ES value for the country by the ratio of total CR cover to CR cover in the Ocean Province:

$ES_{OP} = ES_{tot} \times CR_{OP}/CR_{tot}$

First, we had to calculate CR_{OP} and CR_{tot} in ArcGIS using *zonal statistics* (Graph1). Then, we calculated CR_{OP}/CR_{tot} in excel (Table A.2.). We applied the formula to get ES_{OP} for ASM, AUS, COK, COL, CRI, FJI, IND, KIR, MEX, PAN, SOM, WLF. For the USA, data were already disaggregated between Hawaii and Mexico.



Graph1: Model to calculate the coverage of coral reefs per EEZ and per Ocean Province for the countries which EEZ overlap more than one Ocean Province.

Table A.2. Calculation of ratio for coral reefs in countries with more than 1 Ocean Province

CR op / CR tot					
Country	ISO_3digit	OP	CR op	CR tot	CR op / CR tot
American Samoa	ASM	Central Pacific	14	380	0.037
American Samoa	ASM	Polynesia	366	380	0.963
Australia	AUS	Great Barrier Reef	144040	165150	0.872
Australia	AUS	South East Asia	4915	165150	0.030
Australia	AUS	Western Australia	16195	165150	0.098
Cook Islands	COK	Central Pacific	953	1901	0.501
Cook Islands	COK	Polynesia	948	1901	0.499
Colombia	COL	Caribbean	5346	5448	0.981
Colombia	COL	Eastern Pacific	102	5448	0.019
Costa Rica	CRI	Caribbean	58	398	0.146
Costa Rica	CRI	Eastern Pacific	340	398	0.854
Fiji	FJI	Great Barrier Reef	54	23412	0.002
Fiji	FJI	Micronesia	2512	23412	0.107
Fiji	FJI	Polynesia	20846	23412	0.890
Andaman and Nicobar	IND	South East Asia	4808	11811	0.407
India	IND	Central Indian Ocean	7003	11811	0.593
Line Group	KIR	Central Pacific	1513	10692	0.142
Line Group	KIR	Polynesia	132	10692	0.012
Kiribati	KIR	Micronesia	9047	10692	0.846
Mexico	MEX	Caribbean	5563	5632	0.988
Mexico	MEX	Eastern Pacific	69	5632	0.012
Panama	PAN	Caribbean	3850	4672	0.824
Panama	PAN	Eastern Pacific	822	4672	0.176
Somalia	SOM	Middle East	510	2082	0.245
Somalia	SOM	Western Indian Ocean	1572	2082	0.755
Hawaii	USA	Central Pacific	15242	19963	0.764
United States	USA	Caribbean	4721	19963	0.236
Wallis and Futuna	WLF	Micronesia	277	2317	0.120
Wallis and Futuna	WLF	Polynesia	2040	2317	0.880

To validate this method, we looked at the actual ratio of ES for the USA. Using our method, we find that 76% of coral reefs are located in Hawaii, and 24% in Florida. For coastal protection ES, the data shows that 30% of the total number of protected people are protected in Hawaii, against 70% of the total number of protected people are protected in Florida. For the number of fishers, Hawaii hosts 70% of the total US coral reef fishers, whereas Florida hosts 30%. So, we see that the ratio we obtain using our method is validated for the fishers ES, but not for the coastal protection ES (which is somewhat logical since fish is directly correlated with coral cover, but housing is not).

The situation in terms of coral cover is very unbalanced for Australia, American Samoa, Colombia, Fiji, Kiribati, and Mexico, with ~90% of CR cover in one ocean province and ~10% or less in the other provinces in which these countries have CR, so that there is less chance of our method being far from the truth. However, Cook Islands and India have ~50% of their CR in an ocean province, and 50% in another, similar to the USA.

We then incorporated ES from all other countries to get ES by Ocean Province (Table A.3.). To do this, we first used *spatial join* in ArcGIS on EEZ and "ocean_provinces" and exported the table as "eez_op". We then incorporated ES per EEZ from the previous analyses.

Table A.3. Ecosystem Services Dependence per Ocean Province

Tot ES per OP			
OP	Fishers	Value of catch	low_prot_pop
Brazilian Province	144433	180174864	1239637
Caribbean	276826	726828415	8300897
Central Indian Ocean	620974	168726685	5054227
Central Pacific	25495	1811215	1536879
Eastern Pacific	23123	17415220	108616
Great Barrier Reef	225201	413564715	1441968
Micronesia	72340	11688205	407388
Middle East	345455	669087061	6535613
Polynesia	84622	17189967	809403
South East Asia	3971693	3768035428	33187672
Western Australia	2902	45816675	30990
Western Indian Ocean	228112	66251593	4271981

3. Results at the country level

These results are simply a geographical arrangement of the dependence indicator on the one hand, and DHW (Figure A.6.) or OA on the other (Figure A.7.). No further geostatistical analysis was conducted to produce these maps.

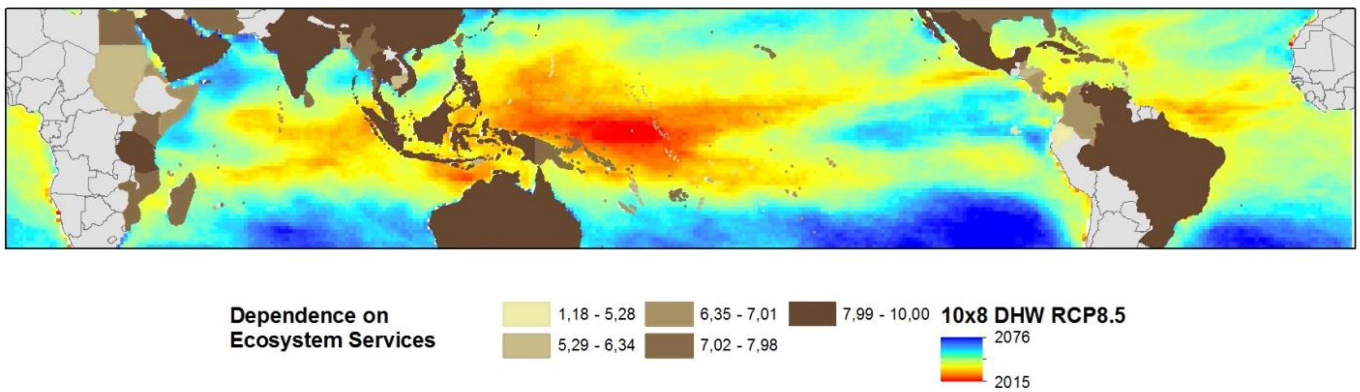


Figure A.6. Country-level dependence on ecosystem services, and future threat of coral bleaching as year when 10x8 DHW is reached under RCP8.5 scenario, cross section of the globe between 32°N and 32°S of latitude

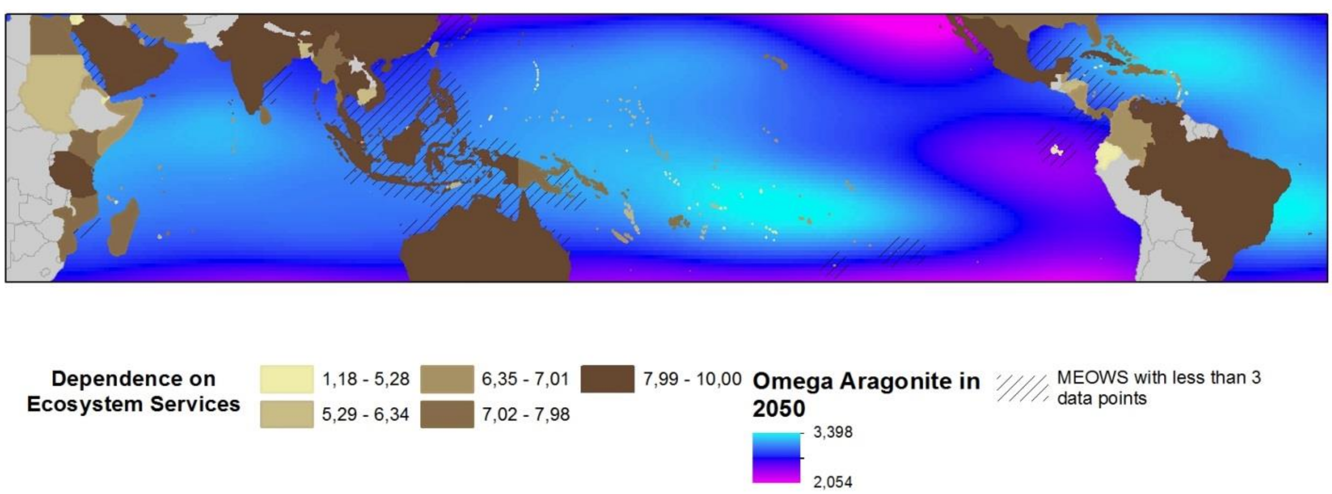
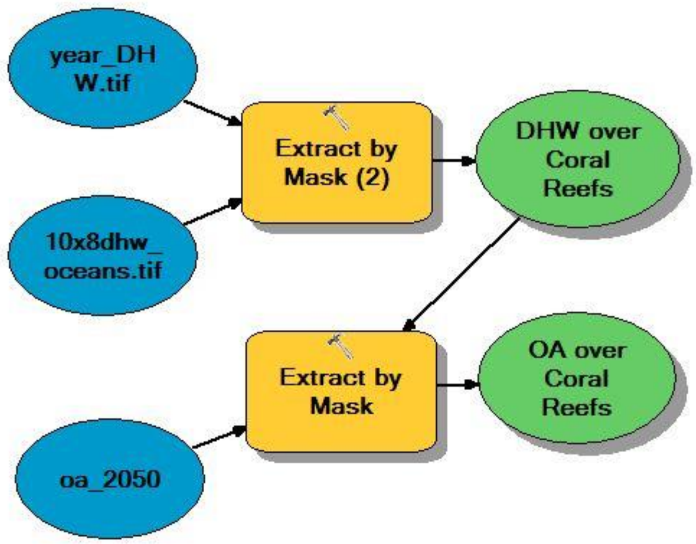


Figure A.7. Country-level dependence on ecosystem services, and future risk of ocean acidification as omega aragonite level in 2050, cross section of the globe between 32°N and 32°S of latitude

4. Results for DHW and OA at the regional level

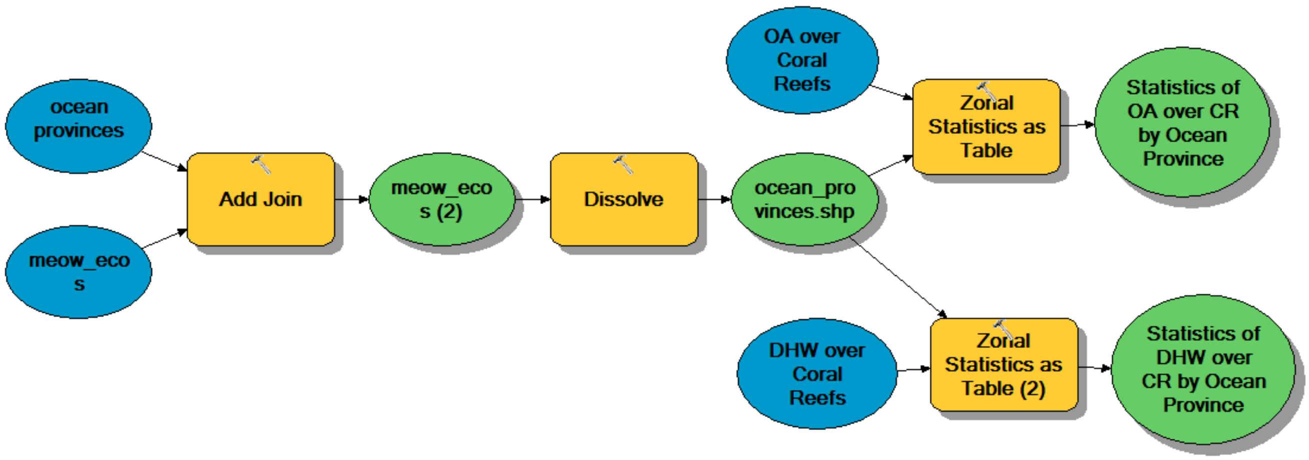
We created 10x8DHW RCP8.5 by using *extracting by mask* data on the full ocean provided by Ruben van Hooidonk (NOAA), with the mask being Year_DHW (Graph2). Because this result had slightly less pixels than the Year_DHW layer, we used it to recalculate the layer of OA over Coral Reefs (Graph2).



Graph 2: Model to calculate the OA layer over coral reefs

Since the OA layer is a projection interpolated on the entire globe, and since coral reefs location and the DHW raster do not match 1:1, it is possible to try two methods to get OA in 2050 values over coral reefs per country: (i) clip the global projection of OA with coral reefs, and then get *zonal statistics* per EEZ, or (ii) clip the global projection of OA with the DHW grid, and then get the *zonal statistics* per EEZ. The first method will be more accurate, but the second method will keep the accuracy of the DHW analysis and so will be more conservative. For the method (ii), we used *extract by mask* tool in ArcGIS to create “oa_mask_dhw” (Graph1). This last file was used as the OA over coral reefs layer.

We then overlaid the DHW over coral reefs and ocean provinces and the OA over coral reefs and ocean provinces. We then performed *zonal statistics* to get DHW and OA values per ocean provinces (Graph3). The results are displayed in Table A.4. for DHW and Table A.5. for OA.



Graph 3: Model to calculate the statistics of OA and DHW per ocean provinces.

Finally, we created maps of OA and DHW by rescaling them to 1-10 using the formula
A=min value, B=max value
a=1, b=10
x' = a + (x-A)(b-a)/(B-A)

and adding them (Graph4) over coral reefs (Figure A.8.), over the whole ocean, and in the 32° and -32° latitudinal range (Figure A.9.).

Table A.4. 10x8DHW RCP 8.5 over coral reefs for each Ocean Province; count is the number of pixels (approximation of the size of reef area)

Ocean Province	ZONE_CODE	COUNT	MIN	MAX	RANGE	MEAN	STD
Brazilian Province	1	17	2041	2045	4	2043	0.76
Caribbean	2	161	2038	2055	17	2044	2.41
Central Indian Ocean	3	45	2036	2063	27	2046	5.72
Central Pacific	4	70	2031	2053	22	2043	6.45
Eastern Pacific	5	21	2043	2059	16	2052	4.40
Great Barrier Reef	6	210	2027	2068	41	2044	9.12
Micronesia	7	130	2023	2042	19	2035	4.06
Middle East	8	60	2040	2072	32	2057	5.97
Polynesia	9	160	2036	2066	30	2048	6.85
South East Asia	10	411	2030	2076	46	2042	5.83
Western Australia	11	16	2033	2061	28	2046	9.50
Western Indian Ocean	12	75	2041	2058	17	2049	4.34

Table A.5. Omega Aragonite level in 2050 over coral reefs for each Ocean Province; count is the number of pixels (approximation of the size of reef area)

Ocean Province	ZONE_CODE	COUNT	MIN	MAX	RANGE	MEAN	STD
Brazilian Province	1	17	3.17	3.37	0.19	3.31	0.06
Caribbean	2	161	2.92	3.32	0.40	3.18	0.10
Central Indian Ocean	3	45	2.99	3.24	0.25	3.17	0.06
Central Pacific	4	70	3.00	3.39	0.39	3.16	0.13
Eastern Pacific	5	21	2.22	2.93	0.70	2.65	0.16
Great Barrier Reef	6	210	2.44	3.24	0.80	3.10	0.14
Micronesia	7	130	3.15	3.31	0.17	3.20	0.04
Middle East	8	60	3.03	3.11	0.08	3.07	0.02
Polynesia	9	160	2.63	3.39	0.76	3.23	0.14
South East Asia	10	411	2.74	3.18	0.44	3.08	0.09
Western Australia	11	16	2.75	3.12	0.38	3.02	0.11
Western Indian Ocean	12	75	2.87	3.22	0.35	3.12	0.09

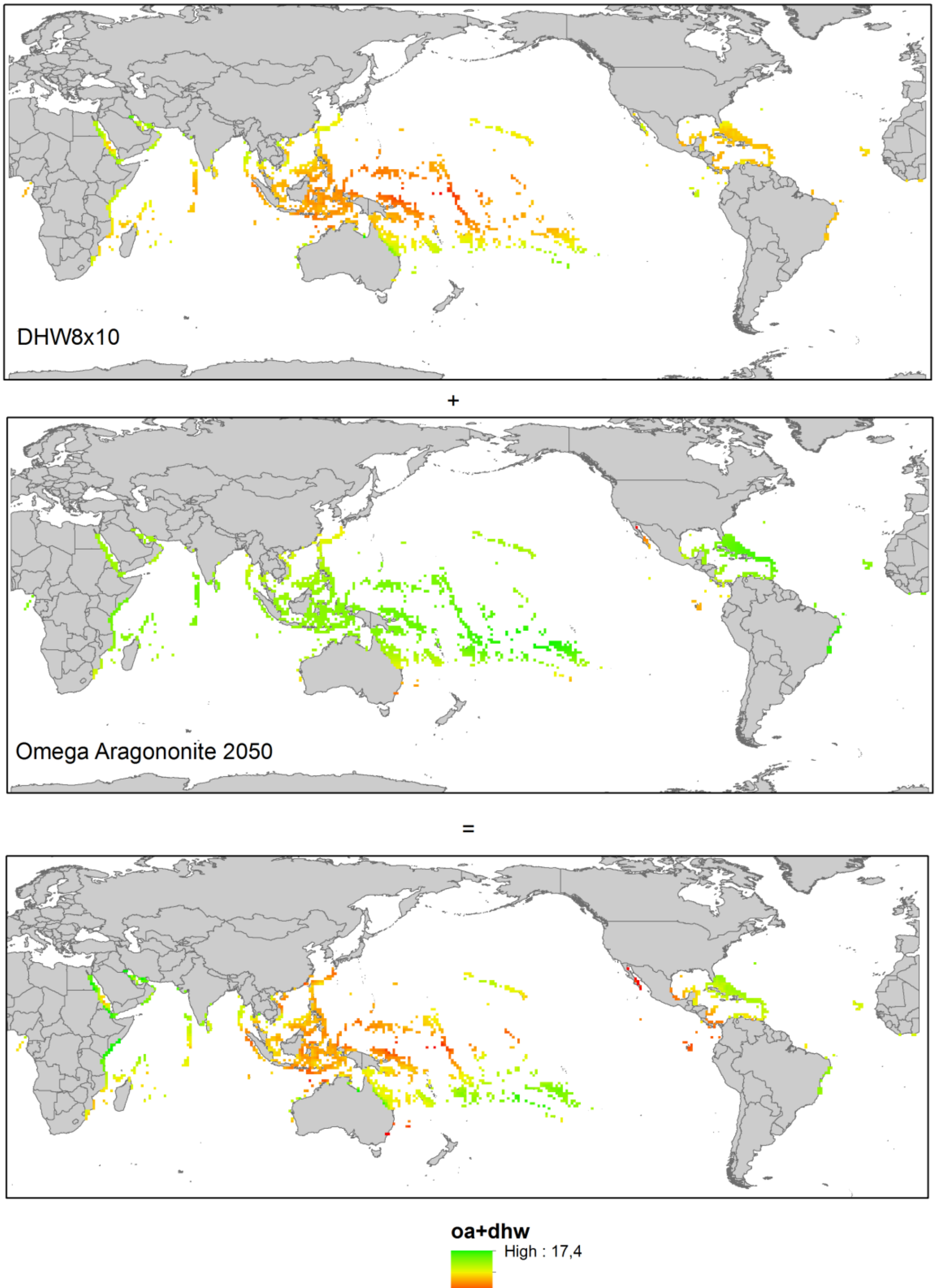


Figure A.8. OA (rescaled 1-10) + DHW (rescaled 1-10), over coral reefs. Lowest value= highest threat

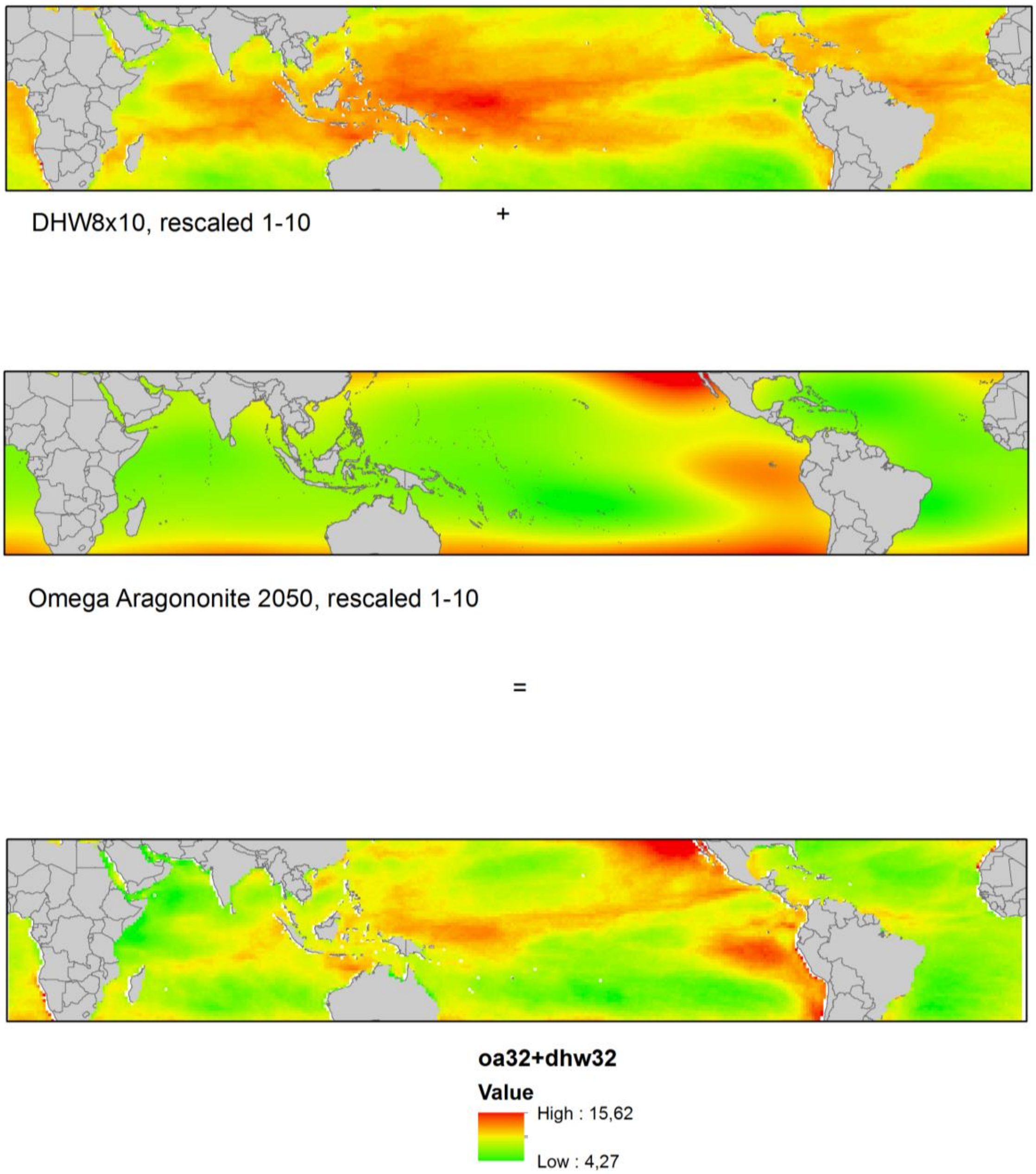
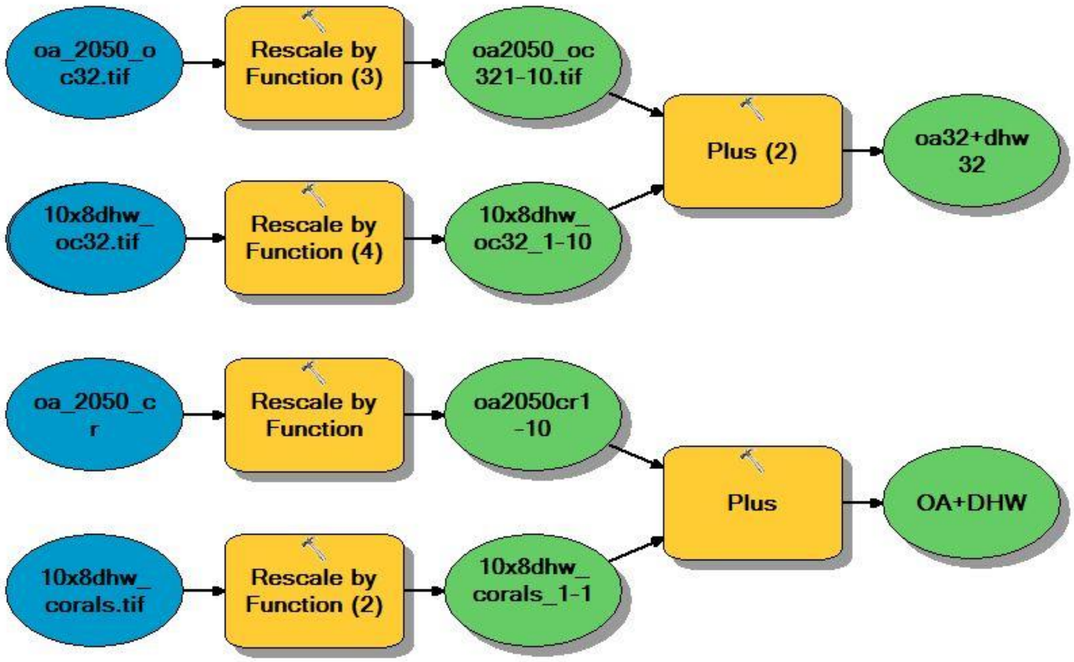
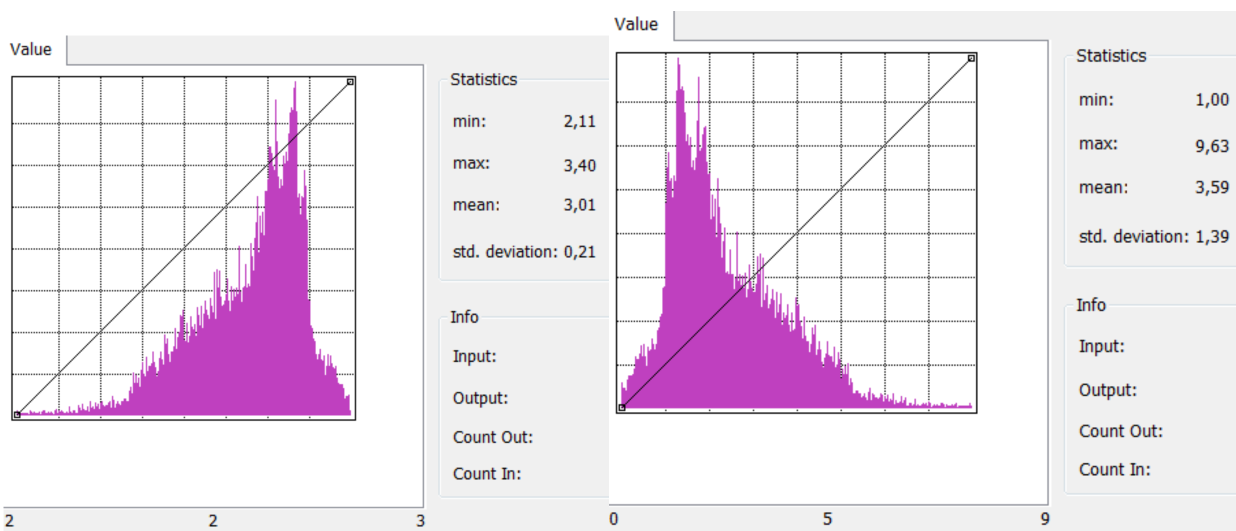


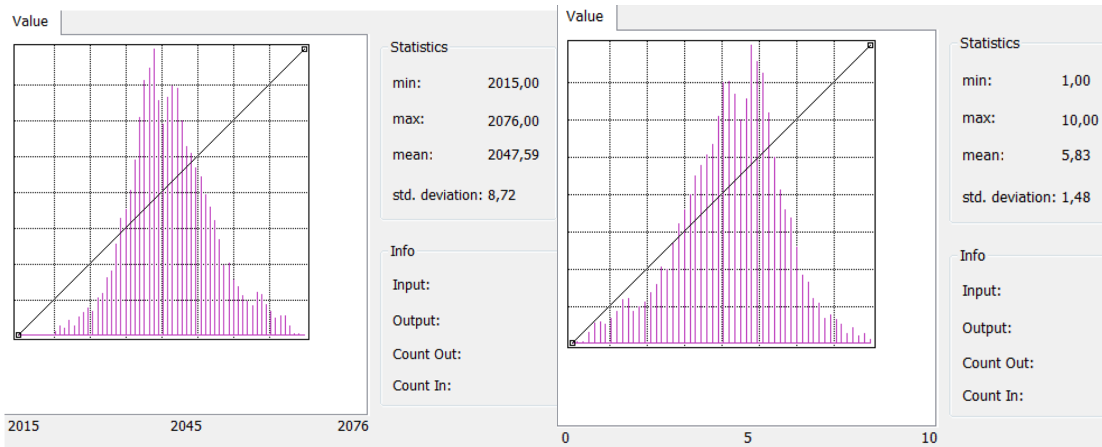
Figure A.9. OA (rescaled 1-10) + DHW (rescaled 1-10), over whole ocean between 32° and -32°. highest value= highest threat



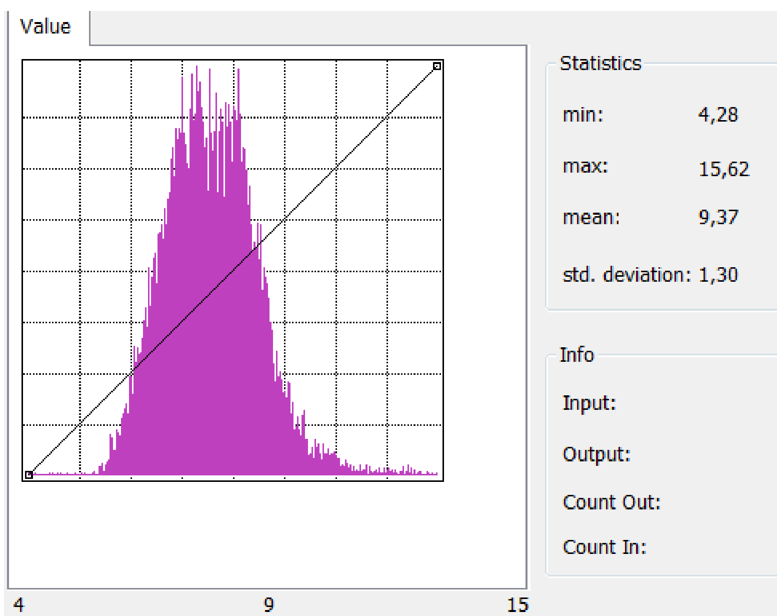
Graph 4: Model to calculate OA+DHW (with a 1-10 scale) over coral reefs, and over the whole ocean (32° latitude)



Histograms of distribution of values for OA and OA rescaled 0-10 (between latitude 32° and -32°). Y axis represents number of pixels (1 pixel is 0.5° by 0.5°). Figures are screenshots of raw outputs taken in ArcGIS©



Histograms of distribution of values for DHW and DHW rescaled 0-10 (between latitude 32° and -32°). Y axis represents number of pixels (1 pixel is 0.5° by 0.5°). Figures are screenshots of raw outputs taken in ArcGIS©



Histogram of distribution of values of DHW+OA (between latitude 32° and -32°). Y axis represents number of pixels (1 pixel is 0.5° by 0.5°). Figures are screenshots of raw outputs taken in ArcGIS©

Annex B. Sensitivity analysis on two greenhouse gas emission scenarios applied to ocean warming and acidification at coral reefs locations

1 Introduction

In chapter 3 on people and reefs in a high CO_2 world, we used a business-as-usual greenhouse gas (GHG) emission scenario to calculate the future level of threats posed by ocean warming (as measured by year when 10x8DHW is reached) and acidification (measured by level of aragonite saturation state Ωar in 2050) on coral reefs and people who depend on them (chapter 3). Empirical evidence suggests that using DHW is coherent with experienced bleaching in the Great Barrier Reef in Australia, where only the northern part has been affected in past bleaching events (Hughes et al., 2017). This scenario, called representative concentration pathway 8.5 (RCP8.5) was developed in addition to three other scenarios (RCP2.6, RCP4.5 and RCP6) for the climate science community and especially the IPCC (van Vuuren et al., 2011). The RCP8.5 corresponds to a business-as-usual scenario of activities that generate GHG that would lead to a radiative forcing of 8.5W/m^2 (or ~1370 ppm CO_2eq) by 2100.

Many uncertainties arise when constructing composite indicators as the ones used in chapter 3, from selecting variables to aggregating them (Burgass et al., 2017). When dealing with climate change, two major uncertainties concern climate sensitivity (i.e. how the concentration of GHG in the atmosphere will influence temperature and acidification), and the political and economic decisions that will shape the future concentration of GHG. We conduct a sensitivity analysis to estimate different possible trajectories of ocean warming and acidification on coral reefs locations. The aim of this analysis is to understand if different emission scenarios would change the spatial distribution of these threats.

Similar sensitivity analysis has been done recently (Gattuso et al., 2015; van Hooidonk et al., 2016). We use the RCP at the other end of the spectrum in terms of future emissions, the RCP2.6, to encapsulate the full range of uncertainty linked to future GHG emissions. This RCP would lead to a radiative forcing of 2.6W/m^2 (~490 ppm CO_2eq) by 2100. Even though this scenario anticipates a dramatic reduction in CO_2 emissions, climate change under this scenario is still predicted to have negative impacts on coral reefs (Gattuso et al., 2015). By examining outcomes at both high and low projected levels of CO_2 emissions, we are able to reduce the uncertainty linked to projecting scenarios of GHG emissions and explore the potential benefits of implementing policies that will follow RCP2.6 emissions compared to a business-as-usual scenario. This has been done recently for warming globally (Hoegh-Guldberg et al., 2017; van Hooidonk et al., 2016) and for ocean acidification in the Florida Keys (Okazaki et al., 2017).

2. Methodology

We use the same methodology used to calculate and project indicators of DHW and OA impacts as in chapter 3. We map DHW and OA separately for the ocean located between 32° North and 32° South of latitude (a range that contains known coral reefs locations), and then calculate and map the sum of both indicators to give an indication of where combined threats from bleaching and OA will be the greatest. We focus specifically where coral reefs are located (Figure B.1.). To understand if the two climate scenarios result in different relative distributions of impacts associated with these combined threats, we also map the difference of the individual and combined indicator (RCP8.5-RCP2.6) on coral reefs locations.

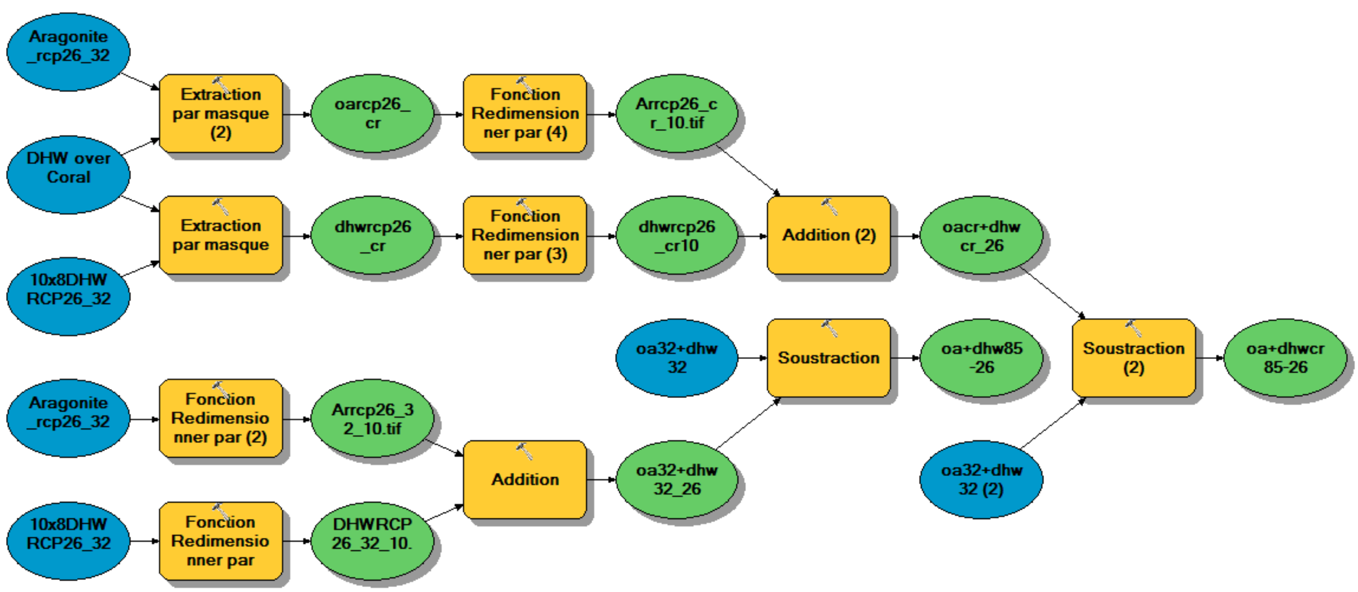


Figure B.1. Model to calculate OA+DHW with RCP2.6 over coral reefs; and over a segment of the ocean (32° latitude North, 32° latitude South) and reclassification on a 1-10 scale in the software ArcGIS©

3. Results

The timing (Figure B.2.) and the relative spatial distribution (Figure B.3.) for reaching 10x8DHW is similar whether we use RCP2.6 or RCP8.5. The area that will reach high level of bleaching threat is located in Southeast Asia and Micronesia in both emission scenarios. However, large areas of the ocean (between 32°N and 32°S) will not experience 10x8DHW by the end of the century when using the RCP2.6 scenario. These low-threats areas are located in the South Pacific, around Western Australia, and around the Middle East. The shades of colors show that 10x8DHW will occur later in the century for the RCP2.6 scenario. The mean year at which 10x8DHW will occur over coral reefs globally is 2051 with RCP2.6 compared to 2044 with RCP8.5 (Figure B.4.). This seven year difference is not large. It gives barely more time for societies and ecosystems to respond, and provides ecosystem services for seven more years. This result confirms the postulate made by Gattuso et al. (2015) that reaching the 2°C target (which corresponds to RCP2.6) will still have high impacts for coral reefs.

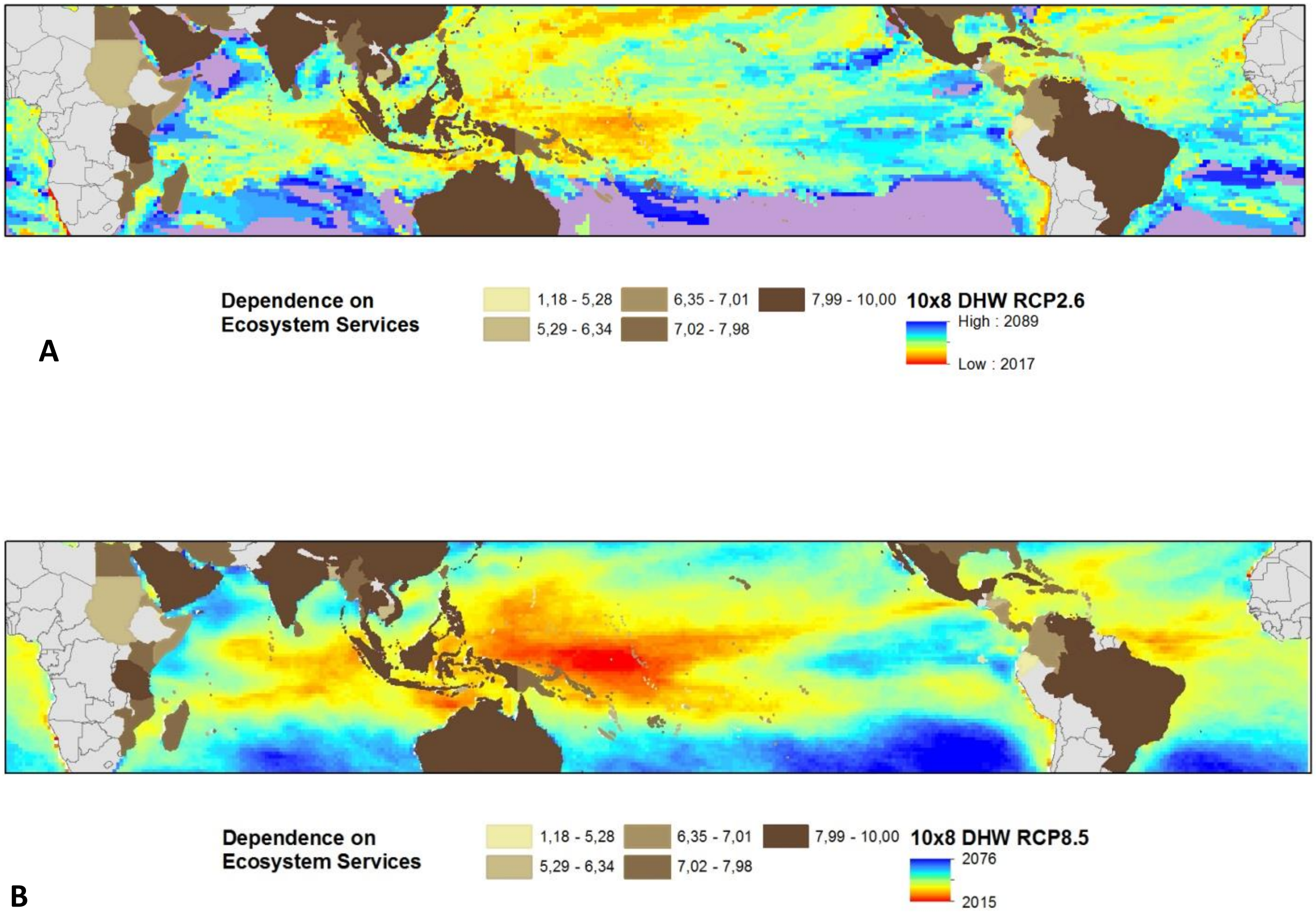


Figure B.2. Country-level dependence on ecosystem services, and future threats of coral bleaching as year when 10x8 DHW is reached under (A) RCP2.6 scenario and (B) RCP8.5 scenario. Areas that will not experience 10x8DHW during the century displayed in lilac/purple

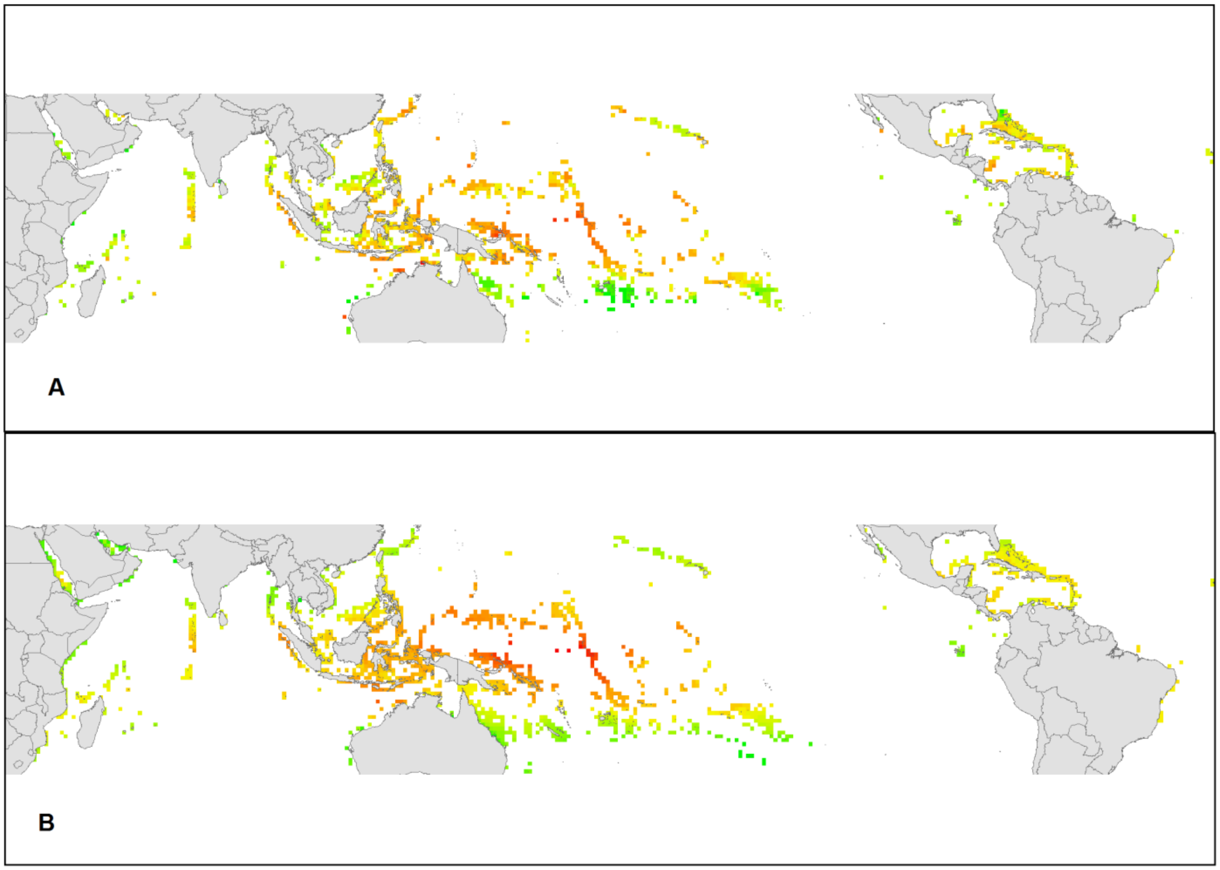


Figure B.3. Relative spatial distribution at coral reefs locations of the threat of bleaching (high – red; low – green) for (A) RCP2.6 and (B) RCP8.5 emission scenarios

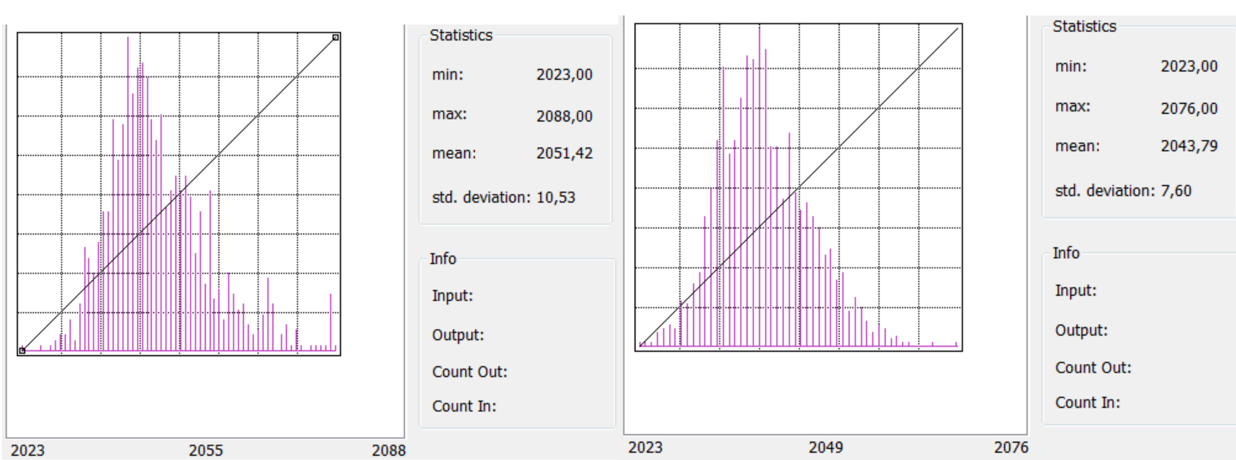


Figure B.4. Histograms of distribution of values over coral reefs worldwide for 10x8DHW with RCP2.6 (left) and 10x8DHW with RCP8.5 (right). Y axis represents number of pixels (1 pixel is 0.5° by 0.5°). Figures are screenshots of raw outputs taken in ArcGIS©

For ocean acidification, the analysis with RCP2.6 was not done in regions where data availability was poor (Figure B.5.). The notable difference for OA is a higher value of aragonite saturation state (so a lower impact) on the Eastern and South Pacific ocean provinces in the RCP2.6 scenario. The average Ωar at coral reefs locations in 2050 is 3.76 with RCP2.6 compared to 3.39 in 2050 with the RCP8.5 scenario (Figure B.6.). This 0.37 difference in averages can mean a significant marginal benefit for coral calcification and growth considering a linear decrease in calcification of 15% per unit of Ωar (Chan and Connolly, 2013). This would mean the calcification rate would be 5.5% higher on average in year 2050 in a world with lower carbon emissions (RCP2.6 compared to RCP8.5). The spatial distribution of OA is similar in both scenarios (Figure B.7.).

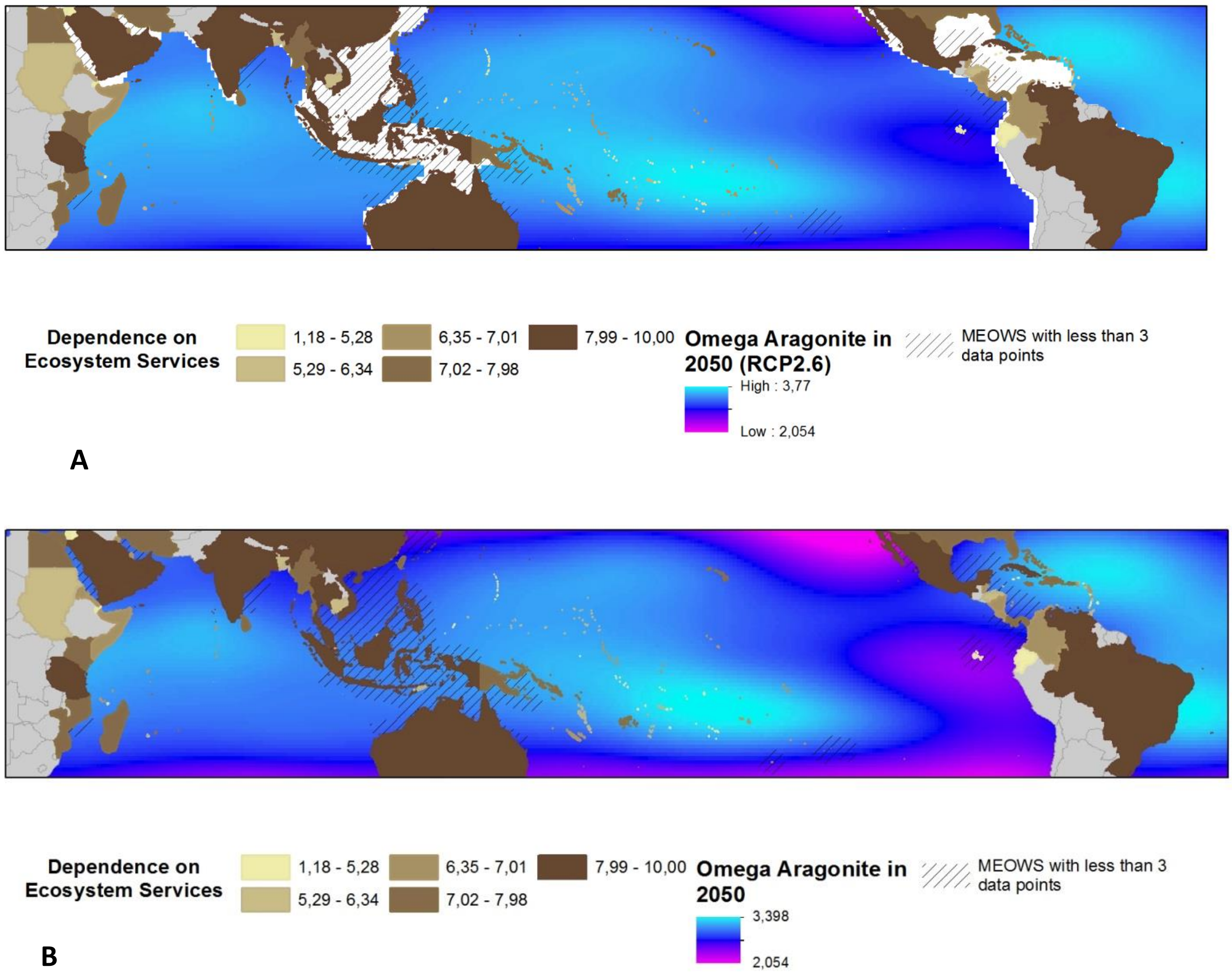


Figure B.5. Country-level dependence on ecosystem services, and future risk of ocean acidification as omega aragonite level in 2050 using (A) RCP2.6 scenario and (B) RCP8.5 scenario.

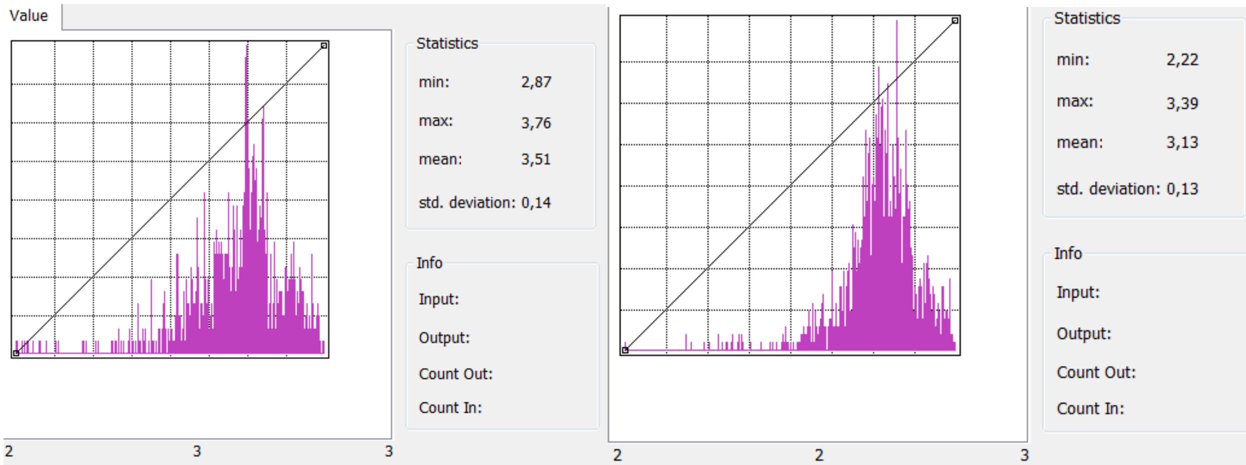


Figure B.6. Histograms of distribution of values over coral reefs worldwide for aragonite saturation state with RCP2.6 (left) and with RCP8.5 (right). Y axis represents number of pixels (1 pixel is .5° by .5°). Figures are screenshots of raw outputs taken in ArcGIS©

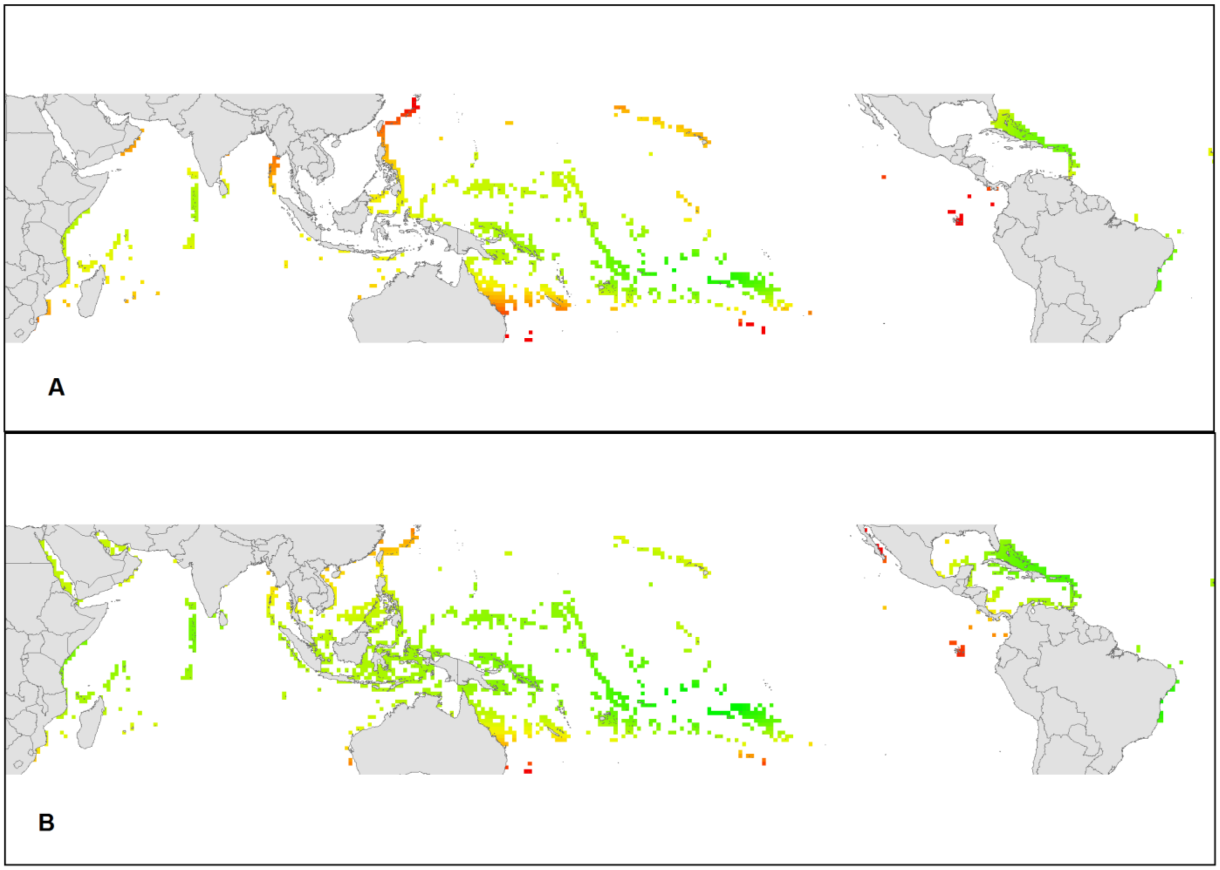


Figure B.7. Relative spatial distribution at coral reefs locations of the threat of OA (high – red; low – green) for (A) RCP2.6 and (B) RCP8.5 emission scenarios

When combining the threats of bleaching and OA under RCP2.6, the number of data points is low (Figure B.8.). This is due to the combination of the facts that several areas do not reach 10x8DHW under this scenario, and that many areas do not have data for OA, notably the Gulf of Mexico and the South China sea. This therefore skews the relative spatial distribution of combined threats towards high values (Figure B.8). It appears that the onset of potential coral loss is more evenly distributed with RCP2.6 compared to RCP8.5, but this may be because of this loss of data.

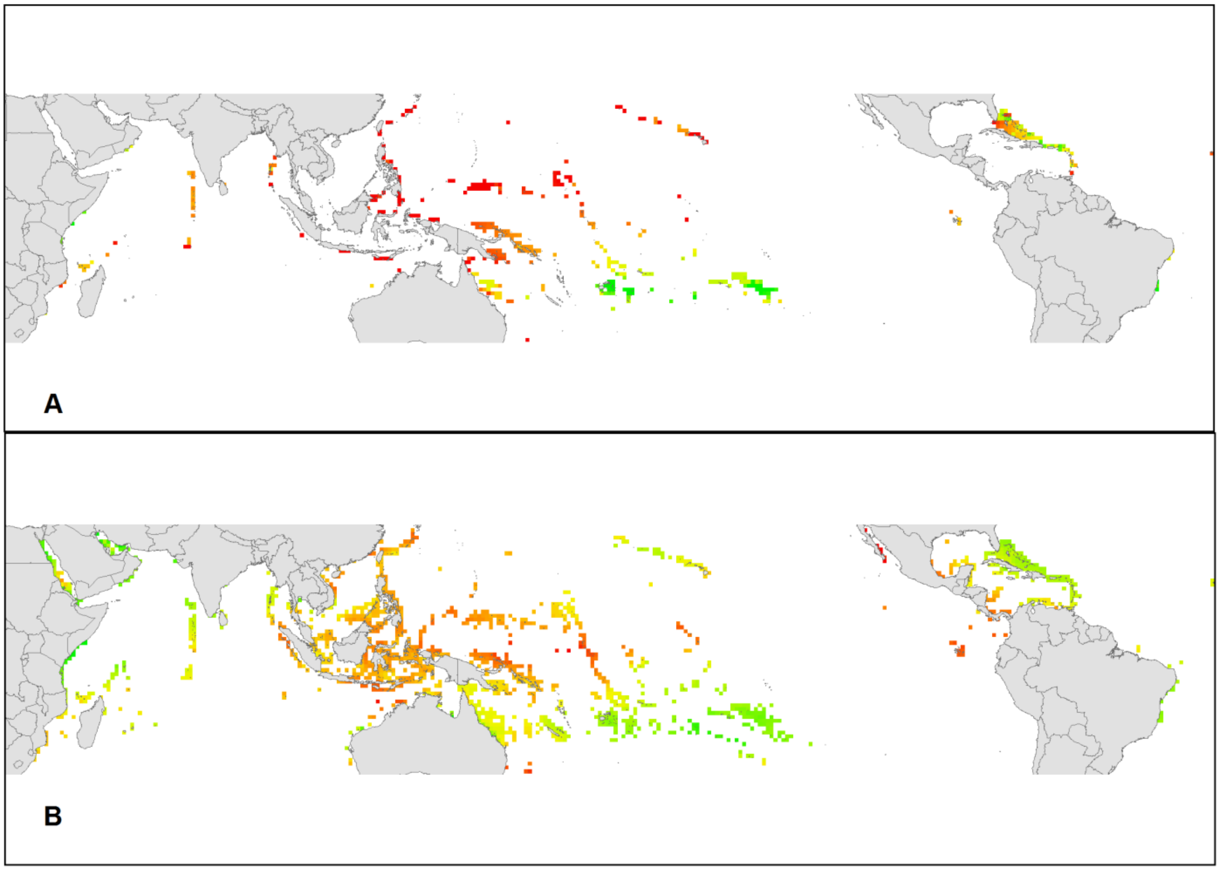


Figure B.8. Relative spatial distribution at coral reefs locations of the combined threats of bleaching and OA (high – red ; low – green) for (A) RCP2.6 and (B) RCP8.5 emission scenarios

4. Discussion

We show that RCP2.6 delays slightly the impacts of ocean warming and acidification compared to RCP8.5, but the relative spatial distribution and the timing of these threats remain similar. Our results for warming are similar to the ones found in van Hooidonk et al. (2016) that find an 11 year delay on average with RCP4.5 instead of RCP8.5. The difference in our results and theirs may be due to the fact that we measure the change in averages between the two scenarios while they measure the average change between the two scenarios.

Given the similarities in results across the two RCPs, it is important to emphasize the limited role of mitigation strategies for coral reefs in the short to medium terms (Frieler et al., 2012). In the long term, aggressive reduction in GHG could have significant positive impacts for coral reefs during the second half of this century (Schleussner et al., 2016).This sensitivity analysis validates the results of our evaluation in chapter 3 regarding the spatial distribution of the threats posed by ocean warming and acidification on coral reefs and people.

Other uncertainties exist and have not been considered here (Figure B.9.). In addition to uncertainties linked to scenarios, models have built in uncertainties linked to their structure, internal variability, and choice of parametrization (Payne et al., 2016). We assume that the impacts of warming and acidification are additive, and that they are equally important. These two assumptions are uncertain (chapter 2). Some studies have found synergistic effects between acidification and warming on coral reefs health. Others have found antagonistic relationships. In addition, it seems that for the moment warming is the primary driver of coral degradation, but changes in OA may lead to detrimental effects in the near future.

Uncertainties also exist regarding how these changes in environmental conditions will affect coral reefs ecosystems (Pandolfi, 2015). There will be some winners and losers (Hughes et al., 2017), and it is hard to predict which species composition will dominate under climate change (Horwitz et al., 2017). Feedbacks between different effects also make the system's responses more complex. For instance, ocean warming may exacerbate the adverse effects of diseases (Maynard et al., 2015b) but ocean acidification may lower disease virulence (Muller et al., 2017). Some species may also acclimate and adapt to future environmental conditions, even though the time scale given to them to do so is very rapid. Then, how these changes in the ecosystems will affect the provision of ecosystem services is also uncertain. How long after mortality will coral structure still provide coastal protection and habitat for fish (Rogers et al., 2015)? Finally, how human populations will respond in terms of policy and management decisions to deal with these issues is also uncertain. Do they perceive the risks (D. Biggs et al., 2015)? What are the barriers and limits to action (Evans et al., 2016)? Do they have the capacity to act (Cinner et al., 2016a)?

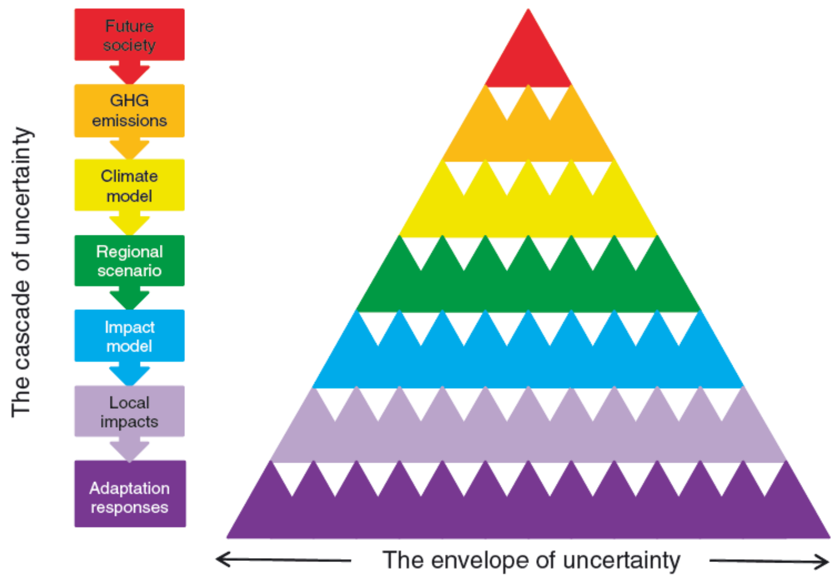


Figure B.9. Envelope of uncertainty to climate change, taken from Wilby and Dessai, (2010)

The marginal benefits for coral reefs of reaching the 2°C global target for climate mitigation compared to a business-as-usual scenario and the uncertainty of the potential impacts on coral reefs and people is not an excuse to delay action since a number of ways exist to deal with these factors (Hallegatte, 2009). We stress that more attention has to be given to adaptation strategies (Chapter 4).

Annex C. Comprehensive discussion of management strategies found in the systematic literature review

1 Mitigate

a. Limiting CO_2

Reducing greenhouse gases, and especially CO_2, is the first response to the impacts of GEC on coral reefs (Billé et al., 2013; Gattuso et al., 2015). CO_2 is the GHG most important for coral reefs, since it contributes both to sea temperature rise and ocean acidification, while the other GHG only contribute to sea temperature rise. However, it is largely outside the capacity and the mandate of coral reefs managers and local decision-makers. Several big emitters, including first Australia, the United States, but also China and Japan are obtaining benefits from coral reefs and have the capacity to reduce global levels of CO_2 emissions and the political power to influence climate negotiations. There are several ways to limit CO_2 by either reducing its emissions from polluting industries and change in land-use, or by directly removing it from the atmosphere. Carbon sequestration in marine and coastal ecosystems such as mangroves and seagrasses also has the potential to remove large quantities of CO_2 from the atmosphere. Other innovative strategies exist to sequester more carbon into the ocean through increasing the storage life of CO_2 in the ocean in the form of organic matter for instance (Rau et al., 2012).

b. Reducing the effects of other GH

Reducing the amount of GHG is important to prevent warming of the ocean that can trigger mass bleaching events (Adam et al., 2015; Billé et al., 2013). Reduction of greenhouse gases requires a global effort and is largely beyond the means of many coral reef dependent countries. The benefit of reducing GHG and the actions available to do so have been covered extensively in the literature (for example Harrould-Kolieb and Herr, 2012; Wolff et al., 2015). In addition, geoengineering strategies exist: solar radiation management (SRM) and carbon management. SRM does not address the root causes of the problem and creates and may actually lead to its increase by des-incentivizing the reduction of CO_2 emissions (Williamson and Bodle, 2016); therefore it is not an appropriate strategy for coral reefs ecosystems (Crabbe, 2009). Carbon dioxide removal addresses both thermal stress and ocean acidification, thus being an interesting avenue for future development, including ecosystem-based sequestration of CO_2 which is readily available and provides multiple ecosystem services benefits (e.g. Serafy et al. 2015).

c. Coastal pollution

Coastal pollution coming from the land is a major issue that needs to be dealt with to reduce pollution on coral reefs (Brodie and Pearson, 2016). Coastal pollution contributes to global threats to coral reefs. Watershed management is an important tool to reduce land-based coastal pollution (Keller et al., 2009; Mumby and Steneck, 2008). Sediment, sewage, and agricultural waste runoffs effects are diffuse sources of pollutants that can be best managed at the watershed level. Watershed management could be effective but a lot of concertation is needed to manage coastal pollution because of the high number of conflicting interests and the complexity of governing bodies and socio-ecological systems (Lebel, 2012). To prevent coastal pollution from the agricultural sector, a suite of management tools have been identified (Kroon et al., 2014). Fertilizer use can be reduced since nitrogen and phosphorous lead to eutrophication of coastal waters and modify the ocean pH (Anthony et al., 2015). Antisprawl land-use plans (Anthony et al., 2015; Kelly et al., 2011) and preventing deforestation would limit runoff to the sea (Maynard et al., 2015a). Infrastructure and impacts from the industry can be improved, including using settling ponds to deal with effluent, improving water treatment facilities, and using storm water surge prevention equipment for example (Ateweberhan et al., 2013; Kelly et al., 2011; Kroon et al., 2014). Coastal pollution may also come from marine activities. To reduce these impacts, it is possible to control ballast water (Burke et al., 2011; Mumby and Steneck, 2008), to improve waste management at ports, to modify shipping lanes, or to regulate oil and gas activities offshore (Burke et al., 2011).

Restoring wetlands and buying back agricultural land may also improve water quality surrounding reef areas (Burke et al., 2011; Kroon et al., 2014; Maynard et al., 2015a; Mumby and Steneck, 2008). Watershed restoration has been proposed as a solution to reduce erosion that contributes to coastal pollution (Shelton and Richmond, 2016). These techniques include the use of sediment traps, avoiding drainage and erosion, creating riparian buffers through ecological restoration, and stabilizing stream banks (Burke et al., 2011; Maynard et al., 2015a).

Mitigate	
Limiting CO_2	reduce CO_2 emissions
	remove CO_2 from atmosphere
	increase photosynthesis through ocean fertilization
	carbon sequestration in marine ecosystems

	increase storage life of organic matter in ocean
	store agricultural crop waste in ocean
Reducing the effects of GH	limit warming through reducing other GHG
	limit warming through Solar Radiation Management
	enforce existing federal emissions limits for pollutants such as nitrogen oxide and sulfur oxide
Coastal pollution	manage watershed
	improve management of catchment
	manage agriculture pollution
	reduce economic livestock numbers
	control tillage
	reduce fertilizer use
	manage livestock waste
	control grazing
	reduce point source pollution from industry and agriculture
	plan land-use against sprawl
	control coastal development activities
	reduce sedimentation
	use sediment traps
	avoid drainage and erosion
	direct effluent to settling ponds
	route discharge offshore
	avoid dredging and landfilling
	alter zoning provisions and general plans to safeguard waters
	improve water quality by limiting deforestation
	create coastal and riparian buffers
	improve onsite water treatment facilities
	stabilize stream banks
	restore vegetation at land-water intersections
	control transport such as sediment trapping dams
	reduce industrial pollution
	upgrade sewage treatment
	reduce runoff from mines
	monitor and limit precipitation runoff and associated pollutants
	prevent storm water surge with holding tanks
	treat and control ballast water
	improve waste management at ports and marinas
	regulate and prevent access to offshore oil and gas activities
	designate safe shipping lanes

2. Protect

a. Reduce local stressors to improve resilience

The resilience of coral reefs is determined by the amount of local and global factors that threaten them (Scheffer, 2015). Reducing local stressors is essential to improve the resilience of coastal ecosystems and allow the continued provision of ecosystem services under climate change. Coastal pollution has already been addressed in the mitigation section, but other local threats can be managed, including fishing, recreation, trade in reefs products, and biological threats (e.g. starfish and invasive species).

Reducing fishing pressure could help delay the negative impacts of climate change and OA on reefs by improving their resilience (MacNeil et al., 2015). Large herbivorous fish, particularly grazers such as parrotfish are important to maintain resilience and promote the recovery of coral reefs after disturbances (Bozec et al., 2016; Hughes et al., 2007; McClanahan et al., 2009). Reducing the fishing pressure on herbivores is one of the most commonly cited measures to protect coral reefs (Anthony et al., 2015; Billé et al., 2013; Graham et al., 2013; MacNeil et al., 2010; Maynard et al., 2015a; Mcleod et al., 2013; Rogers et al., 2015), a view that is shared by MPA managers (Hopkins et al., 2016). Other fishing restrictions include stopping destructive fishing practices (Anthony et al., 2015; Ateweberhan et al., 2013), and decreasing commercial and recreational efforts globally (Anthony et al., 2015; Ateweberhan et al., 2013; Rau et al., 2012). Actions can be taken on fishing gears by banning gear that targets ecologically important species, restricting the use of some gears, or encouraging the use of alternative gears to divert effort (Bozec et al., 2016; Graham et al., 2013; MacNeil et al., 2015, 2010). Finally, measures such as species restriction or access restriction may be useful to improve the resilience of the reefs (MacNeil et al., 2015). Fishing restrictions could also be timed after disturbances, where the abundance of large fish is critical for the recovery of reef systems (Graham et al., 2013).

Other stressors have to be taken into account to maintain and improve the resilience of coral reefs. Biological threats including Crown-of-Thorn Starfish (CoTS) can be managed (Anthony et al., 2015). Invasive species, including lionfish and invertebrates may benefit from climate change and disturb ecosystem functioning. Therefore they need to be controlled, for instance through culling efforts (Côté and Green, 2012; Grieve et al., 2016; Przeslawski et al., 2008). Coral diseases are rising and management tools to deal with this issue need to be developed (Page et al., 2009), including promotion of fish richness that seem to contribute to reduce the occurrence of diseases (Lamb et al., 2016). Regulations can be implemented to reduce trade in reef products and to prevent using reef materials for construction (Burke et al., 2011).

b. Protection of ecosystems and associated ecosystems

Marine Protected Areas (MPAs), specifically no-take marine reserves and networks of MPAs have been identified as a strategic tool to enhance the resilience of coral reefs to climate change (Hughes et al., 2003). The effectiveness of these measures to protect coral reefs against global environmental change is debated. MPAs have not been shown to protect coral reefs against the effect of rising temperature (Selig et al., 2012), but are linked to multiple factors of reefs resilience. Empirical evidence suggest that no-take reserves, while increasing fish abundance, does not improve the resilience of coral reefs or coral cover (Toth et al., 2014). From (runo and Valdivia, (2016): "This interpretation is consistent with numerous local, regional, and global studies indicating that local protection, does not measurably lessen the impacts of ocean warming on coral populations". However, their importance may lie in their improvement of resilience and therefore on the recovery of coral reefs after disturbances such as bleaching events (Hughes et al., 2017; West and Salm, 2003). No-take marine reserves have been showed to increase coral cover in some parts of the world (Magdaong et al., 2014) and to mitigate the impacts of other external stressors such as floods (Olds et al., 2014) and diseases thanks to the prevention of physical damage from fishing (Lamb et al., 2015).

Protecting associated ecosystems can increase the resilience of coral reefs to CO_2 (Ateweberhan et al., 2013; Burke et al., 2011; Green et al., 2014; Keller et al., 2009; Mcleod et al., 2013; Mumby and Steneck, 2008). These ecosystems include mangroves and seagrasses. Protecting associated ecosystems may yield co-benefits in terms of carbon sequestration and other ecosystem services that will be important in the face of climate change, including coastal protection services by mangroves (Das and Vincent, 2009). Mangroves provide shoreline protection and important habitat for commercially and nutritionally important fish species. To protect associated ecosystems including mangrove and seagrass, these ecosystems should be included in the design of coral reefs MPAs to form a coherent ecological unit (Keller et al., 2009). Mangrove ecosystems associated with coral reefs may help reduce the impact of climate change and OA on coral reefs. For instance, mangroves reduce nutrients suspended in the water column and export dissolve inorganic carbon that buffer the effect of OA on coral reefs locally (Andersson, 2015 ; Sippo et al., 2016).

Networks of MPAs are an important strategy, and should be combined with other management efforts to be effective at reducing CO_2 threats on coral reefs by promoting recovery after disturbances as well as allowing for coral migration towards less exposed areas (Keller et al., 2009). The capacity of countries to effectively design, implement, monitor and enforce these types of policies varies across the globe (Mora et al., 2009). There are challenges to implement management measures. MPAs are costly to maintain and may encounter resistance from local populations over conflicts of use. Similarly, fishing restrictions may be harmful for local communities who depend on fishing for subsistence. In order to protect mangroves and other associated ecosystems, it may be desirable to link terrestrial and marine protected areas (Burke et al., 2011). To protect marine and land areas Integrated Coastal Zone Management (ICZM) can be used in coordination with marine protected areas (Rau et al., 2012). Integration of MPAs with coastal zone management is important to coordinate action on reducing both land and marine-based local anthropogenic threats to the resilience of coral reefs.

c. Protecting ecological refugia

Climate change and ocean acidification will be a major driver of reef degradation in the future (Cinner et al., 2016b; Chapter 2). Some areas will be less affected by these effects and can be considered "ecological refugia" that may be sources for coral reefs to thrive again when climate change has been addressed (Chollett and Mumby, 2013). A preliminary requirement for this design feature is to identify ecological connections between habitats, and then protecting them to ensure recruitment in the future (Keller et al., 2009). However, these refugia may ultimately be inadequate to sustain healthy reef ecosystems (Hoegh-Guldberg, 2014). It is therefore argued that places where reefs are less vulnerable to climate change should be protected (Anthony et al., 2015; Mcleod et al., 2013). Refugia are found where thermal stress and where ocean acidification are projected to be lower (Magris et al., 2015; Mumby and Steneck, 2008; chapter 3). Modelling approaches have been used to attempt to forecast suitability of refugia for coral reefs under higher SST (Chollett and Mumby, 2013; Holstein et al., 2016). Refugia can also be found where corals are more resistant and resilient to thermal stress and ocean acidification (Knudby et al., 2013). Corals in these sites already experience large variations in temperature or acidity conditions, or have the genetic diversity to adapt to future conditions (Billé et al., 2013; Green et al., 2014; Keller et al., 2009). Finally, refugia could be places where other stress are at low levels, for instance places with low cyclone activity (Mcleod et al., 2013), or where local human impacts can be managed well (Harris et al., 2017).

Protect	
Reduce local stressors to improve resilience	reduce fishing pressure
	reduce fishing of herbivores
	manage pressures from recreational use
	stop destructive fishing practices

	protect food provision for organisms
	close fisheries
	restrict or modify fishing gear used
	restrict species fished
	restrict access to fisheries
	control Crown-of-Thorns Starfish (CoTS) at local scales
	protect CoTS predators
	tactical CoTS control
	monitor and control coral diseases
	manage invasive species such as lionfish
	regulate trade in reef products internationally
	don't obtain construction materials from mining CR
Protection of ecosystems	establish Marine Protected Areas (MPAs)
	enhance reef fish biomass and diversity across depth zones through no-take marine reserves
	replicate habitat types in multiple areas to spread risks
	Include whole ecological units (e.g., offshore reefs) in marine reserves
	ensure that the full breadth of habitat types is protected (e.g., fringing reef, fore reef, back reef, patch reef)
	identify and protect ecologically significant areas such as nursery grounds, spawning grounds, and areas of high species diversity
	protect mesophotic reefs
	maximize connectivity within networks of source and sink reefs
	develop networks of marine reserves that protect diverse habitats and maintain connectivity among reefs
	Include/link MPAs with other ecosystems such as seagrass beds and mangroves
	link terrestrial and coastal MPAs
	integrate MPAs with coastal zone management to control both marine- and land-based threats
Protecting ecological refugia	identify the sites with high or low resilience that are currently outside established no-take MPAs
	identify and protect areas that appear to be resistant to climate change effects or to recover from climate-induced disturbances
	prioritize areas where local threats can be effectively managed
	prioritize new MPAs based on their historical and projected thermal stress profile
	protect locally adapted species
	protect of reefs with low exposure from storms
	protect natural refugia (reefs less exposed, less sensitive, and with more adaptive capacity)
	protect important ecosystem components to combat locally intensified acidification

3. Repair

a. Restoring degraded ecosystems

Coral reefs restoration has been promoted to re-build coral cover in degraded areas. Restoration of coral reefs can take several forms (dela Cruz et al., 2015). Some techniques often called reef gardening involve the cultivation of coral fragments in nurseries and their transplantation in the environment (Rinkevich, 2014). Restoring coral reefs ecosystems may involve physically removing algae, to attract herbivorous fish that are important for the good health of the ecosystem (Adam et al., 2015). Restoration of reefs is essential to break feedbacks that currently keep reefs in degraded states (Adam et al., 2015). Engineering solutions have been proposed, such as translocating corals that are the most adapted to thermal stress within a basin or across basins, and constructing artificial refugees (Coles and Riegl, 2013). Active restoration of corals and reef habitats can be effective if ecological principles are followed, and coral translocation techniques are emerging to do so (Maynard et al., 2015a; Mumby and Anthony, 2015; Rogers et al., 2015). The effectiveness of coral restoration through transplantation will depend on the goal of restoration and the choice of species transplanted (Lirman et al., 2014; Muko and Iwasa, 2011). Inversely, restoring CR without managing for external sources of disturbances such as sedimentation may not be effective (Adam et al., 2015). Restoration provides win-win situations where other ecosystem services are provided by the restoration, including GHG sequestration, coastal protection, and improving the resilience of CR ecosystems.

One of the main barriers of restoration is its cost (Bayraktarov et al., 2016). Restoring coral reefs using transplantation may be feasible, but the cost-effectiveness of this strategy needs to be assessed (Guest et al., 2014). Nonetheless, the cost of restoration is less expensive in developing countries, and markets for ecosystem services could finance the development of reef restoration (Rinkevich, 2015). A clear limit of coral reefs restoration is that the environment in which reefs are restored is still warming and acidifying, so that the underlying threats are still present. Until global threats are dealt with, reefs restoration may be a waste of resources outside of scientific research.

Associated ecosystems, including mangroves and seagrasses, can also be restored to promote biodiversity and resilience of reef systems. While coral reefs and seagrasses are expensive to restore, mangrove restoration is cheaper (Bayraktarov et al., 2016). These associated ecosystems provide important ecosystem function such as fish nurseries. They may also locally mitigate the effects of acidification (Camp et al., 2016). Restoration can be conducted upstream with riparian vegetation and wetlands to reduce local threats such as sedimentation and turbidity to coral reefs

(Shelton and Richmond, 2016). These can involve coastal floodplain and land vegetation restoration or large dam removal (Kroon et al., 2014).

b. Assist evolution

One last resort strategy is human-assisted evolution for coral reefs to be able to cope with the increasing threats of thermal stress and ocean acidification (van Oppen et al., 2015). These methods consist in selectively breeding resistant organisms (Billé et al., 2013; Rau et al., 2012; van Oppen et al., 2015), using genetic engineering and protective culturing (Rau et al., 2012). Assisting evolution can be done through induced acclimatization, modification of microbial symbiont community, and evolution of symbiodinium (van Oppen et al., 2015). Ex situ methods include coral nurseries and creating gene banks and can prevent the permanent loss of genetic diversity and help continuing coral reefs in the future. Exposing corals to future environmental conditions in laboratory settings can improve trans-generational acclimation and adaptation in some corals (Chakravarti et al., 2016).

c. Add alkaline material & local engineering to mitigate CO_2 effects

Several options exist to buffer the effect of ocean acidification on coral reefs locally. Artificial ocean alkalinization, the addition of chemicals and alkaline materials like lime and seashells to the water have been proposed (Billé et al., 2013; Burke et al., 2011; Gattuso et al., 2015; Rau et al., 2012) and may buy some time before ocean acidification impacts coral reefs (Feng (冯玉铭) et al., 2016). Alternatively, waste carbon dioxide can be converted to ocean alkalinity (Rau et al., 2012). Novel engineering techniques to locally increase pH to delay the negative impacts of ocean acidification are starting to emerge, such as bubble stripping (Koweek et al., 2016) or installing seaweed farms in close proximity to coral reefs to remove carbon from the ocean (Mongin et al., 2016a). Engineering solutions proposed to buffer the increase in ocean temperature include artificial shading and artificial upwelling to cool the sea temperature around corals (Rau et al., 2012), and low-voltage direct current to improve coral resistance to environmental change (Rau et al., 2012).

Repair	
Local engineering	install low-voltage direct current
	disseminate shell material
	reduce acidity with chemicals
	add alkaline material, lime and base minerals to increase local pH
	convert waste carbon dioxide to ocean alkalinity
	restore ecosystems (seaweed, seagrass beds and mangroves) to buffer local acidification
	introduce CO_2 bubble stripping
	use artificial shading
	use artificial upwelling
Assist evolution	selectively breed lines of resistant organisms
	actively "thoughen" species
	use genetic manipulations techniques
	use protective culturing techniques
	create gene banks
	use induce acclimatization techniques
	modify the microbial symbiont community
	encourage evolution of symbiodinium
	other ex situ methods of preventing permanent loss of genetic diversity
Restore degraded ecosystems	restore coral and reef habitat
	restore associated ecosystems: estuaries, oyster reefs, seaweed, seagrass beds and mangroves
	translocate coral
	construct artificial refuges
	increase vegetation cover
	remove large dam
	restore coastal floodplains
	restore land vegetation
	restore wetlands

4. Adapt

a. Adapt to the loss of coastal protection

The destruction of coral reefs because of climate change, OA, and local stressors will hamper the role of natural barrier that coral reefs have, thus increasing erosion and the impact of extreme events on the coastlines (Ferrario et al., 2014; Sheppard et al., 2005). Combining with the other effects of climate change, sea-level rise and increasing extreme weather events (Cinner et al., 2016), coastal populations will have to adapt to the loss of coastal protection provided by reefs. First, soft options exist, such as local planning for storm preparedness and recovery (Anthony et al., 2015). Forecasting and response capabilities to coastal disasters can be improved with prevention and management systems (Cai et al., 2015). Hard solutions, like coastal infrastructure for flood protection, can compensate the loss of natural coastal protection (Cai et al., 2015). In case of situations where conditions do not allow for coastline protection, compensatory measures can be taken such as investments in social protection and alternative livelihoods (Anthony et al., 2015).

b. Adapt to the loss of livelihood in fishing and tourism

Fishing and tourism are two of the most important economic activities linked to coral reefs worldwide. Human populations who dependent on reef fish for their livelihood will have to adapt (Teh et al., 2013). Altered human behavior in fishing areas can improve fish biomass and diversity (Graham et al., 2013). Changing practices can involve changing fishing gear towards the ones less impacted by coral bleaching such as hand lines (Cinner et al., 2013). Fishing effort can shift from traditional stocks towards underexploited ones or towards aquaculture (MacNeil et al., 2010). Technical and financial strategies to cope with the impacts of GEC on reef fish exist, including capital investment in fisheries (MacNeil et al., 2010), expansion of fair trade and green markets (Hughes et al., 2012a), or decreasing exports of reef fishes (Mumby and Steneck, 2008). The seafood supply chain can adapt on several fronts including fuel efficiency, industry structure and regulations, or breeding programs (Weatherdon et al., 2016). In case of severe impacts, programs to deal with reef-fisheries collapse can be implemented (MacNeil et al., 2010). Supporting alternative livelihood is commonly referenced as an adaptation strategy in the literature (Anthony et al., 2015; Cinner et al., 2013; MacNeil et al., 2010; Weatherdon et al., 2016), even though the effect of fisheries and aquaculture on food security is unclear (Béné et al., 2016). Alternative sources of protein from agriculture and aquaculture can be found (Hughes et al., 2012a). Infrastructure development in rural areas can be used to relocate communities that will be impacted by the loss reef fishes (Cinner et al., 2013). The tourism industry will also be impacted by the loss of coral reefs, and will need to adapt (Anthony et al., 2015), for instance through sustainable tourism practices (Burke et al., 2011).

c. Relocate activities, and migrate

The loss of ecosystem services will also weaken the economic network of coastal communities. Several actions can aim at improving the socio-economic situation of these communities. Because the loss of coral reefs will not be uniform across space and time, it may be feasible to relocate activities and species in areas less affected, for example where ocean acidification will be lower (Billé et al., 2013). International companies in the fishing and tourism sector could also relocate their activities (Weatherdon et al., 2016). Where impacts will be very high and people are very dependent on coral reefs, migration could be the only option in the future. In addition, some people may be displaced or will have to change activity because of the establishment of protected areas, and these people will need assistance to transition (Mumby and Steneck, 2008).

d. Ecosystem-based adaptation

While coral reefs ecosystems are under threat from climate change, in some cases reefs and associated ecosystems can be maintained to help humans adapt to the direct negative effects of climate change. These strategies are termed ecosystem-based adaptation or nature-based solutions to climate change (Jones et al., 2012). Protecting and restoring coastal habitats and managing coastal realignments are options to proactively plan for future conditions (Weatherdon et al., 2016). Coral reefs and mangroves have been shown to dissipate wave energy and thus protect coastlines (Villanoy et al., 2012). Planning mechanisms such as zoning can anticipate climate-related impacts such as sea-level rise to minimize them. In addition, the cost of coral reefs restoration may be less expensive than the cost of building coastal protection infrastructure so that it may be feasible and cost-effective to use coral restoration for ecosystem-based adaptation (Ferrario et al., 2014; Narayan et al., 2016).

Adapt	
Adapt to the loss of coastal protection	promote marine climate-disaster forecasting and response capability
	plan for preparedness and recovery locally
	install climate-related coastal disaster prevention and management systems
	build coastal infrastructure for flood protection and drainage
	invest in alternative livelihoods and social protection for those displaced because of habitat protection
	invest in insurance schemes
Adapt to the loss of livelihood from tourism and fisheries	work with fishers and tourism operators to help build resilience in their industries
	adapt revenue-generating activities such as fisheries and aquaculture to OA
	promote the use of gears less likely to be negatively impacted by coral bleaching (e.g. hand lines)
	shift target species from traditional stocks to new or

	underutilized ones, and to aquaculture
	capital investments in fisheries
	altered human behavior in fishing areas
	boost fair trade and green markets
	use fish-aggregation devices
	fishing training
	gear provision
	transitioning traditional to novel fisheries
	decrease international export of reef fishes
	adapt seafood supply chain (fuel efficiency, breeding programs, altered industry structure, simplified regulations)
	increase flexibility through alternative fisheries
	simplify regulations
	develop sustainable fisheries management plans
	improve income inequality and trade deficits to improve flexibility
	increase sources of protein and nutrient dense food
	increase availability and accessibility of alternative protein sources
	increase alternate protein sources through agriculture and aquaculture
	Increase incentives for nondestructive harvest of resource
	encourage and improve aquaculture
	diversify livelihoods in response to reduced production
	establish programs to deal with reef-fisheries collapse
	implement sustainable tourism
	Tourism outreach and stewardship
	support alternative livelihoods transitioning
	develop supplemental livelihood activities
	compensatory measures
	social protection
	migrate activities where OA is lower
	co-management
	Microcredit schemes
	support for community savings
	Eradication of corruption
	Support for economic growth
	Poverty alleviation plans and pro-poor growth policies
	boost financial, natural, and physical assets
	improve labor policies and practices to decrease inequalities
	infrastructure development in rural areas
	increase social mechanisms for sustainability
	use climate funding to reduce vulnerability of CR-dependent

	communities
Ecosystem based adaptation	use coastal ecosystems to protect asset
	Managing realignment of coastal ecosystems as they migrate landwards or poleward
	hybrid engineering structures can provide an integrated way of conserving ecosystems and ecosystem services
	maintaining species biodiversity
	restoring and maintaining coastal habitats
	maximizing ecosystem services in degraded reefs
	provision of artificial complexity
	coral restoration
	habitat migration
	integrated coastal management
Migration and displacement	migrate activities where OA and CC impacts are lower
	displacement linked to livelihood transitioning
	migrate activities
	relocate international investments
	relocate species
	conserve reefs ex-situ

5. Indirect strategies

a. Research and monitoring

The main objectives of the articles reviewed here are to understand the impacts of climate change, ocean acidification, and/or local stressors on coral reefs ecosystems, how their vulnerability and resilience will be influenced by such changes and how they will be affected in the future. In some cases, studies attempt to understand how these will impact society (e.g. Johnson and Welch, 2016). Climate change models can be important tools to provide information to decision-makers and managers. Several scientific articles discuss improving forecasting abilities to better manage for future conditions and to include more potential impacts such as diseases (Caldwell et al., 2016; Harvell et al., 2004). Future projections can help management and design of future MPAs to protect potential refugia (Chollett et al., 2014b; Magris et al., 2015). Monitoring is an essential management tool for ecosystems like coral reefs that are prone to phase shifts (Selkoe et al., 2015) and needs to integrate various tools such as remote sensing (Hedley et al., 2016), as well as field data on ecosystem health and resilience and socio-economic impacts (Zeller et al., 2016). Monitoring conditions can be used in adaptive management of coral reefs to improve their resilience (Ladd and Collado-Vides, 2013). Better collection of baseline ocean conditions (Strong et al., 2014), ecological conditions, and socio-economic routine collection data (Chapter 2, 3) is needed for future research and management success.

b. Capacity building

Managers, decision-makers, and stakeholders that have a footprint on coral reefs will not act if they are not aware of the problem. Raising awareness to a wide variety of stakeholders is a first step towards action. Communication can be done through scientific engagement with the public (Schuldt et al., 2016). Community engagement on climate change between researchers and local communities is building their capacity to respond to climate hazards (Leon et al., 2015). Direct engagement of scientists with managers, decision-makers, and other stakeholders such as fishing, tourism, and agriculture communities can improve their capacity to act and help change practices. For instance, there is a lack of understanding of adaptive management and adaptation by governments and MPA managers (Hopkins et al., 2016). Scientists can work with local communities that depend on fishing and tourism to develop adaptation and livelihood transitioning strategies (Anthony et al., 2015).

Governance regimes and institutions are very important to ensure the implementation and success of management strategies (Barnett et al., 2015; Cvitanovic et al., 2014). Collaboration between countries across different scales of governance can help build capacity where it is lacking (Kim, 2012). International agreements and treaties such as the Paris Agreement on climate change are foundations to ensure the implementation of management strategies to deal with the impacts of GEC on coral reefs and their ecosystem services. International scientific cooperation can also improve understanding and management of coral reefs to respond to future threats, especially ocean acidification (Strong et al., 2014).

Indirect	
Research and monitoring	develop climate models
	project changes in seawater chemistry
	observe, study, and assess climate change and ocean acidification
	coordinate domestic research and communication efforts with international programs to amplify attention to OA
	identify synergistic effects of multiple stressors
	extend research on impacts, dependence, resilience, and adaptation
	national and international funding in research and human capacity to understand the ecology
	funding in research and human capacity
	public participation in research
	conduct economic valuation
	continue developing a coordinated regional network of monitoring stations to map the vulnerability of coastal areas to OA
	collect data and create network systems for sharing for the management of environmental stressors
	monitoring state of ecosystem using indicators (and thresholds)
	establish ocean chemistry baseline
	standardize global monitoring on OA
	establish ecological baselines
	determine easy-to-measure biological indicators as proxies for ecosystem health
	determine species, habitat, and community sensitivity
	monitoring socio-economic state using indicators (and thresholds of poverty traps)
	measure and monitor changes the ocean's physical, chemical, and biological response
	monitoring near-shore systems
	extend monitoring to near-shore systems relevant to management jurisdictions
	monitor management of herbivore fishing
Capacity building	influence national emissions policies through education and awareness raising around climate change, land use and run-off
	public awareness
	educate local communities
	raise awareness of stakeholders of the tourism industry
	improve learning capabilities of government
	communicate
	train and build capacity of stakeholders
	launch public education programs around OA and its causes to foster public awareness and stakeholder engagement
	build capacity of local communities and regional government bodies

	support for community initiatives/organizations
	support decision makers
	involve local stakeholders in decision-making
	support community initiatives/organizations
	educate local population and participation in research
	improve learning capabilities of government and population
	tourism outreach and stewardship
	strengthening of community-based enforcement of regulations
	foster concerted action among multiple local jurisdictions (address erosion within an entire watershed)
	strengthen cooperation between local, state, and federal governments for water catchment management
	requiring integrated governance of factors affecting reefs (e.g. fisheries, development, agriculture)
	introduce regional agreements and cooperations
	establish integrated governance structures for coastal management that extend from the watershed to the reef system
	leverage existing coalitions or form new task forces to facilitate multistakeholder solutions for regional OA issues
	create a new multilateral environmental agreement on OA to fill regulatory gap
	coordinated action at local, regional, global levels
	facilitate multistakeholder solutions
	increase international collaboration on OA
	international cooperation in marine affairs to improve fisheries management and sustainable marine aquaculture
	ratify and enforce UNCLOS, CITES, MARPOL, UNFCCC
	expansion of the current REDD+ scheme to include vegetative coastal ecosystems
	Integrate the threat of OA into existing and new climate change programs
	include the impact of permitting actions on OA when conducting environmental impact assessments
	establishing multi-lateral fisheries agreements
	enforce existing regulatory measures
	climate funding to reduce vulnerability
	change governance systems towards co-management

Annex D. Equations used in Web of Science and Scopus on the period 1990-2016 to retrieve peer reviewed research articles on coral reefs in particular and on climate change in general

1 Four equations were used in Web of Science and Scopus on the period 1990-2016 to retrieve peer reviewed research articles for coral reefs:

Equation 1:

("chang* climat" OR "climat* chang*" OR "climat* impact*" OR "ocean* acidification" OR "ocean warming")) *AND* TOPIC: ("coral* reef*" OR coral OR corals OR reef*) *AND* TOPIC: (mitigat* OR "manage* option*" OR "manage* action*")

Equation 2:

("chang* climat" OR "climat* chang*" OR "climat* impact*" OR "ocean* acidification" OR "ocean warming") *AND* TOPIC: ("coral* reef*" OR coral OR corals OR reef*) *AND* TOPIC: (polic* OR "threat* manag*" OR "impact* manag*" OR mitigat* OR "conserv* manag*" OR "vulnerab* manag*")

Equation 3:

("climat* chang*" OR "climat* impact*" OR "ocean* acidification" OR "ocean warming") *AND* TOPIC: ("coral* reef*" OR coral* OR reef*) *AND* TOPIC: (polic* OR "threat* manag*" OR "impact* manag*" OR mitigat* OR "conserv* manag*" OR "vulnerab* manag*" OR restorat*)

Equation 4:

("chang* climat" OR "climat* chang*" OR "climat* impact*" OR "ocean* acidification" OR "ocean warming") *AND* TOPIC: ("coral* reef*" OR coral OR corals OR reef*) *AND* TOPIC: (recovery OR mitigat* OR manag* OR monitor* OR stop*) *AND* TOPIC: (framework OR tool* OR plan OR plans OR planning OR model OR models OR "key* driver*" OR "environ* driver*" OR protocol*)

2. **Four equations were used in Web of Science and Scopus on the period 1990-2016 to retrieve peer reviewed research articles for the whole field of climate change:**

Equation 1:

("chang* climat" OR "climat* chang*" OR "climat* impact*" OR "ocean* acidification" OR "ocean warming")) *AND* TOPIC: (mitigat* OR "manage* option*" OR "manage* action*")

Equation 2:

("chang* climat" OR "climat* chang*" OR "climat* impact*" OR "ocean* acidification" OR "ocean warming") *AND* TOPIC: (polic* OR "threat* manag*" OR "impact* manag*" OR mitigat* OR "conserv* manag*" OR "vulnerab* manag*")

Equation 3:

("climat* chang*" OR "climat* impact*" OR "ocean* acidification" OR "ocean warming") *AND* TOPIC: (polic* OR "threat* manag*" OR "impact* manag*" OR mitigat* OR "conserv* manag*" OR "vulnerab* manag*" OR restorat*)

Equation 4:

("chang* climat" OR "climat* chang*" OR "climat* impact*" OR "ocean* acidification" OR "ocean warming") *AND* TOPIC: (recovery OR mitigat* OR manag* OR monitor* OR stop*) *AND* TOPIC: (framework OR tool* OR plan OR plans OR planning OR model OR models OR "key* driver*" OR "environ* driver*" OR protocol*)

Annex E. Classification of research articles per journals. Biology and conservation focus (N), Societal focus (H), or Pluri-disciplinary (P)

Journal name	# articles	Category
Plos One	57	P
Coral Reefs	34	N
Global Change Biology	30	N
Marine Policy	28	H
Marine Pollution Bulletin	26	N
Ocean & Coastal Management	20	H
Estuarine Coastal And Shelf Science	18	N
Marine Ecology Progress Series	16	N
Nature Climate Change	15	P
Conservation Biology	15	P
Coastal Management	13	H
Global Environmental Change	11	H
Climatic Change	11	P
Ecological Modelling	10	N
Marine and Freshwater Research	10	N

Annex F. Statistical analyses and exploration of the systematic literature review on management strategies to deal with the effects of climate change on coral reefs

The systematic literature review of action-oriented research articles dealing with GEC and coral reefs generated questions that could be partially answered with statistical analyses. These questions are:

1) Do global bleaching events have an impact on the number of publications through time?

2) Do proportions of the 4 categories of management strategies found in research articles change through time?

3) Is the distribution of research in countries across the globe influenced by GDP, coral extent, and level of ecosystem services?

1 Do global bleaching events have an impact on the number of publications through time?

The data suggests a rapid increase in the number of publications around the year 2005 until present. What could explain the sudden and very rapid rise in the number of publications on this topic? Here, two hypotheses are formulated: (i) the trend follows the global trend in increasing research on climate change because this is an important environmental and societal issue and because scientists are more and more expected to publish. Also, (ii) the increasing worry about global bleaching events that have been widely reported by the media and that troubles researchers may have encouraged increased allocation of resources on this area of research. To test these two hypotheses, we first plot the evolution in publications on climate change (CC) in general with publications on coral reefs (CR) and compare with another specific subject for control, here glaciers (Figure F.1.).

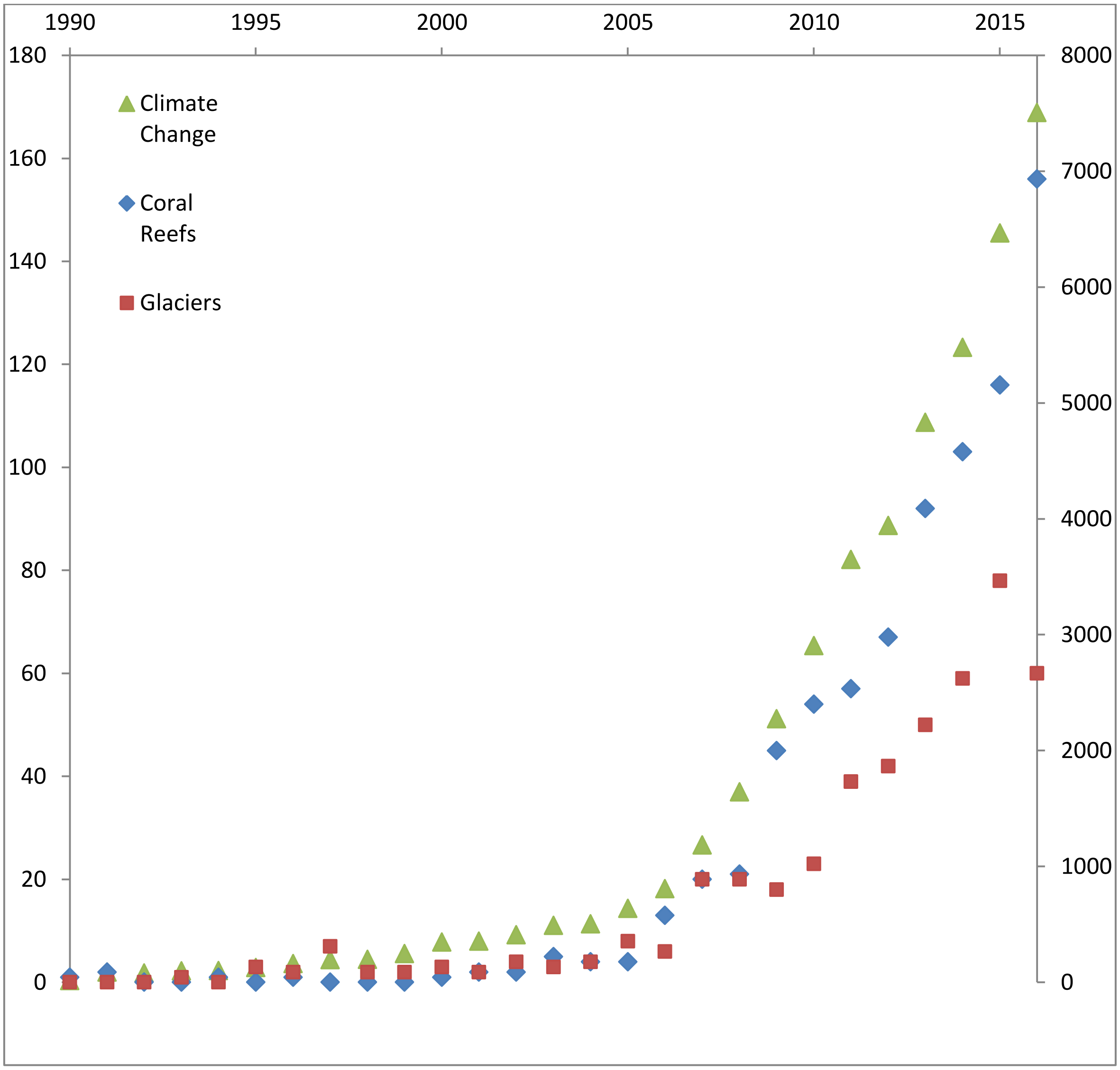


Figure F.1. Number of research articles on climate change in general, on coral reefs, and on glaciers published between 1990 and 2016. Climate change scale on the right, coral reefs and glaciers scale on the left

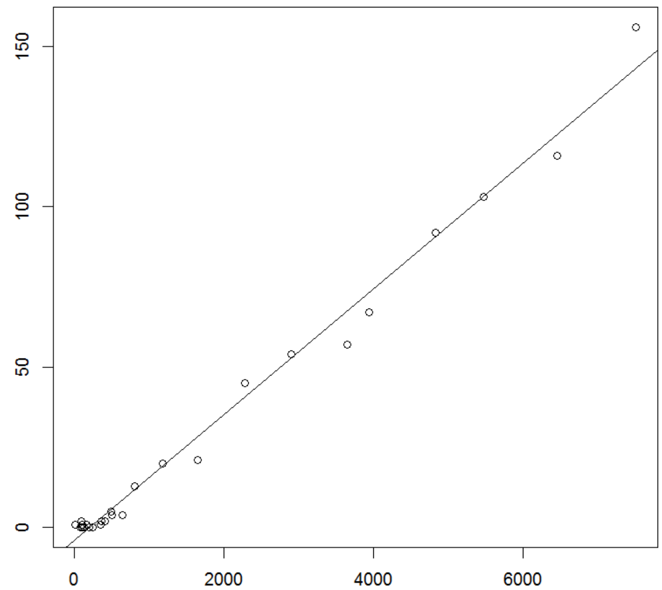


Figure F.2. CR/CC plotted in R, $R^2 = 0.988$

The publications on management under GEC started earlier for the whole climate change field, with CR starting to be a research topic in the early 2000 and then publishing with the same rate as the whole field of climate research. The new focus on CR in the early 2000 may be due to the global bleaching events, but this is not shown in the data.

The bleaching events have been global but some are also regional. To look if there are regional signals in publications influenced by bleaching over the years, we take the example of Australia. We look at Australian authors and case studies in the Great Barrier Reef (GBR) and compare to bleaching events that occurred in Australia in 1997-1998, 2001-2002, 2005-2006, 2010-2011, and 2015-2016 (Figure F.3.). It is not possible to say from a graphical representation if the increase in the number of authors in Australia and case studies on the GBR are directly linked to bleaching events.

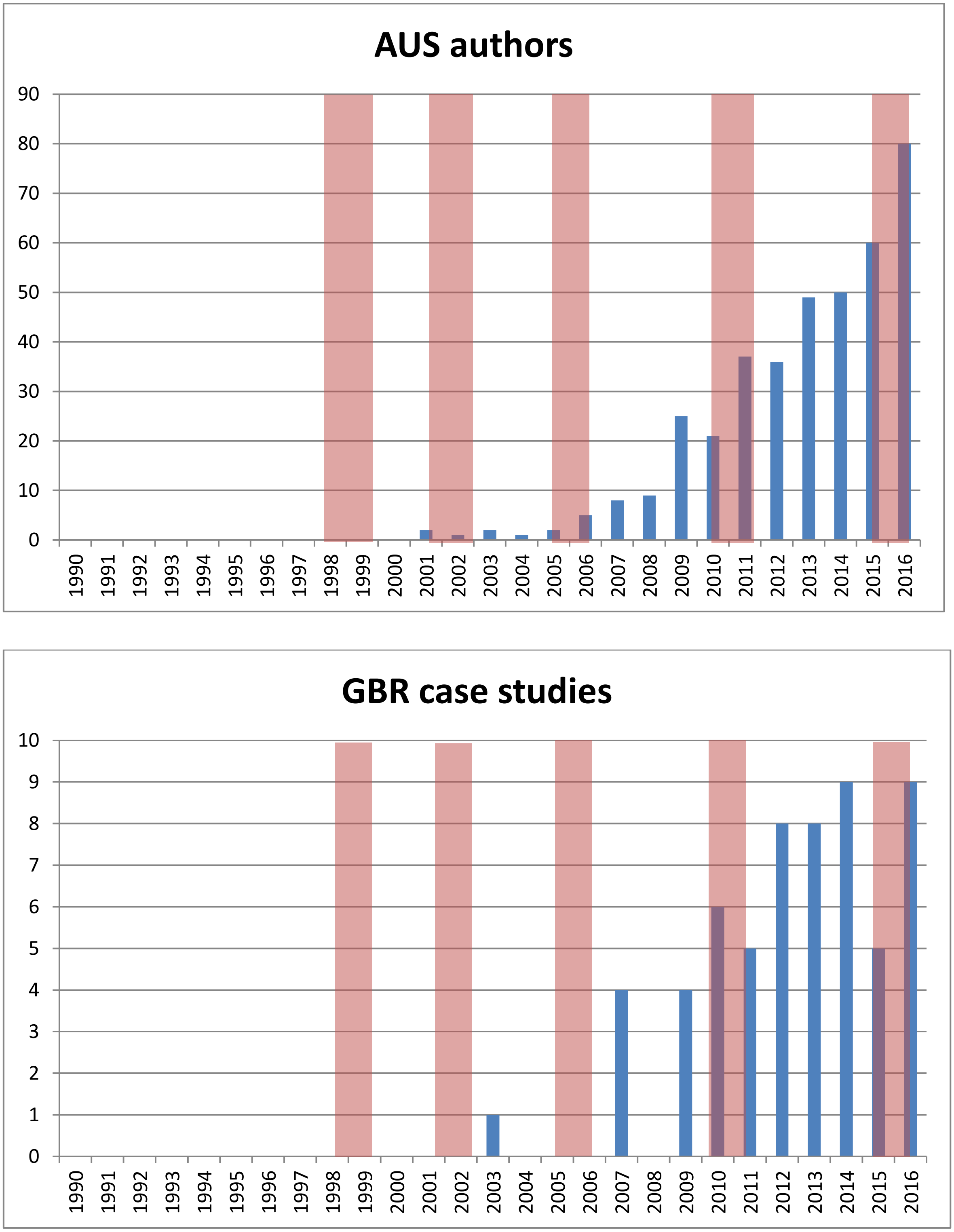


Figure F.3. Distribution of authors from Australia (AUS) and case studies on the Great Barrier Reef (GBR) between 1990 and 2016 (blue); year of bleaching events in the region (red)

2. **Do proportions of the 4 categories of management strategies found in research articles change through time?**

There are four major categories of management strategies that researchers may be inclined to study and advocate for (mitigate, protect, repair, and adapt). In parallel, evolutions in the policy and climate negotiations realms switch the focus from mitigation towards now increasingly focusing on adaptation, partly since the impacts of climate change are starting to emerge. It seems that this change in focus is not observed in the field of coral reefs research (Figure F.4.).

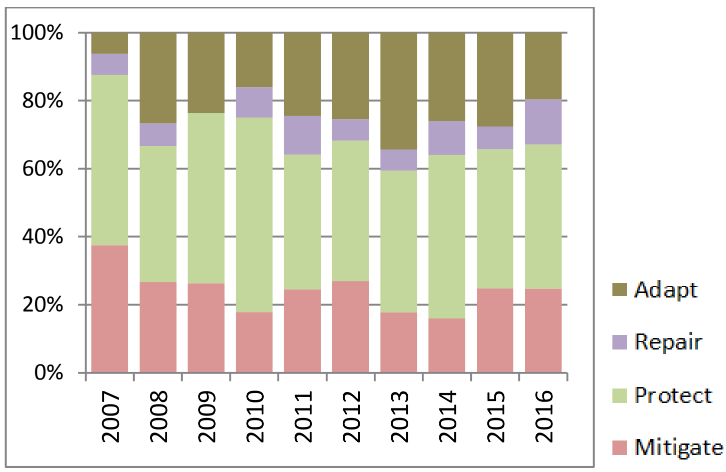


Figure F.4. Percentages of the four categories of management strategies in the literature, between 2007 and 2016.

We use a covariance analysis to look at the slope of change across the four categories of actions using an ANCOVA.

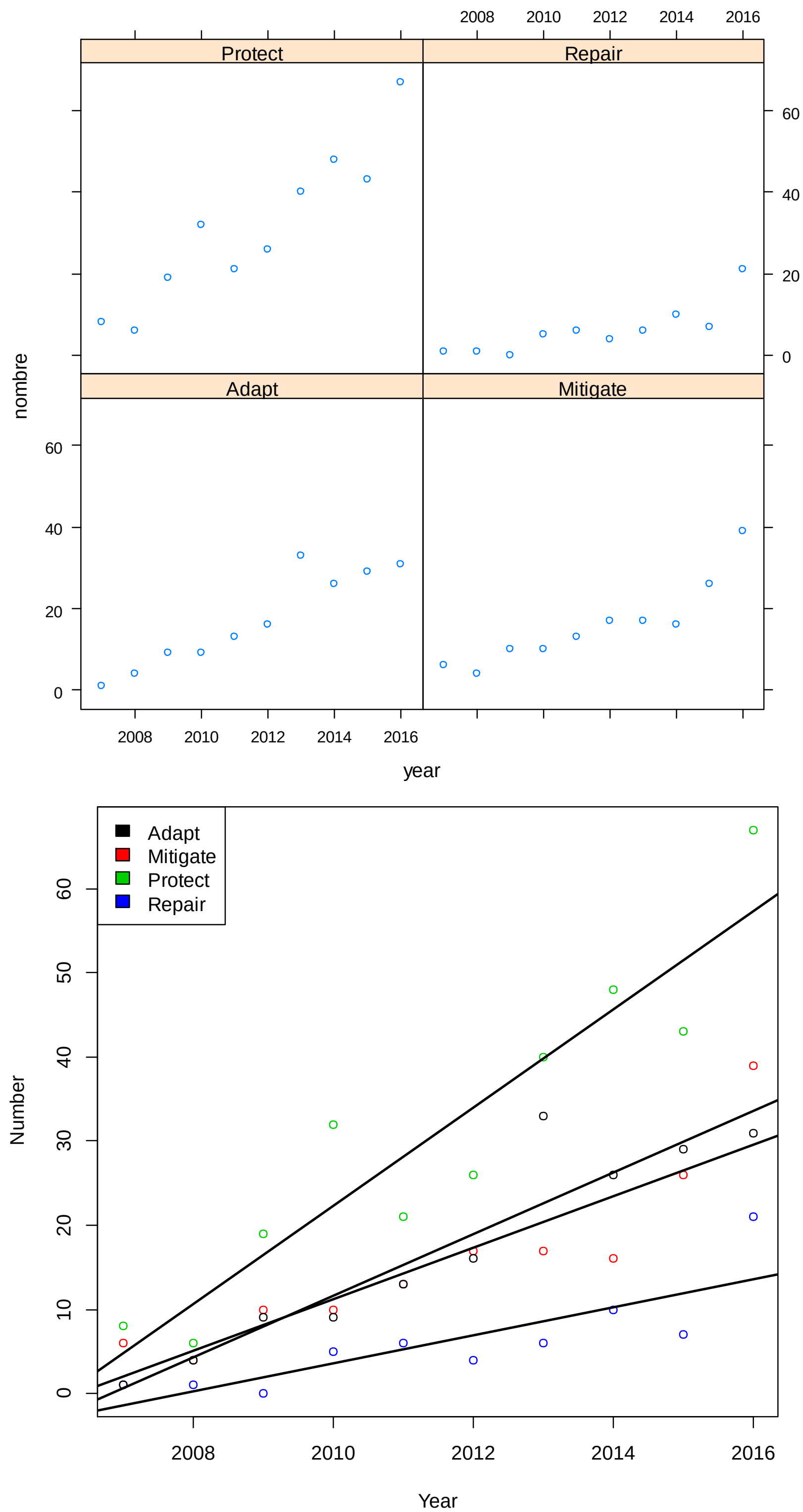


Figure F.5. Covariance analysis on the change in the number of articles from 2007 to 2016 for the four types of management strategies

ANCOVA : Nombre~année * type
Si effet type : différence dans l'intercept
Si effet interaction année*type : différence de pente

R2 : 0.8849

Analysis of Variance Table

Response: ad$nombre

	Df	Sum	Sq Mean	Sq F value	Pr(>F)
ad$year	1	4176.6	4176.6	158.6413	6.057e-14 ***
ad$type	3	3152.6	1050.9	39.9155	6.323e-11 ***
ad$year:ad$type	3	750.3	250.1	9.5001	0.0001228 ***
Residuals	32	842.5	26.3		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

We therefore observe a significant effect of year, category of management strategy, and interaction year/category.

3. Is the distribution of research in countries influenced by GDP, coral extent, and level of ecosystem services?

We have two categories of locations of research articles: (i) number of authors of the research articles affiliated in countries, and (ii) number of case studies in countries. There are different assumptions that go into these two categories. For (i), we can assume that there are more authors in wealthier countries that have more research institutions and budget for research. For (ii), we can assume that researchers conduct field work where coral reefs are located, where conditions are interesting for research, and in close proximity to their affiliated workplace. We also want to see if HDI is better suited to explain distribution of research than GDP, since HDI includes GDP but also a measure of education.

Dataset for authors

Country of authors	# of affiliations	HDI (mean 2010-2014)	Coral extent	GDP per capita (mean 2006-2013)	ES value
American Samoa	1		45.43		5.0056404
Anguilla	0		24.47		5.023789
Antigua and Barbuda	0	0.7825	55.20	13949.244	6.4743719
Aruba	0		66.93	25294.984	5.5859536
Australia	388	0.931	32308.42	52289.219	8.5749628
Austria	4	0.882	0.00	46297.578	
Bahamas	0	0.782	2236.36	22724.236	7.9375130
Bahrain	0	0.8215	87.57	21682.923	8.0581490
Bangladesh	1	0.558	4.55	625.65506	6.1885271
Barbados	3	0.7825	31.41	15868.481	4.7336108
Belgium	7	0.8865	0.00	43847.502	
Belize	2	0.7125	877.22	4613.9345	6.7826141
Bermuda	3		530.44	87926.083	6.0056329
Bonaire, Sint Eustatius and Saba	0				
Brazil	8	0.746	702.03	9507.5528	8.6593711
British Indian Ocean Territory	0		1821.99		
British Virgin Islands	0		138.03		5.8922523
Brunei Darussalam	1	0.8495	63.15	34832.308	1.18198272
Cambodia	2	0.5455	47.76	782.14223	5.3252200
Canada	56	0.908	0.00	46919.959	
Cayman Islands	2		187.74		4.6500591
Chile	4	0.823	0.00	12343.565	

China	20	0.7135	3584.18	4332.9449	9.1308801
Christmas Island	0		5.07		
Cocos (Keeling) Islands	0		115.86		
Colombia	11	0.713	940.65	5972.4236	7.0125406
Comoros	0	0.4955	221.93	800.10209	6.3765478
Cook Islands	0		254.69		5.1804762
Costa Rica	2	0.758	69.75	7512.1711	6.676142
Cuba	1	0.7735	2854.33	5414.5818	8.0934939
Curacao	0				
Denmark	5	0.9155	0.00	57235.928	
Djibouti	0	0.4615	30.70	1348.7332	5.0529879
Dominica	1	0.7235	16.45	6487.2404	4.5821320
Dominican Republic	0	0.708	517.84	4950.4008	7.6248833
Ecuador	1	0.7245	126.26	4510.6944	4.8733007
Egypt	3	0.6855	2240.75	2524.4028	7.9828462
Eritrea	0	0.386	2581.99	367.55779	6.5530377
Federated States of Micronesia	3	0.639	3192.41	2778.3273	6.2981756
Fiji	14	0.722	304.38	4101.7606	7.4491363
Finland	1		0.00	45968.247	
France (metro)	48	0.8845	8253.90	40435.541	
French Polynesia	15		3016.24		6.5440603
Germany	31	0.911	0.00	41561.007	
Greece	1	0.866	0.00	25857.202	
Grenada	1	0.7435	51.06	7468.1782	5.9794659
Guadaloupe	1		128.80		6.7657976
Guam	7		137.70		
Haiti	0	0.477	164.28	688.24406	7.6022944
Honduras	2	0.608	830.83	2009.0596	6.3391097
Hungary	1	0.8245		13116.984	
India	9	0.5975	2035.97	1255.8400	9.5128328
Indonesia	14	0.6745	20105.79	2670.7137	10
Iran	1	0.7545	117.50	5122.0964	7.7347709
Ireland	2	0.912	0.00	51033.911	
Israel	13	0.8885		29347.910	2.9861770
Italy	15	0.871	0.00	35456.827	
Jamaica	3	0.723	439.43	4994.9042	7.6137253
Japan	15	0.8875	1050.22	40000.555	8.5419444
Jordan	1	0.7455	324.25	4090.80349	4.75885024
Kenya	15	0.5385	509.86	803.36975	7.1660669
Kiribati	0	0.589	1973.22	1482.6583	6.9036082

Kuwait	1	0.8125	122.50	46639.631	6.5240369
Liberia	0	0.4175		311.70305	
Madagascar	5	0.507	3424.24	417.90470	7.2074302
Malaysia	13	0.7745	1602.67	8611.7790	8.7468451
Malta	1	0.8315		20090.423	
Maldives	0	0.6945	2714.08	5940.0439	6.7200335
Marshall Islands	1		2005.14	3052.5866	6.0973988
Martinique	2		72.43		6.8073554
Mauritius	2	0.7665	720.10	7561.5895	7.4016720
Mayotte	0				4.8607493
Mexico	14	0.751	931.29	9238.9735	8.4209279
Montserrat	0		2.44		
Monaco	2			160252.02	
Mozambique	2	0.4085	2103.06	450.07587	7.0185506
Myanmar	0	0.528	613.52		7.3731296
Nauru	0		5.96		3.2957793
Netherlands	32	0.9155	250.47	47574.0338	
New Caledonia	19		4597.98		6.6125477
New Zealand	20	0.9095	0.00	33341.156	
Nicaragua	0	0.625	470.82	1544.7131	6.3898216
Niue	0		15.46		3.0210820
Northern Mariana Islands	3		81.88		4.2913168
Norway	5	0.942	0.00	89475.610	
Oman	1	0.794	277.47	20271.001	8.0011813
Palau	5	0.7735	509.70	10555.631	4.7965626
Panama	5	0.7705	635.12	7871.2072	7.4138166
Papua New Guinea	4	0.499	7190.91	1463.8547	7.6751419
Philippines	18	0.661	12206.04	2084.6794	9.8526083
Portugal	9	0.8245	0.00	21570.9673	
Pitcairn	0		39.58		
Puerto Rico	5		159.00	25892.165	7.5905432
Qatar	1	0.847	156.26	78222.976	7.0121141
Reunion	14		12.18		5.7629082
Saint Kitts and Nevis	0	0.7455	42.05	13575.514	5.8484246
Saint Lucia	0	0.7295	29.65	6909.9389	5.4882313
Samoa	1	0.699	201.19	3094.8046	5.9831851
Saudi Arabia	4	0.821	3387.65	20233.948	8.7250642
Senegal	0	0.461		1005.5830	
Seychelles	5	0.7575	1560.16	11733.752	6.5115644
Singapore	6	0.9045	4.35	44966.438	5.9253861

Solomon Islands	3	0.5	2835.09	1381.2423	7.1536234
Somalia	0		259.21		6.7769065
South Africa	16	0.6545	1.40	6420.7318	
South Korea	3	0.892	0.00	22446.247	
Spain	15	0.8715	0.00	30501.343	
Sri Lanka	0	0.7475	122.55	2318.2807	7.3063686
St. Martin	0				
St. Vincent and the Grenadines	0	0.7155	33.60	6230.1253	4.6290590
Sudan	0	0.472	653.89	1361.7612	5.4038750
Sweden	31	0.904	0.00	51285.876	
Switzerland	12	0.927	0.00	70125.025	
Taiwan	8		190.70		7.8784951
Tanzania	4		2126.50	519.65207	8.0966394
Thailand	15	0.721	185.50	4528.9724	8.5511697
Timor Leste	0	0.5975		863.31695	5.5927542
Tokelau	0		97.19		2.5244157
Tonga	0		997.21	3601.8426	5.6917967
Trinidad and Tobago	6	0.772	32.23	17015.829	5.9762878
Turks and Caicos Islands	0		192.56		6.8650253
Tuvalu	0		878.50	3264.6752	4.5314998
United Arab Emirates	4		129.19	40608.054	8.5988799
United Kingdom	135	0.9065		39978.240	
United States	335	0.912	4108.69	49128.799	7.3764596
United States Minor Outlying Islands	0		171.99		
US Virgin Islands	5		33.55		6.4062940
Vanuatu	0	0.5915	710.96	2808.7603	5.9172746
Venezuela	2	0.7595	348.88	11157.025	8.2712187
Viet Nam	3	0.6595	264.61	1331.8971	8.2920513
Wallis & Futuna Islands	0		426.26		5.2833423
Yemen	0	0.497	829.21	1281.0989	8.2279763

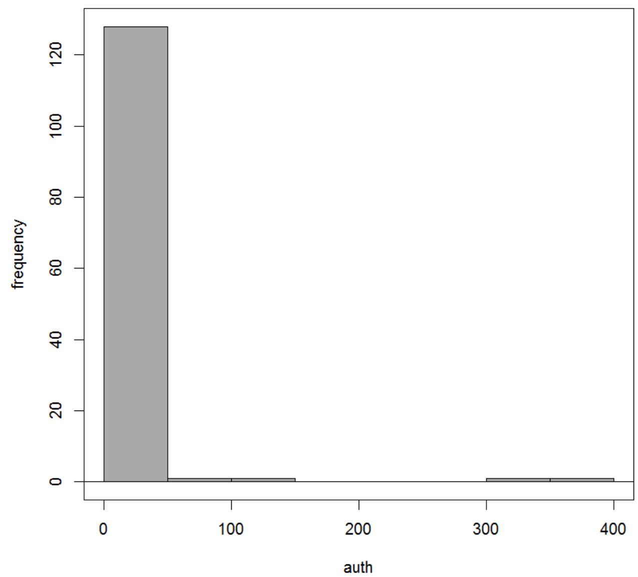


Figure F.6. Frequency distribution of authors per country.

The distribution of authors is not normal and highly skewed with a very long tail. Most countries have very few authors with several countries having a lot authors. This distribution prevents us from doing standard statistical tests.

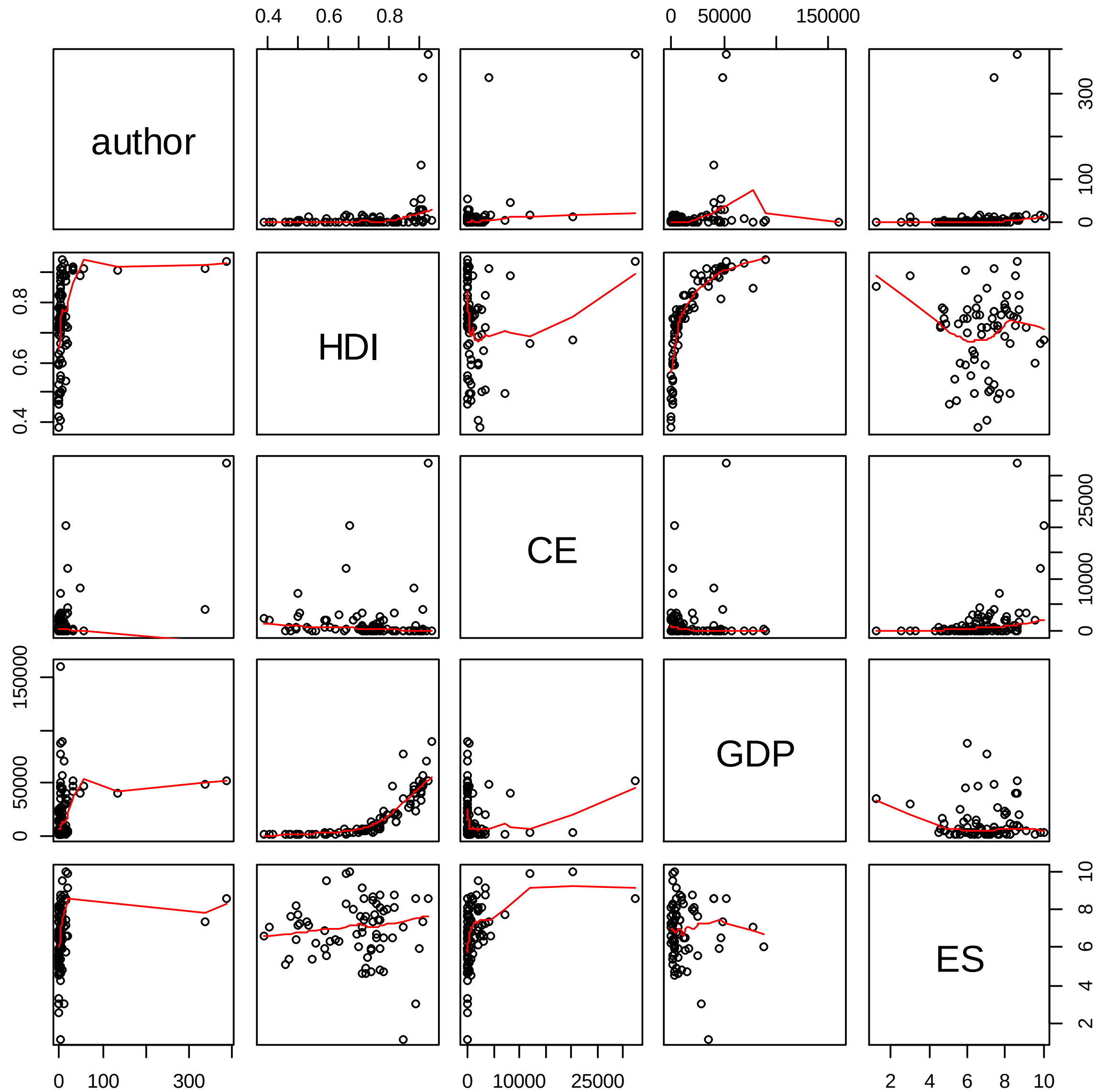


Figure F.7. Correlation table with spleen adjustment / scatterplot matrix

Dataset for case studies (ii)

Country of case study	case studies	HDI	Coral extent	GDP per cap	ES value	OP
American Samoa	2		45.43		5.005640467	4.11
Anguilla	2		24.47		5.02378903	3.94
Antigua and Barbuda	0	0.7825	55.20	13949.24423	6.474371941	3.94
Aruba	0		66.93	25294.98463	5.585953627	3.94
Australia	133	0.931	32308.42	52289.21965	8.574962829	3.66
Bahamas	5	0.782	2236.36	22724.23649	7.937513011	3.96
Bahrain	0	0.8215	87.57	21682.92332	8.058149054	
Bangladesh	3	0.558	4.55	625.6550648	6.188527163	3.50
Barbados	2	0.7825	31.41	15868.48144	4.733610823	3.94
Belgium	0	0.8865	0.00	43847.50222		
Belize	11	0.7125	877.22	4613.934573	6.782614125	
Bermuda	1		530.44	87926.08386	6.005632909	3.96
Bonaire, Sint Eustatius and Saba	3					3.94
Brazil	7	0.746	702.03	9507.552814	8.659371122	4.02
British Indian Ocean Territory	4		1821.99			3.91
British Virgin Islands	2		138.03		5.892252396	3.94
Brunei Darussalam	0	0.8495	63.15	34832.30811	1.18198272	
Cambodia	0	0.5455	47.76	782.1422391	5.325220053	
Canada	0	0.908	0.00	46919.95926		
Cayman Islands	2		187.74		4.650059106	4.03
Chile	0	0.823	0.00	12343.56522		
China	8	0.7135	3584.18	4332.944929	9.130880199	
Christmas Island	1		5.07			3.82
Cocos (Keeling) Islands	0		115.86			3.82
Colombia	5	0.713	940.65	5972.423649	7.012540679	3.92
Comoros	5	0.4955	221.93	800.1020949	6.376547894	3.79
Cook Islands	2		254.69		5.180476285	4.00
Costa Rica	4	0.758	69.75	7512.171178	6.67614224	3.37
Cuba	0	0.7735	2854.33	5414.581863	8.09349395	4.03
Curacao	0					3.94
Djibouti	0	0.4615	30.70	1348.733239	5.052987912	3.79
Dominica	0	0.7235	16.45	6487.24044	4.582132075	3.94
Dominican Republic	3	0.708	517.84	4950.400888	7.624883342	4.01
Ecuador	0	0.7245	126.26	4510.694424	4.873300709	
Egypt	1	0.6855	2240.75	2524.402842	7.982846268	
Eritrea	0	0.386	2581.99	367.5577934	6.553037725	3.79

Federated States of Micronesia	9	0.639	3192.41	2778.327391	6.298175698	3.95
Fiji	9	0.722	304.38	4101.760628	7.449136338	4.00
French Polynesia	12		3016.24		6.544060312	4.08
Grenada	0	0.7435	51.06	7468.178216	5.979465952	3.94
Guadaloupe	1	0.8845	128.80	40435.54124	6.765797601	3.94
Guam	0		137.70			
Haiti	1	0.477	164.28	688.2440693	7.602294417	4.03
Honduras	9	0.608	830.83	2009.05965	6.339109769	3.91
India	8	0.5975	2035.97	1255.840072	9.512832832	3.98
Indonesia	18	0.6745	20105.79	2670.713777	10	3.88
Iran	1	0.7545	117.50	5122.096423	7.734770916	4.02
Israel	1	0.8885		29347.91027	2.986177046	
Jamaica	3	0.723	439.43	4994.904216	7.613725306	4.03
Japan	4	0.8875	1050.22	40000.55596	8.541944472	3.67
Jordan	0	0.7455	324.25	4090.803499	4.758850284	
Kenya	8	0.5385	509.86	803.3697572	7.166066931	3.89
Kiribati	5	0.589	1973.22	1482.658397	6.903608298	3.90
Kuwait	0	0.8125	122.50	46639.63162	6.524036949	
Liberia	1	0.4175		311.7030569		
Madagascar	13	0.507	3424.24	417.9047099	7.207430248	3.78
Malaysia	9	0.7745	1602.67	8611.779012	8.746845104	3.55
Maldives	9	0.6945	2714.08	5940.043993	6.720033549	4.12
Marshall Islands	2		2005.14	3052.586618	6.097398876	3.94
Martinique	1	0.8845	72.43	40435.54124	6.807355424	3.94
Mauritius	7	0.7665	720.10	7561.589569	7.401672018	3.75
Mayotte	3	0.8845		40435.54124	4.860749343	3.77
Mexico	12	0.751	931.29	9238.973522	8.420927946	
Montserrat	1		2.44			3.94
Mozambique	5	0.4085	2103.06	450.0758719	7.018550646	3.78
Myanmar	1	0.528	613.52		7.373129603	3.55
Nauru	1		5.96		3.295779398	3.94
Netherlands	0	0.9155	250.47	47574.0338		
New Caledonia	7		4597.98		6.612547715	3.86
Nicaragua	0	0.625	470.82	1544.713186	6.389821654	3.63
Niue	1		15.46		3.021082034	4.10
Northern Mariana Islands	2		81.88		4.291316808	4.04
Oman	2	0.794	277.47	20271.0018	8.001181384	3.27
Palau	5	0.7735	509.70	10555.63179	4.796562615	3.97
Panama	0	0.7705	635.12	7871.207257	7.413816633	
Papua New Guinea	10	0.499	7190.91	1463.854747	7.675141935	3.94

Philippines	13	0.661	12206.04	2084.679477	9.852608345	3.64
Puerto Rico	4		159.00	25892.16585	7.590543231	4.00
Qatar	1	0.847	156.26	78222.97636	7.012114158	
Reunion	5	0.8845	12.18	40435.54124	5.762908217	3.76
Saint Kitts and Nevis	0	0.7455	42.05	13575.51438	5.848424628	3.94
Saint Lucia	1	0.7295	29.65	6909.938926	5.488231398	3.94
Samoa	1	0.699	201.19	3094.804697	5.983185177	4.15
Saudi Arabia	1	0.821	3387.65	20233.94821	8.725064233	
Seychelles	13	0.7575	1560.16	11733.75231	6.511564439	3.80
Singapore	3	0.9045	4.35	44966.43896	5.925386132	
Solomon Islands	15	0.5	2835.09	1381.242346	7.153623471	3.94
Somalia	2		259.21		6.776906503	3.82
South Africa	2	0.6545	1.40	6420.731826		3.75
Sri Lanka	3	0.7475	122.55	2318.280795	7.306368686	3.87
St. Martin	1					3.94
St. Vincent and the Grenadines	0	0.7155	33.60	6230.125328	4.629059049	3.94
Sudan	0	0.472	653.89	1361.761296	5.403875038	
Taiwan	3		190.70		7.878495128	3.64
Tanzania	12		2126.50	519.6520747	8.09663947	3.85
Thailand	10	0.721	185.50	4528.972423	8.551169712	3.56
Timor Leste	6	0.5975		863.3169585	5.592754274	
Tokelau	0		97.19		2.524415721	4.03
Tonga	1		997.21	3601.842643	5.691796787	4.11
Trinidad and Tobago	3	0.772	32.23	17015.82982	5.976287889	3.91
Turks and Caicos Islands	2		192.56		6.865025388	3.96
Tuvalu	2		878.50	3264.675291	4.531499805	3.94
United Arab Emirates	5		129.19	40608.05408	8.598879916	4.02
United States	53	0.912	4108.69	49128.79911	7.376459625	3.92
United States Minor Outlying Islands	2		171.99			3.86
US Virgin Islands	4		33.55		6.406294083	3.97
Vanuatu	3	0.5915	710.96	2808.760351	5.917274669	3.96
Venezuela	0	0.7595	348.88	11157.02518	8.271218786	3.94
Viet Nam	2	0.6595	264.61	1331.897146	8.292051351	
Wallis & Futuna Islands	1		426.26		5.283342347	4.14
Yemen	0	0.497	829.21	1281.098927	8.227976378	3.66

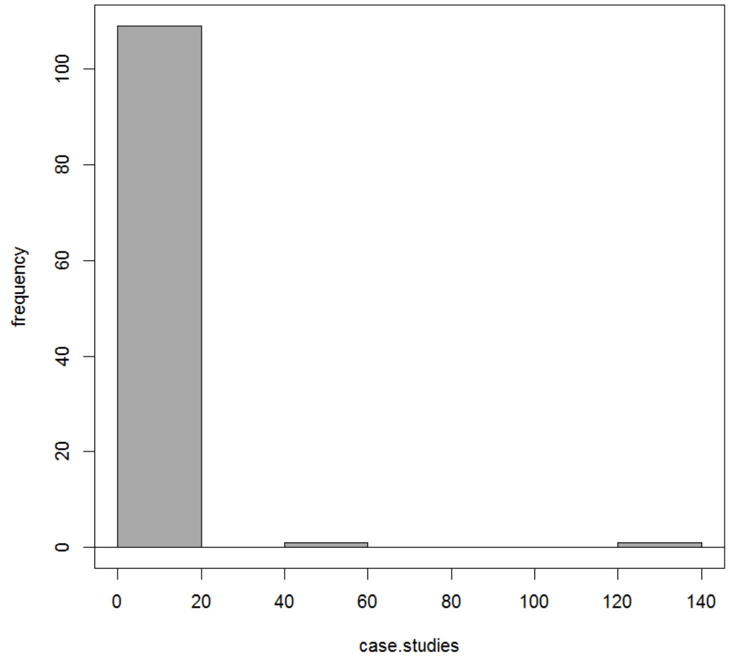


Figure F.8. Frequency distribution of case studies

The distribution of articles is not normal and highly skewed with a very long tail. Most countries have zero or very few case studies, with a very few countries having many case studies. This distribution prevents us from doing standard statistical tests.

The distribution of authors and of case studies is very skewed and influenced by a handful of countries: Australia, USA, UK, Netherlands and France for authors; Australia and USA for case studies. We attempt to redo the statistical analyses after removing these countries from the dataset.

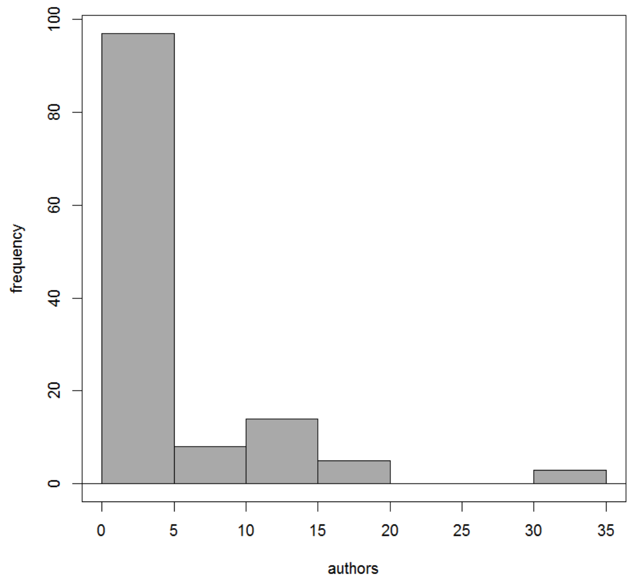


Figure F.9. Frequency distribution of authors without five major countries

The distribution is still not normal, with lots of occurrences having the value 0 and a few having large values.

Correlation matrix:

	authors	Coral.extent	ES.value	GDP.per.cap	HDI
authors	1	0.417**	0.521***	-0.0208	0.1453
Coral.extent	0.417**	1	0.4625**	-0.1647	-0.1503
ES.value	0.521***	0.4625**	1	-0.1099	-0.0052
GDP.per.cap	-0.0208	-0.1647	-0.1099	1	0.6254***
HDI	0.1453	-0.1503	-0.0052	0.6254***	1

There is a major difference when removing major countries. GDP has a negative relationship with presence of authors but is not significant. The value of ES however seems to be correlated with number of authors, with a positive relationship. ES is also correlated with coral extent, which intuitively makes sense.

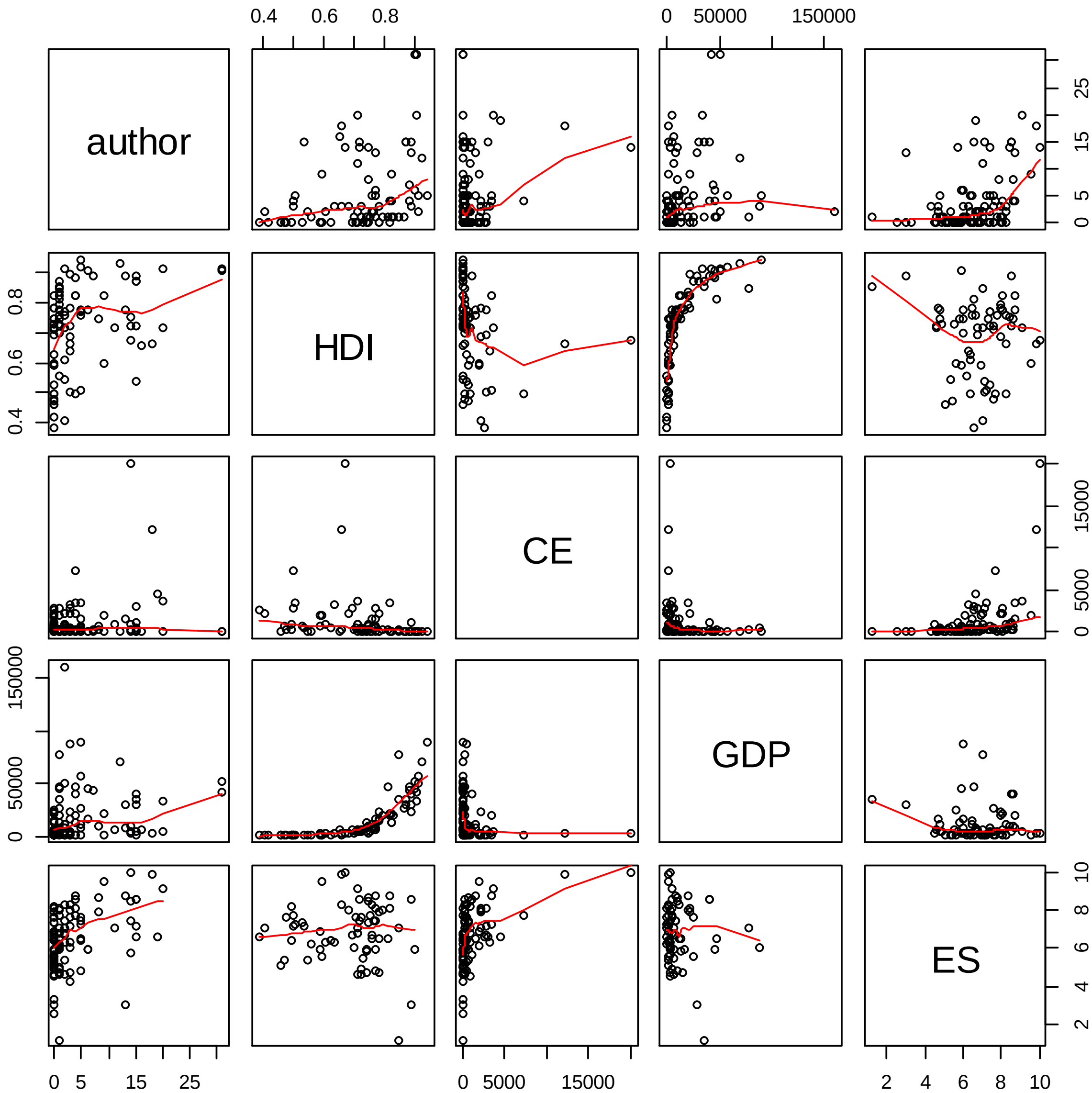


Figure F.10. Correlation table with spleen adjustment / scatterplot matrix

For case studies

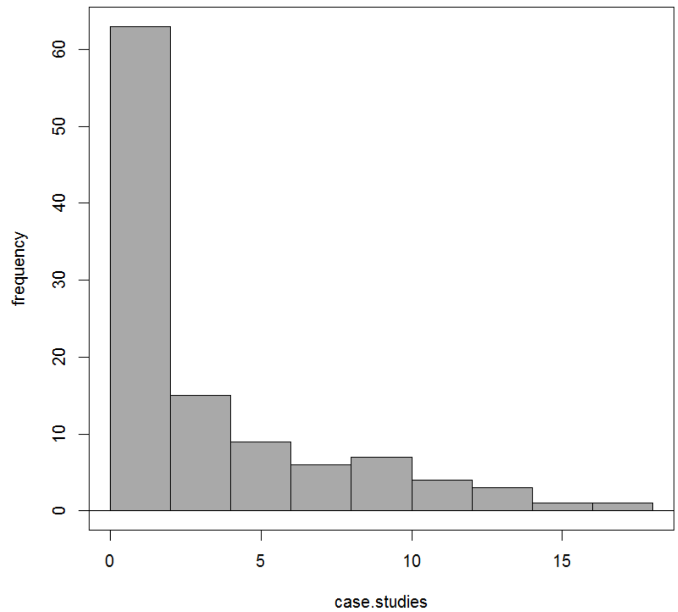


Figure F.11. Frequency distribution of case studies without two major countries

Still not normal with long tail and many instances of zero.

Correlation matrix:

	case.studies	Coral.extent	ES.value	GDP.per.cap	HDI	OP
case.studies	1	0.6364***	0.4605**	-0.2148	-0.1661	-0.0823
Coral.extent	0.6364***	1	0.5239**	-0.1991	-0.1721	-0.0195
ES.value	0.4605**	0.5239**	1	-0.0634	-0.0034	-0.185
GDP.per.cap	-0.2148	-0.1991	-0.0634	1	0.7315***	-0.0682
HDI	-0.1661	-0.1721	-0.0034	0.7315***	1	0.0284
OP	-0.0823	-0.0195	-0.185	-0.0682	0.0284	1

Here, the results of the correlation matrix are also different with and without the major countries. GDP is negatively influencing case studies with no significant value, but coral extent and ES do influence positively and in a significant way case studies.

4. Using Principal Component Analysis (PCA) to explain drivers of case studies

A new sub-dataset of case studies was created, using new GDP per capita (average 2006-2013) from a recent 2017 World Bank dataset, to have data for several countries that were missing.

Country of authors	Country code	case studies	Coral extent	GDP per cap	ES value	latitude	longitude
American Samoa	ASM	2	45.43	10414.17153	5.005640467	-14.271	-170.132
Antigua and Barbuda	ATG	0	55.20	13918.03323	6.474371941	17.06082	-61.7964
Aruba	ABW	0	66.93	25295.0331	5.585953627	12.52111	-69.9683
Australia	AUS	133	32308.42	52343.36573	8.574962829	-25.2744	133.7751
Bahamas	BHS	5	2236.36	22784.00771	7.937513011	25.03428	-77.3963
Bahrain	BHR	0	87.57	21579.73655	8.058149054	25.93041	50.63777
Bangladesh	BGD	3	4.55	719.104481	6.188527163	23.68499	90.35633
Barbados	BRB	2	31.41	15937.59569	4.733610823	13.19389	-59.5432
Belize	BLZ	11	877.22	4439.78113	6.782614125	17.18988	-88.4977
Bermuda	BMU	1	530.44	87777.29408	6.005632909	32.32138	-64.7574
Brazil	BRA	7	702.03	9836.433717	8.659371122	-14.235	-51.9253
Brunei Darussalam	BRN	0	63.15	37695.58029	1.18198272	4.535277	114.7277
Cambodia	KHM	0	47.76	784.8014363	5.325220053	12.56568	104.991
Cayman Islands	CYM	2	187.74	64104.7516	4.650059106	19.51347	-80.567
China	CHN	8	3584.18	4464.27999	9.130880199	35.86166	104.1954
Colombia	COL	5	940.65	6044.947983	7.012540679	4.570868	-74.2973
Comoros	COM	5	221.93	760.878705	6.376547894	-11.875	43.87222
Costa Rica	CRI	4	69.75	7875.610179	6.67614224	9.748917	-83.7534
Cuba	CUB	0	2854.33	5721.419864	8.09349395	21.52176	-77.7812
Djibouti	DJI	0	30.70	1331.105998	5.052987912	11.82514	42.59028
Dominica	DMA	0	16.45	6577.804398	4.582132075	15.415	-61.371
Dominican Republic	DOM	3	517.84	5206.68166	7.624883342	18.73569	-70.1627
Ecuador	ECU	0	126.26	4641.127701	4.873300709	-1.83124	-78.1834
Egypt	EGY	1	2240.75	2434.584546	7.982846268	26.82055	30.8025
Eritrea	ERI	0	2581.99	381.2061744	6.553037725	15.17938	39.78233
Federated States of Micronesia	FSM	9	3192.41	2753.610817	6.298175698	7.425554	150.5508
Fiji	FJI	9	304.38	4085.502367	7.449136338	-16.5782	179.4144
French Polynesia	PYF	12	3016.24	18650	6.544060312	-17.6797	-149.407
Grenada	GRD	0	51.06	7468.118739	5.979465952	12.26278	-61.6042
Guadaloupe	GLP	1	128.80	40435.54124	6.765797601	16.99597	-62.0676
Haiti	HTI	1	164.28	680.5914858	7.602294417	18.97119	-72.2852
Honduras	HND	9	830.83	2031.597042	6.339109769	15.2	-86.2419
India	IND	8	2035.97	1202.767379	9.512832832	20.59368	78.96288

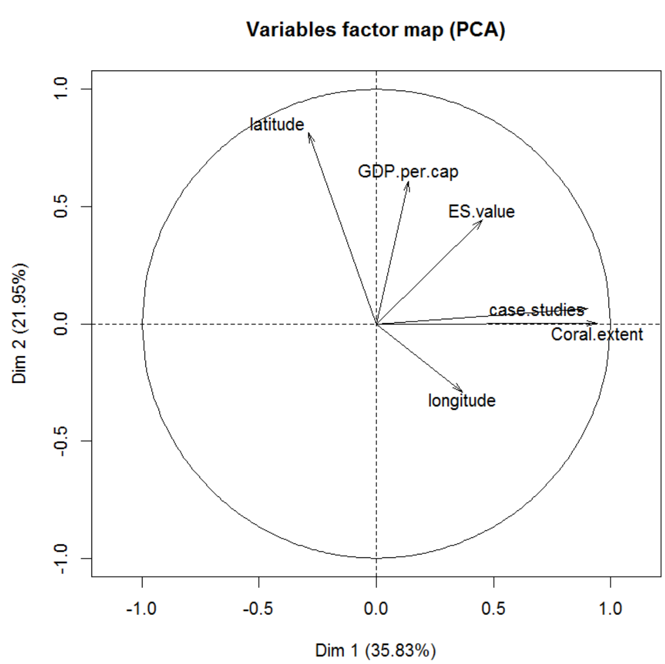
Indonesia	IDN	18	20105.79	2748.302722	10	-0.78928	113.9213
Iran	IRN	1	117.50	5972.803119	7.734770916	32.42791	53.68805
Jamaica	JAM	3	439.43	4896.742247	7.613725306	18.10958	-77.2975
Japan	JPN	4	1050.22	41587.84146	8.541944472	36.20482	138.2529
Jordan	JOR	0	324.25	3818.721755	4.758850284	30.58516	36.23841
Kenya	KEN	8	509.86	987.7135248	7.166066931	-0.02356	37.90619
Kiribati	KIR	5	1973.22	1486.693541	6.903608298	-3.37042	-168.734
Kuwait	KWT	0	122.50	45442.61356	6.524036949	29.31166	47.48177
Madagascar	MDG	13	3424.24	417.4382692	7.207430248	-18.7669	46.86911
Malaysia	MYS	9	1602.67	8817.102868	8.746845104	4.210484	101.9758
Maldives	MDV	9	2714.08	5963.989848	6.720033549	3.202778	73.22068
Marshall Islands	MHL	2	2005.14	3132.259913	6.097398876	7.131474	171.1845
Martinique	MTQ	1	72.43	40435.54124	6.807355424	14.64153	-61.0242
Mauritius	MUS	7	720.10	7968.055844	7.401672018	-20.3484	57.55215
Mexico	MEX	12	931.29	9204.997346	8.420927946	23.6345	-102.553
Mozambique	MOZ	5	2103.06	487.9312107	7.018550646	-18.6657	35.52956
Myanmar	MMR	1	613.52	801.1117893	7.373129603	21.91397	95.95622
Nauru	NRU	1	5.96	6091.700225	3.295779398	-0.52278	166.9315
New Caledonia	NCL	7	4597.98	32820	6.612547715	-20.9043	165.618
Nicaragua	NIC	0	470.82	1550.121028	6.389821654	12.86542	-85.2072
Northern Mariana Islands	MNP	2	81.88	14940.37811	4.291316808	17.33083	145.3847
Oman	OMN	2	277.47	19275.60471	8.001181384	21.51258	55.92326
Palau	PLW	5	509.70	9795.066527	4.796562615	7.51498	134.5825
Panama	PAN	0	635.12	8215.866894	7.413816633	8.537981	-80.7821
Papua New Guinea	PNG	10	7190.91	1478.854178	7.675141935	-6.31499	143.9556
Philippines	PHL	13	12206.04	2093.479485	9.852608345	12.87972	121.774
Puerto Rico	PRI	4	159.00	25937.22061	7.590543231	18.22083	-66.5901
Qatar	QAT	1	156.26	77481.00979	7.012114158	25.35483	51.18388
Reunion	REU	5	12.18	40435.54124	5.762908217	-21.1151	55.53638
Saint Kitts and Nevis	KNA	0	42.05	13806.78887	5.848424628	17.35782	-62.783
Saint Lucia	LCA	1	29.65	6917.418065	5.488231398	13.90944	-60.9789
Samoa	WSM	1	201.19	3562.357168	5.983185177	-13.759	-172.105
Saudi Arabia	SAU	1	3387.65	19675.69381	8.725064233	23.88594	45.07916
Seychelles	SYC	13	1560.16	12065.66864	6.511564439	-4.67957	55.49198
Singapore	SGP	3	4.35	45104.27753	5.925386132	1.352083	103.8198
Solomon Islands	SLB	15	2835.09	1381.288559	7.153623471	-9.64571	160.1562
South Africa	ZAF	2	1.40	6661.030556	1	-30.5595	22.93751
Sri Lanka	LKA	3	122.55	2532.007835	7.306368686	7.873054	80.7718
St. Vincent and the Grenadines	VCT	0	33.60	6215.80444	4.629059049	12.98431	-61.2872
Sudan	SDN	0	653.89	1384.572758	5.403875038	12.86281	30.21764
Tanzania	TZA	12	2126.50	689.7398454	8.09663947	-6.36903	34.88882

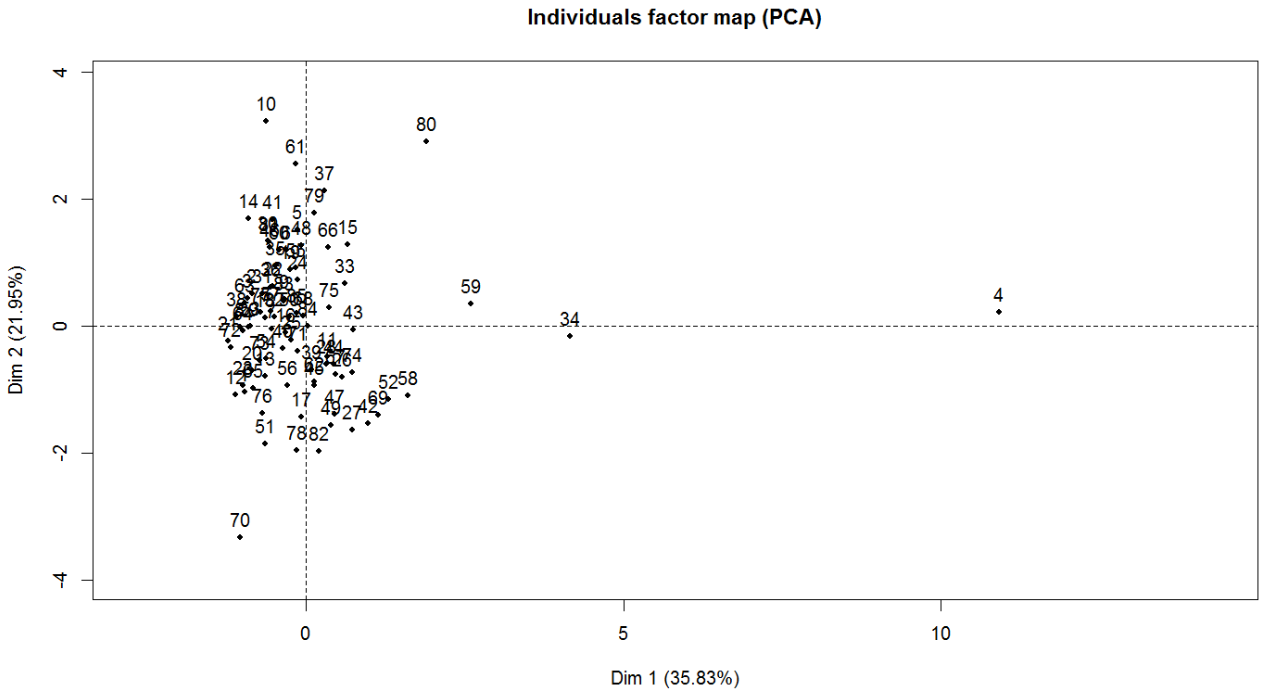
Thailand	THA	10	185.50	4840.183522	8.551169712	15.87003	100.9925
Tonga	TON	1	997.21	3587.573176	5.691796787	-21.179	-175.198
Trinidad and Tobago	TTO	3	32.23	17602.64874	5.976287889	10.6918	-61.2225
Tuvalu	TUV	2	878.50	3266.992195	4.531499805	-7.10954	177.6493
United Arab Emirates	ARE	5	129.19	40428.89389	8.598879916	23.42408	53.84782
United States	USA	53	4108.69	49030.05416	7.376459625	37.09024	-95.7129
US Virgin Islands	VIR	4	33.55	40168.02079	6.406294083	18.33577	-64.8963
Vanuatu	VUT	3	710.96	2793.521553	5.917274669	-15.3767	166.9592
Venezuela	VEN	0	348.88	10899.68816	8.271218786	6.42375	-66.5897
Viet Nam	VNM	2	264.61	1331.403669	8.292051351	14.05832	108.2772
Yemen	YEM	0	829.21	1233.612018	8.227976378	15.55273	48.51639

a. PCA on the whole database, with and without geographic positions

A first analysis includes all the variables and the data points. Geographic coordinates are defined as latitude and longitude of the centroids of each country.

With geographic coordinates



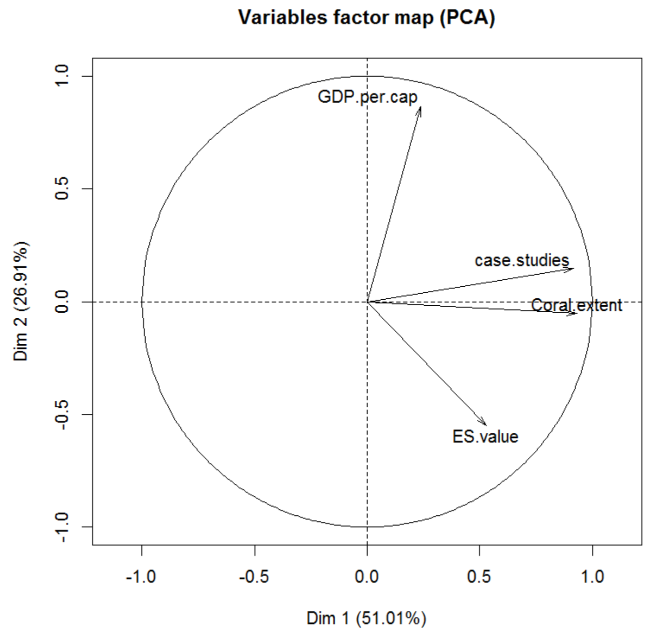


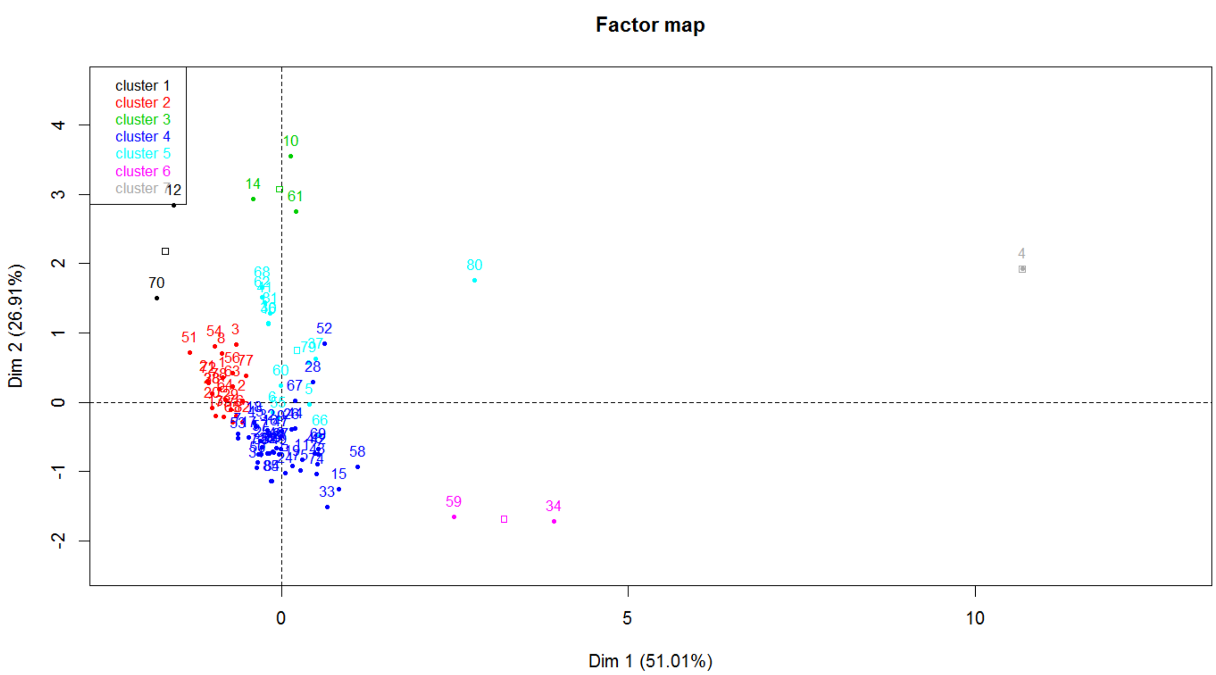
The distribution of variables is first influenced by a combination of the number of case studies and coral extent (Dim1). A second influential dimension combines latitude and GDP (Dim2). These two variables co-vary since high latitude countries tend to have higher GDP than lower latitude countries (with the exception of the Gulf countries). Here, ecosystem services and longitude do not explain much variability in the data.

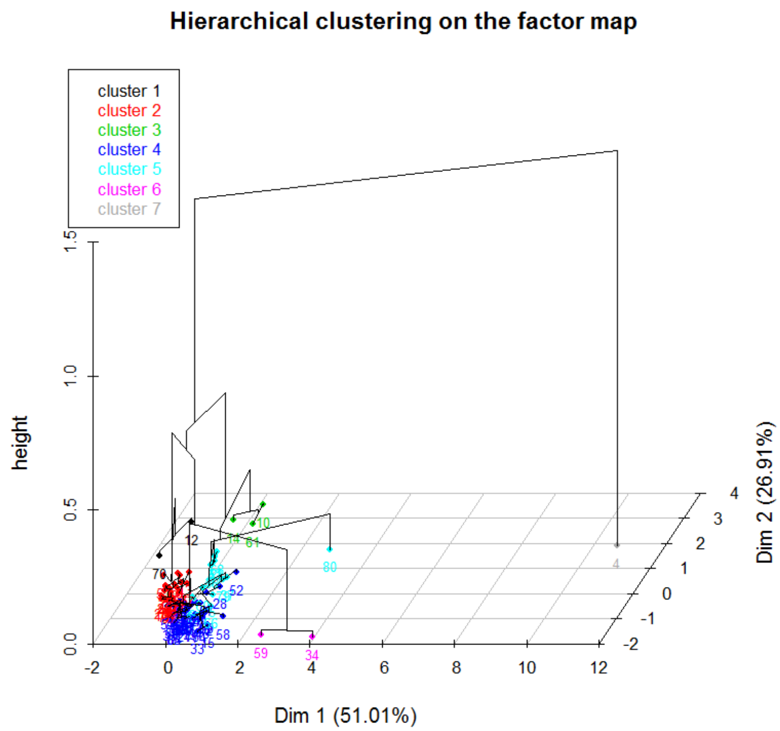
Latitude and longitude that could produce a geographic effect on the number of studies, does not explain the distribution of case studies and were therefore disregarded in future analyses.

PCA without geographic coordinates

This analysis was done without latitude and longitude. A hierarchical clustering was used to create clusters of countries that have similar characteristics.


Variables factor map (PCA)
GDP.per.cap
case.studies
Coral.extent
ES.value
Dim 1 (51.01%)
Dim 2 (26.91%)

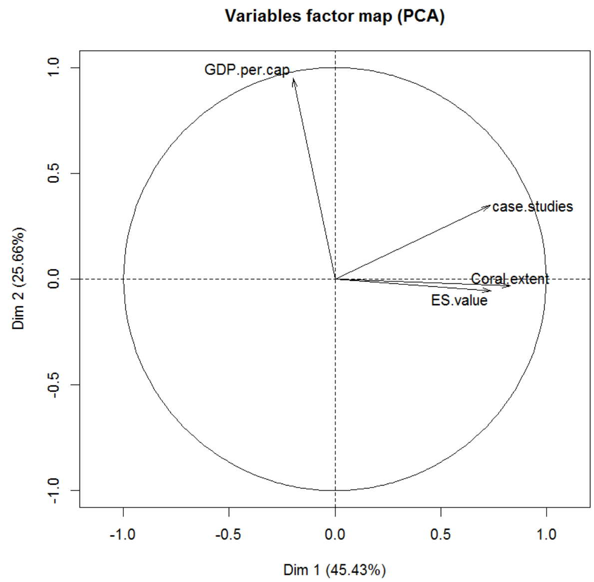

Factor map
cluster 1
cluster 2
cluster 3
cluster 4
cluster 5
cluster 6
cluster 7
Dim 1 (51.01%)
Dim 2 (26.91%)

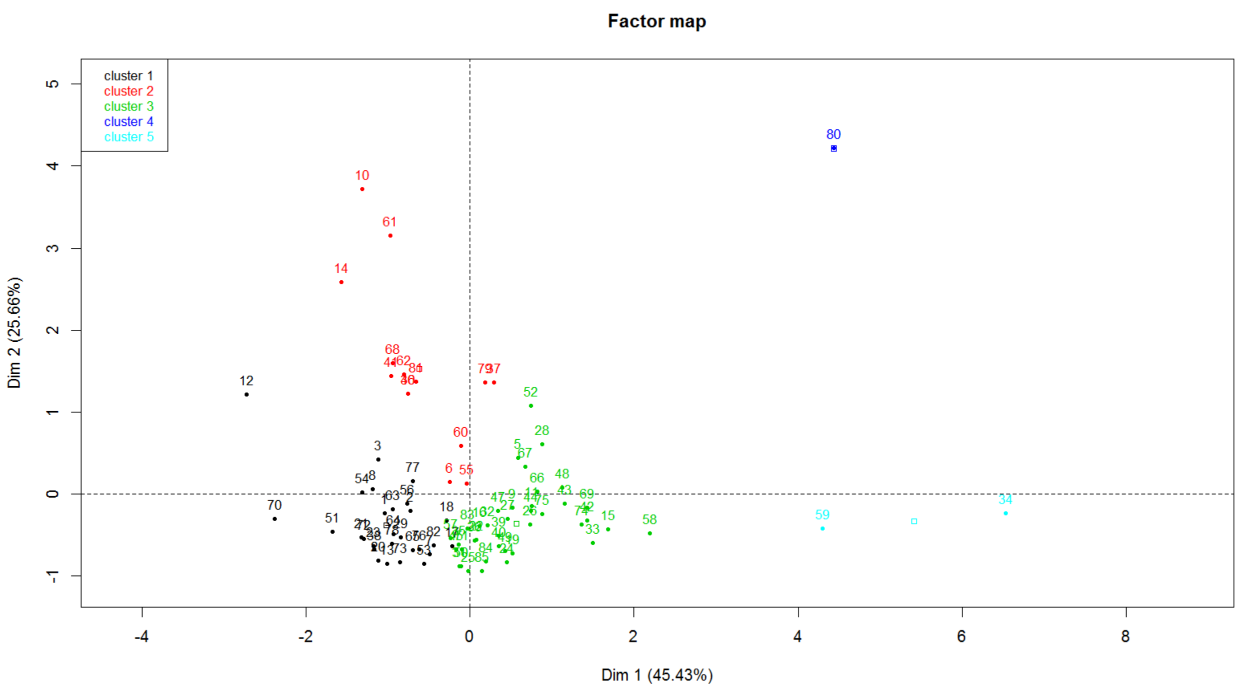


The variability is first explained by a combination of case studies and coral extent (Dim1) A second dimension is driven by GDP (Dim2), and ecosystem services have little influence.

The classification shows that country 4, Australia, stands alone. This country has the highest number of case studies and the largest extent of coral cover. Given the fact that we can explain this outlier, we remove it from further analysis to understand what can explain the variability in the distribution in other countries.

PCA without geographic coordinates and excluding Australia

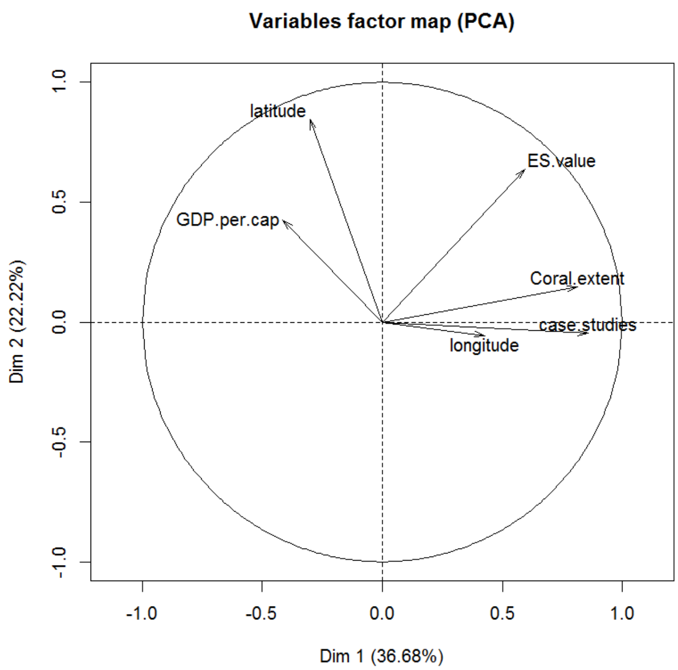


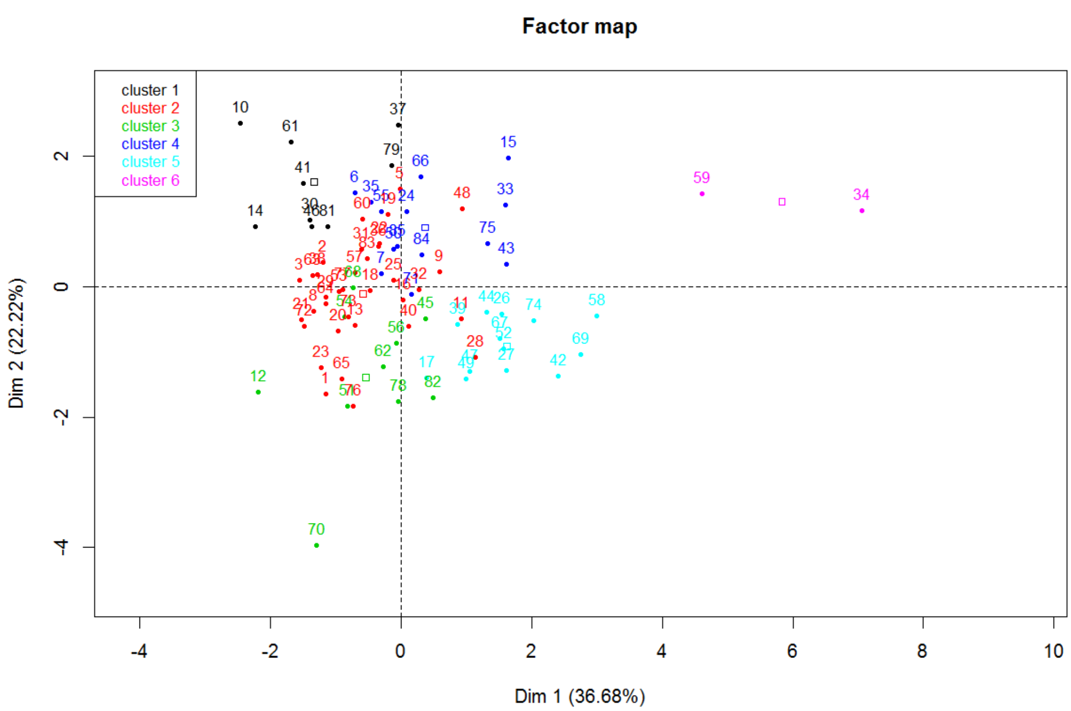


The data point 80, the United States, is a single cluster. Here again, this classification can be explained by the fact that the USA are the second largest country in terms of case studies after Australia but far ahead of the other countries. It seems useful then to remove the USA and re-run the analysis.

b. PCA without Australia and the USA

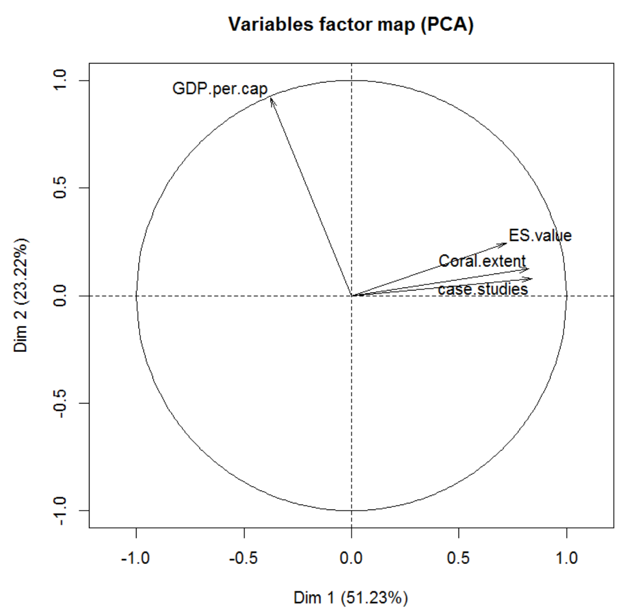
PCA including geographic coordinates

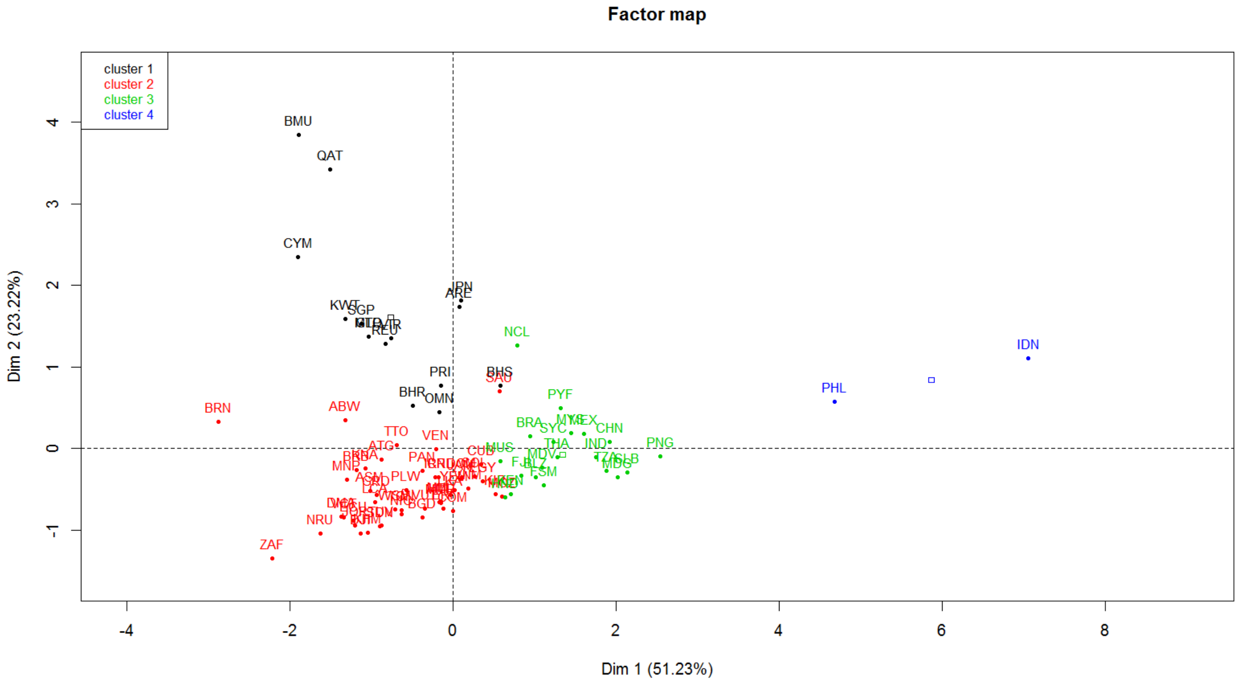




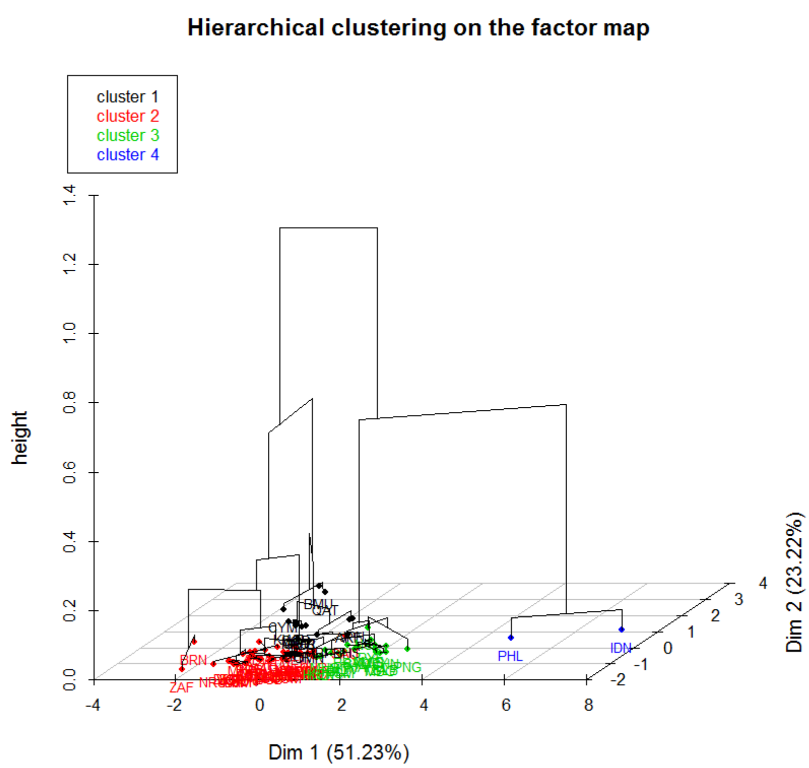
The dimensions explain a small percentage of the variability of the dataset. Latitude is also correlated with GDP, and the influence of longitude is weak in the first dimension. We therefore decided to remove geographic coordinates and redo the analysis.

PCA without Australia and the USA, and without geographic coordinates





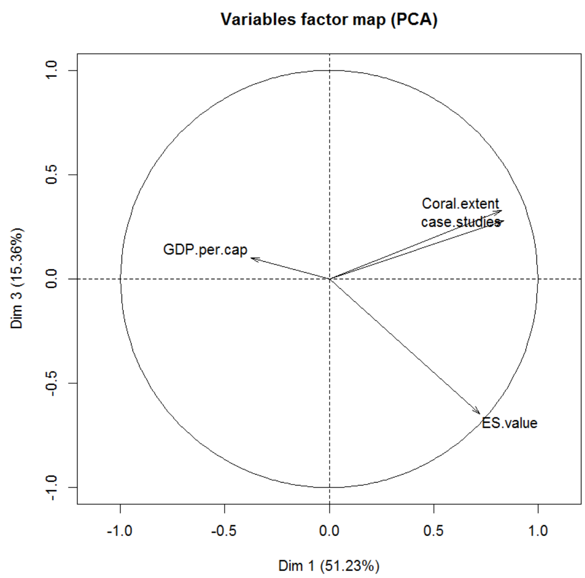
Factor map
cluster 1
cluster 2
cluster 3
cluster 4
Dim 1 (51.23%)
Dim 2 (23.22%)
BMU
QAT
CYM
IDN
PHL
BRN
ABW
ZAF
NRU
NCL
PYF
CHN
PNG



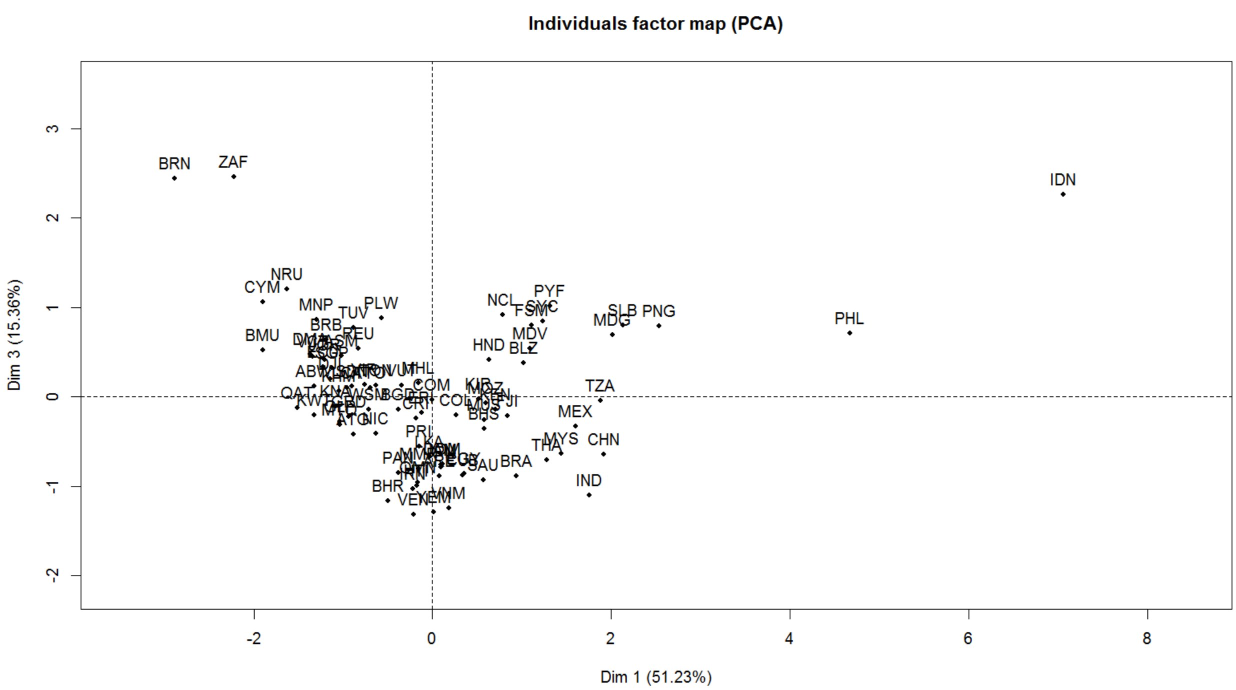
Hierarchical clustering on the factor map
cluster 1
cluster 2
cluster 3
cluster 4
height
Dim 1 (51.23%)
Dim 2 (23.22%)

This result is the analysis that was used in the Chapter 4. The variables factor map and the factor map of the two first dimensions explain a large part of the variability and the results can be interpreted.

We then explore graphically the third dimension



:



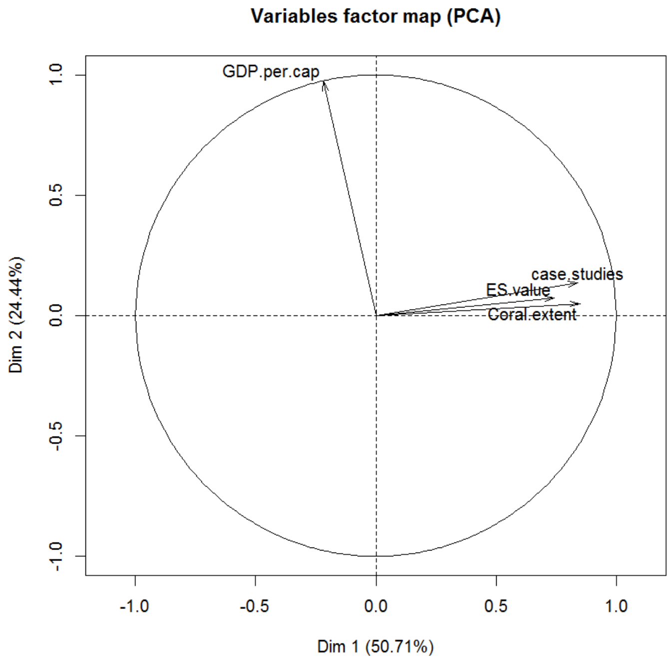
The first two dimensions explain 74% of the variability, they are sufficient to interpret the results. The third dimension explains 15.36% of the variability, and does not improve the information compared to the first two dimensions. The first dimension includes variables of case studies, coral extent, and ecosystem services, while the second axis is GDP per capita.

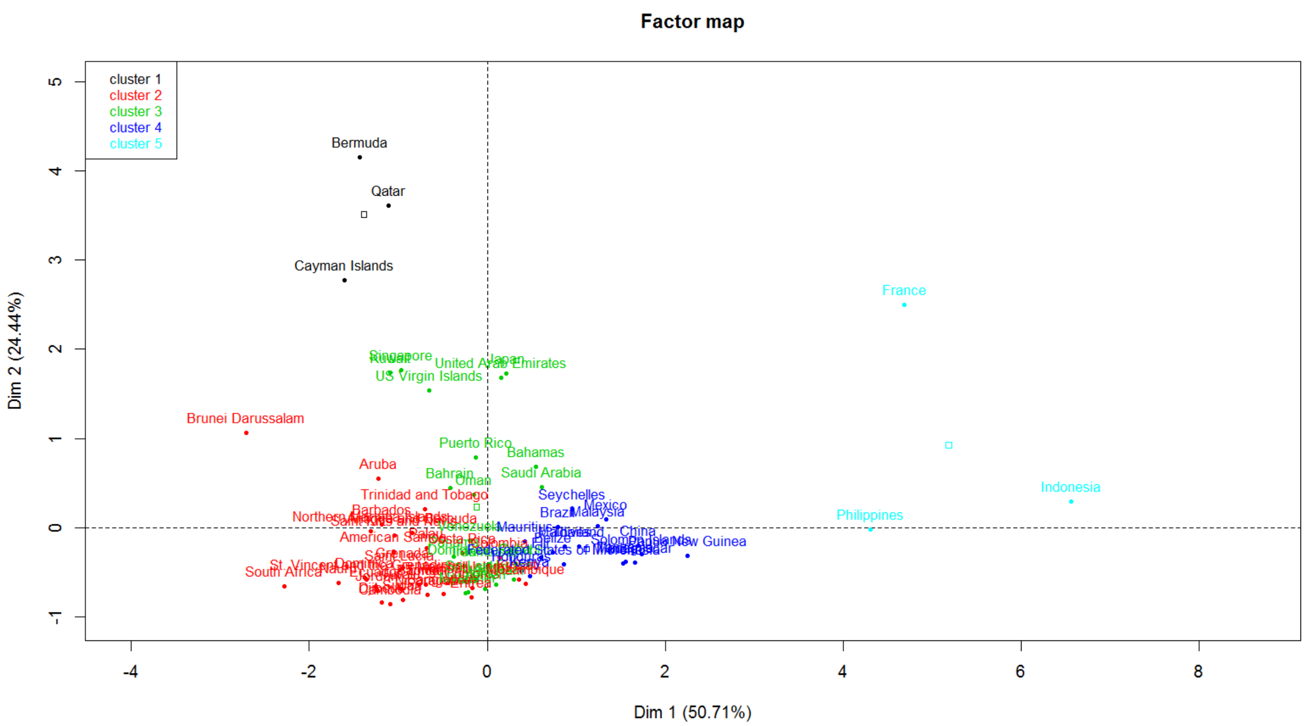
These two dimensions are different than the two first dimensions of the analysis that includes Australia and the United States. GDP per capita and ecosystem services have a higher influence in the first case, which is probably because Australia and the USA are outliers in terms of number of case studies.

The hierarchical classification was set to group the data in 4 clusters that represent the highest differences and that still allow for interpretation (it is more difficult to interpret the results when more clusters are allowed). The first cluster contains countries with a very high level of GDP per capita such as the Gulf countries, Singapore or Bermuda. The second cluster includes small developing states such as Nauru, Aruba, or Brunei. They have small coral extent, few case studies, and a low GDP per capita. This cluster also includes developing countries of average size that do not have case studies, including Cuba, Vietnam or Panama. These countries would be a fifth cluster if we had allowed it. The cluster three includes large countries such as Brazil and India, and countries with high coral extent such as Thailand or French Polynesia, which also have higher ecosystem services. Finally, the cluster four groups together Philippines and Indonesia. These two countries have a high number of case studies (notably thanks to the Coral Triangle Initiative and other scientific programs in the coral triangle), and have high coral extent and associated high ecosystem services.

c. Grouping French overseas territories

Research institutions and programs on coral reefs in overseas territories are by large funded or hosted in France, such as the CNRS and EPHE/CRIOBE. It is therefore legitimate to group the different French overseas territories (La Réunion, Mayotte, Guadeloupe, Martinique, Polynésie, Nouvelle Calédonie et Wallis et Futuna) as a single country in the analysis (note : no data are available for St-Martin and St-Barthelemy).





When grouping French overseas territories, France changes cluster and moves to the cluster with Philippines and Indonesia, characterized by high levels of case studies, coral extent, and ES. It also has a higher GDP per capita. However, it does not form a cluster on its own like the United States did.

d. Code in R (Rcmdr and FactoMineR packages)

```
> pcacs.PCA<-pcacs[, c("case.studies", "Coral.extent", "GDP.per.cap",
+   "ES.value", "latitude", "longitude")]
> res<-PCA(pcacs.PCA , scale.unit=TRUE, ncp=5, graph = FALSE)
> plot.PCA(res, axes=c(1, 2), choix="ind", new.plot=TRUE, habillage="none",
+   col.ind="black", col.ind.sup="blue", col.quali="magenta", label=c("ind",
+   "ind.sup", "quali"))
> plot.PCA(res, axes=c(1, 2), choix="var", new.plot=TRUE, col.var="black",
+   col.quanti.sup="blue", label=c("var", "quanti.sup"), lim.cos2.var=0)

pcacs <-
  read.table("C:/Users/comte/Documents/UBO/Coral studies/Data analysis/analyses in R/pca cs.txt",
   header=TRUE, sep="\t", na.strings="NA", dec=".", strip.white=TRUE)
pcacs <- pcacs[-c(4,80),]
pcacs.PCA<-pcacs[, c("case.studies", "Coral.extent", "GDP.per.cap",
  "ES.value", "latitude", "longitude")]
res<-PCA(pcacs.PCA , scale.unit=TRUE, ncp=5, graph = FALSE)
res.hcpc<-HCPC(res ,nb.clust=0,consol=FALSE,min=3,max=10,graph=TRUE)
plot.PCA(res, axes=c(1, 2), choix="ind", new.plot=TRUE, habillage="none",
  col.ind="black", col.ind.sup="blue", col.quali="magenta", label=c("ind",
  "ind.sup", "quali"))
plot.PCA(res, axes=c(1, 2), choix="var", new.plot=TRUE, col.var="black",
  col.quanti.sup="blue", label=c("var", "quanti.sup"), lim.cos2.var=0)
remove(pcacs.PCA)
pcacs.PCA<-pcacs[, c("case.studies", "Coral.extent", "GDP.per.cap",
  "ES.value")]
res<-PCA(pcacs.PCA , scale.unit=TRUE, ncp=5, graph = FALSE)
res.hcpc<-HCPC(res ,nb.clust=0,consol=FALSE,min=3,max=10,graph=TRUE)
plot.PCA(res, axes=c(1, 2), choix="ind", new.plot=TRUE, habillage="none",
  col.ind="black", col.ind.sup="blue", col.quali="magenta", label=c("ind",
  "ind.sup", "quali"))
plot.PCA(res, axes=c(1, 2), choix="var", new.plot=TRUE, col.var="black",
  col.quanti.sup="blue", label=c("var", "quanti.sup"), lim.cos2.var=0)
remove(pcacs.PCA)
```

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Afterword

A PhD on global environmental change could not end without assessing its own contribution to the problem. Most human activities contribute to the emission of greenhouse gases, but a PhD targeted to the study of tropical coral reefs from a "non-tropical" location (i.e. Brest) is particularly harmful for the environment. The different trips taken during the PhD by the author and the organization of different meetings during the PhD accounted for about 11 tons of CO_2e. Carbon credits from a Plan Vivo Standard certified forest conservation project in Fidji were purchased to offset these emissions.

Fully detailed table of content

Coral reefs ecosystem services under global environmental change; Interdisciplinary approaches to guide science and action

Global environmental change (GEC) in the ocean threatens marine ecosystems and the people who depend on them. A growing scientific effort is attempting to evaluate the impacts of environmental changes on ecosystems and ecosystem services and guide policy-making to respond to this global issue. Focusing on social-ecological systems of coral reefs, this thesis critically reviews the approaches put forward in the literature to understand gaps and to design new methodologies, assessments, and indicators to guide science and policy. Our findings show that a regionally targeted strategy of research should address complexity and provide more realistic projections about the impacts of GEC on coral reefs ecosystems and ecosystem services. We map global-scale indicators to understand where human dependence on coral reef ecosystems will be affected by globally-driven threats expected in a high-CO_2 world. We then analyze how science is responding to the challenge posed by GEC on coral reefs and to identify gaps in research. Finally, we attempt to operationalize an overlooked component of vulnerability assessments, ecological adaptive capacity, to serve as a tool to help assess where local actions can be effective in the context of climate change. This manuscript contributes to theoretical and methodological advances to evaluate impacts, vulnerability and adaptation to GEC. It develops interdisciplinary approaches for the study of social-ecological systems and ecosystem services, targeting coral reefs as a case study. Finally, it synthesizes critically the emergence of a scientific field on solutions to GEC for coral reef social-ecological systems.

Keywords: global environmental change, climate change, ocean acidification, coral reefs, ecosystem services, multiple stressors, vulnerability, resilience, adaptive management, global assessments, adaptation

Services écosystémiques associés aux récifs coralliens dans un contexte de changements environnementaux globaux ; Approches interdisciplinaires pour guider la science et l'action

Les changements environnementaux globaux (CEG) menacent les écosystèmes marins et les populations humaines qui en dépendent. Une recherche scientifique croissante tente d'évaluer les impacts des changements environnementaux sur les écosystèmes et les services écosystémiques, notamment pour guider les politiques publiques. Focalisée sur les systèmes socio-écologiques (SSE) des récifs coralliens, cette thèse analyse les approches proposées dans la littérature et conçoit de nouvelles méthodologies, évaluations et indicateurs pour guider la science et l'action publique. Nous montrons qu'une stratégie de recherche régionale doit prendre en compte la complexité et produire de meilleures projections des impacts des CEG sur les récifs coralliens et les services associés. Nous cartographions des indicateurs à l'échelle globale pour évaluer où la dépendance des sociétés aux récifs coralliens sera affectée par les menaces globales dues à un niveau de CO_2 élevé. Nous analysons comment la science répond aux impacts des CEG sur les récifs coralliens et nous identifions des pistes pour la recherche. Enfin, nous opérationnalisons une facette de la vulnérabilité, la capacité d'adaptation écologique, pour servir d'outil pour évaluer l'effectivité des actions locales dans un contexte de CEG. Ce manuscrit contribue à des avancées théoriques et méthodologiques sur l'évaluation des impacts, de la vulnérabilité et de l'adaptation aux CEG. Il développe des approches interdisciplinaires pour l'étude des SSE et des services écosystémiques, ciblant les récifs coralliens comme étude de cas. Enfin, il analyse l'émergence d'un champ scientifique sur les solutions aux GEC pour les récifs coralliens.

Mots-clés : changements environnementaux globaux, changements climatiques, acidification de l'océan, récifs coralliens, services écosystémiques, facteurs de stress multiples, vulnérabilité, résilience, gestion adaptative, évaluations globales, adaptation