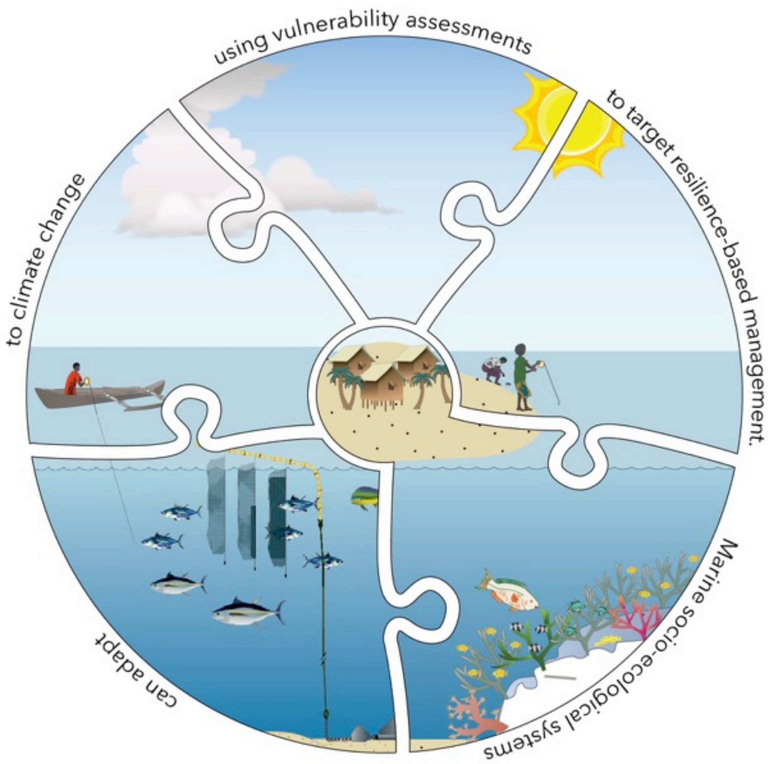

Development and implementation of a vulnerability assessment tool to inform decision-making in socio-ecological systems

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Statement of Contribution

The research presented in this thesis is based on papers published *prior* to enrolment as per the James Cook University HDR PhD procedures. The papers include some contributions from co-authors. Each chapter is anchored by a paper or book chapter where I am the lead author, and includes a statement of each authors' contribution. In addition, each chapter is supported by additional publications where I am either the lead or co-author, that strengthen my contribution to the field of work, and these are listed in Appendix 1 as further reading.

Acknowledgements

My PhD candidature was by prior publication and represents 12 years of work progressing assessments of vulnerability to develop an approach that delivers quantitative results to inform management and conservation. I am grateful for the support of my supervisors: Professors Michael Kingsford and Helene Marsh for advising me as I compiled my 'story', for their comments on my PhD 'package' and aspects of the work contained within this thesis. The research presented within the thesis was made possible by grants, contract projects, and logistical support from the following (in no particular order): Great Barrier Reef Marine Park Authority, Pacific Community (SPC), SPREP, Food and Agriculture Organization of the United Nations (FAO), WorldFish, Australian Department of Climate Change, James Cook University, Torres Strait Regional Authority, Australian Fisheries Management Authority and the Protected Zone Joint Authority, Australian Fisheries Research and Development Corporation, Australian Department of Foreign Affairs and Trade AusAID program, National Climate Change Adaptation Research Facility (NCCARF), USA Climate Change Science Program, USAID Pacific-American Climate Fund, Queensland Parks and Wildlife Service, and the Coral Reef Watch program at NOAA.

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My close friend and colleague Dr Jeff Maynard provided a consistent and valued source of support (and pressure) during my decision to undertake my PhD, and helped with funding and his unique intellect to bring together a logical and cogent argument. I'm also indebted to other key sources of working inspiration in my life, Dr Johann Bell and Jane Waterhouse.

The final versions of most of the figures produced for the thesis were created in collaboration with Dieter Tracey.

Editors and reviewers have a thankless job at times so I acknowledge their time, support, and critical comments here. Editors, reviewers, administrative and publishing staff at the following journals all contributed their time and insightful comments to the publications produced during my candidature: Climatic Change, Nature Climate Change, International Journal of Ecology, Reviews in Fisheries Science, Marine Policy, Environmental Management, Conservation Letters, Coral Reefs, Australasian Journal of Environmental Management, FAO Fisheries and Aquaculture Proceedings, and Wiley Publications.

Lastly, I would like to thank my parents, Alkis and Irene Johnson, who have always been supportive of my journey in life, my career as well as all my travels and adventures. Without their support and positive attitude to life, I could not have pursued so many fulfilling projects or dragged my family around the world with me in our magical mystery ride.

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Abstract

The Intergovernmental Panel on Climate Change (IPCC) identified the implications of global warming and ocean acidification for marine ecosystems worldwide in the second and third assessment reports released in 1995 and 2001, respectively. Evidence of impacts strengthened with the most extensive and severe thermal coral bleaching event globally in 1998, where 16% of the world's coral reefs were damaged, followed by a second global event in 2002 and a third global event in 2016. Declines in reef habitat consequently affected fish and invertebrate populations, fisheries and resource-dependent communities. In an effort to minimise impacts and support recovery, research focused on gaining a better understanding of the impacts of climate change on marine systems. Importantly, focus also increased on the flow-on effects of ecological impacts to society and economies; coupled socio-ecological systems (SES). This thesis outlines the evolution of a method that provides resource managers faced with climate change, with an assessment approach for focusing local action to increase the resilience of ecosystems by reducing the stresses of human activities.

The IPCC defines vulnerability to climate change as "*the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes*". Understanding vulnerability initially took the form of qualitative assessments that aimed to include social, ecological and economic information, as have been applied in other domains, such as hazard risk and human health, and linking public and expert knowledge to policy and sustainability governance. Through this body of work and the work of other researchers, these assessments have become more empirical over time, providing information on vulnerability by using an integrated approach that includes scientific data, traditional and community knowledge, and expert elicitation.

Information on the responses and impacts of climate change on marine SES also began to show that events were progressing faster than anticipated and some ecosystems were already changing structurally and functionally. Resource-dependent industries, such as fisheries, were already experiencing declines and there was a need for empirical vulnerability assessments to inform adaptation through decision-support tools. This matured vulnerability assessments further with targets for management a critical consideration in developing a structured approach.

The objective of this thesis was to review the evolution of climate change vulnerability assessments, and move beyond documenting the responses to and potential impacts of climate change to understanding the flow-on effects to the industries and communities that

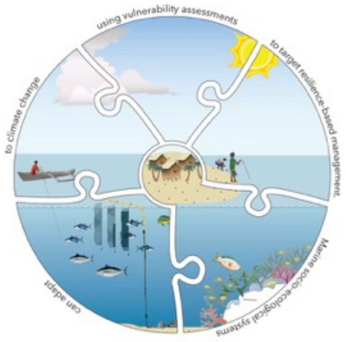
depend on marine resources, and quantitatively identifying adaptations. This thesis contributes to new knowledge in the field of climate change vulnerability by:

- Taking a conceptual model and developing indicators and criteria for quantifying vulnerability to clearly identify the drivers of vulnerability and provide a clear pathway for targeting effective adaptation actions.
- Designing a step-wise process that incorporated management objectives and evaluation of results, and
- Testing this novel criteria-based method that integrates socio-ecological factors in a range of locations and systems to field test its utility and demonstrate its application in a range of settings.

The thesis outlines the development of a Semi-quantitative Vulnerability Assessment (SQA) tool that transforms theory into practice to inform decision-making and support local resource managers in targeting their actions. The method includes explicit steps for setting management objectives, identifying indicators and criteria, and empirically scoring vulnerability to deliver outputs that address management objectives, adaptation planning, policy and resilience-based actions. The rapid assessment tool was applied in different locations and settings to deliver empirical results using available data and expert judgement to support management decisions about where to focus resources and effort. With conservation and management operating under resource limitations, the approach described in this thesis delivers assessment results that rank relative vulnerability to climate change to provide specific targets for adaptation action.

The design of the approach focused on combining empirical data and expert knowledge for ecological and social dimensions through a participatory approach to inform management. The method was applied to six locations with critically important marine resources where impacts were being observed and immediate decision-support was needed: (1) strategic planning of Torres Strait fisheries to identify which species and sectors require adaptation support, (2) food security for 22 Pacific Island Countries and Territories, (3) fisheries in northern Australia to inform future adaptation actions, (4) reefs in the Keppel Islands after a coral bleaching event to inform local actions that can support resilience, (5) the Pacific nations with coastal communities most vulnerable to ocean acidification, and most recently, (6) resource-dependent communities in Western Province, Solomon Islands.

The ability to quantify vulnerability, and apply the SQA tool to different spatial and temporal scales, is critical for the utility of results to practitioners for informing management. Importantly, management operates in an integrated sphere, where ecological and social factors contribute to vulnerability and adaptation success. The SQA tool was designed to be easy to understand, apply and communicate, and addresses the needs and issues of practical management and conservation. The tool was tested in different marine socio-ecological systems and improved based on learnings in each of these systems. The tool can now be applied to a diverse range of systems. The move from theory to practice has been important, and enables empirical vulnerability assessment results to inform adaptation actions that meet both ecological and social goals.



Chapter 1

Introduction

The global scale and complexity of climate change has driven a need for decision-support tools that inform local management of natural resources. In addition, the interdependencies between social and ecological processes have created a demand for integrated climate change assessments that can identify key sources of vulnerability and target effective adaptation. Over the last two decades, there have been many interpretations of vulnerability and the different scales it applies to (e.g. individuals, communities, ecosystems, nations), as well as fields of application for studying, characterising and understanding vulnerability (FAO 2015). In this thesis, it is postulated that using a criteria-based and integrated approach to assess vulnerability can identify key targets for management action for any linked social-ecological system. That is, complex, integrated systems in which humans are part of nature (Berkes and Folke 2000, Berkes et al. 2000), and encompass both biophysical and social factors that regularly interact to drive dynamic and complex responses (Redman et al. 2004).

Vulnerability is defined as: *the degree to which a system or species is susceptible to, or unable to cope with, the adverse effects of climate change, and depends on* *__exposure__* *(extrinsic factor),* *__sensitivity__* *and* *__adaptive capacity__* *(intrinsic factors)* (IPCC 2001, 2007, 2014). Adaptive capacity is the potential to adjust to climate change so as to moderate or cope with damages, and is functionally synonymous with recovery potential (Anthony et al. 2015). Resilience, defined as *the capacity to absorb recurrent disturbances or shocks and adapt to change without fundamentally switching to an alternative stable state* (Hughes et al. 2010), is considered a subset of vulnerability that encapsulates both sensitivity (tolerance and resistance to changes) and adaptive capacity (Marshall et al. 2013) (Figure 1).

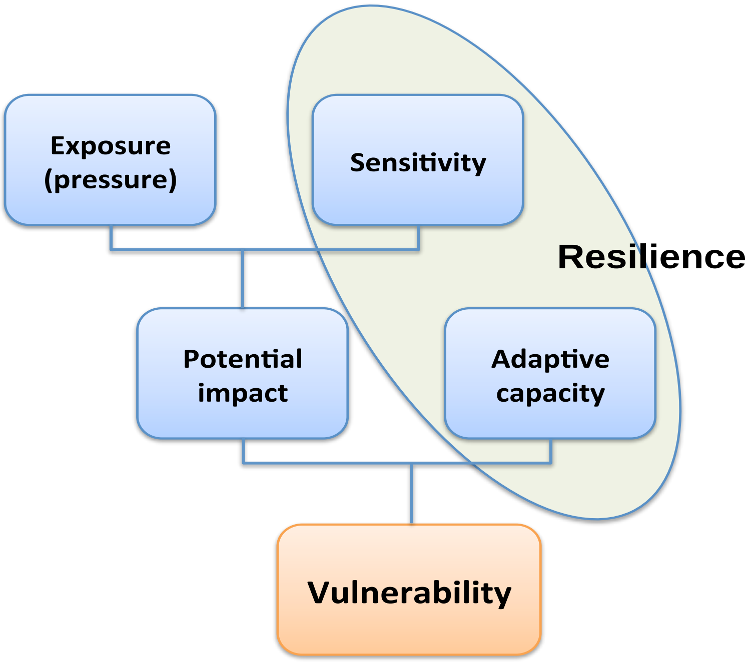


Figure 1. Conceptual framework of vulnerability used by the IPCC and UNFCCC, where resilience encapsulates sensitivity and adaptive capacity (Adapted from Schneider et al. 2007, Marshall et al. 2013).

A Socio-Ecological System (SES) that is highly exposed to a series of climate perturbations may ultimately have low vulnerability if it is resilient (tolerant or resistant) to those perturbations or can readily recover or adapt. For example, bleaching and disease affect physiologically resistant taxa less than susceptible taxa, and may provide some adaptation potential, and thus resistance to future thermal stress (McClannahan et al. 2007). Conversely, a reef system exposed to similar or less severe disturbances may be highly vulnerable if it has low resilience (tolerance or resistance). The greater the resilience, the better the system will be able to withstand damaging external conditions and/or recover from perturbations, ultimately maintaining essential functions, and goods and services in the long term (Nyström et al. 2000; Folke et al. 2004). Understanding and quantifying vulnerability to climate change allows natural resource managers to target actions to reduce vulnerability, that is, through minimising exposure and sensitivity and/or increasing adaptive capacity. Such actions can be thought of as resilience-based strategies; an increasing focus for natural resource management as an effective approach for providing insurance in the face of increasing climate-driven pressures (Nyström et al. 2008; Graham et al, 2013; Maynard et al. 2015a). Vulnerability assessments are a useful tool to help identify species, habitats or locations that are most susceptible to harm and to identify actions that reduce their susceptibility (Downing et al. 2001; Douglas 2007; Polsky et al. 2007).

While an ecosystem goods and services approach links biological and environmental resources with society by valuing natural capital that provides long-term benefits to people and society (Costanza et al. 2006), it does not explicitly allow for assessments of future scenarios. In addition, placing a monetary value on natural capital by considering services that provide economic value to human beings is too anthropocentric and often undervalues intrinsic and functional values of ecological components or systems. While useful for informing policy and planning to consider “trade offs” in protecting natural capital, the approach is not comprehensive and under-represents subsistence activities, intrinsic values and temporal trajectories (Bennett et al. 2015; Locatelli et al. 2017). Monetary estimates of ‘public good’ or ‘common resources’ cannot be accurate using conventional markets, and it is recognised that valuing these services requires new and better asset approaches (Costanza et al. 2014). Thus understanding ecosystem goods and services is only part of the solution to addressing climate change impacts (Locatelli 2016).

1.1 Niche for a new approach

With the historic view that natural resources are merely commodities for human society now widely rejected (Berkes and Folke 2000; Folke 2006), a key component of successful climate change adaptation remains the ability to link social and ecological elements to inform resilience and sustainable management. Effective management of coupled human-environmental systems needs to go beyond a purely anthropocentric or ecological approach, and requires people to make choices about how they interact with all components of the environment. The social characteristics (vulnerability or resilience) of a community influence the likelihood of establishing management actions with long-term sustainability. The knowledge that resource-dependent people critically contribute to ecological resilience – and to do so must be socially resilient – is important for effective conservation (Bahadur et al. 2013). Such community-based management is based on the idea that if conservation and social development could be simultaneously achieved, then the interests of both would be served (Ensor et al. 2016). Although many initiatives have focused on systematically integrating social and ecological systems as a pathway to adaptation (e.g. Marshall et al. 2010), practical solutions have been elusive (see Fisher et al. 2007; Metternicht et al. 2014).

Therefore, the potential of vulnerability and resilience concepts to be incorporated into management decisions to improve outcomes for both ecosystems and communities has yet to become a mainstream reality. Governments, resource managers, and communities recognise the value of assessing the social and ecological impacts of projected climate change together, but there is little consensus on the most effective framework to support integrated assessments. A comprehensive review of Vulnerability, Risk and Adaptation Assessment methods used in the Pacific (Hay and Mimura 2013) found that vulnerability assessments failed to adequately factor in details of the specific climate features, that is the pressure or hazard driving the risk, and placed disproportionate focus on the underlying determinates of vulnerability. The review characterized the use of such assessments as *"…a series of independent shifts in approaches and methods, rather than as an evolutionary progression*".

In addition, quantitative assessments of vulnerability have been rare because available frameworks are complex and lack guidance for dealing with data limitations and the complexity of integrating across scales and disciplines. A number of challenges clearly remain to achieving effective socio-ecological integrated assessments, and accurately predicting vulnerability to inform practical decision-making:

1. Management objectives need to be clearly specified, and the prioritisation of adaptation actions framed within the local context (Pacifici et al. 2015).
2. Creating a link between the projected impact of climate change on species, habitats, industries or communities, and clear actions that can best address those impacts (Poiani et al. 2011).
3. Assessments can be vague about the valued attribute of concern that the vulnerability analysis is meant to capture, or about the temporal framework within which the analysis is set (Tonmoy et al. 2014).
4. Difficulties in including two key inter-dependencies that influence how these concepts are embedded into management and conservation: (i) explicit recognition of spatial dynamics (nesting and multiple scales), and (ii) linkages between social and biophysical systems (Tonmoy et al. 2014).
5. Assumptions of simple linear relationships between indicators and vulnerability that do not reflect the key processes driving vulnerability (Tonmoy et al. 2014).
6. Lack of scientifically sound aggregation approaches that recognise and incorporate different sources of data and uncertainty (Tonmoy et al. 2014).
7. Lack of guidance on approaches and tools for conducting vulnerability assessments and insufficient evaluation and sharing of results (Metternicht et al. 2014; Hay and Mimura 2013).
8. While the use of scenarios to assess future climate change vulnerability is emphasised in many frameworks (e.g. Nakalevu 2006; USAID 2008, 2009; UNFCCC 2008), guidance is needed to demonstrate how scenarios can and should be implemented (McLeod et al. 2015).

Structured criteria-based vulnerability assessments provide a framework for meeting many of these challenges. Criteria-based approaches are suitable for identifying regional management priorities, particularly in data-limited circumstances, and are less resource-intensive (Pacifici et al. 2015). They also provide an avenue for prioritising management actions for multiple sectors, since it is not possible to manage for all species, communities or sites (Bottrill et al. 2008). Effective decision-making is about prioritising actions to meet management objectives for a specific sub-set of the SES (Game et al. 2011), which in this case, are those components most vulnerable to climate change.

1.2 The challenge for marine managers

Anthropogenic climate change (global warming and ocean acidification) poses a major threat to marine ecosystems and resource-dependent industries and communities – collectively referred to as socio-ecological systems (SES). Although predicting the exact impacts of climate change on marine ecosystems is difficult, scientists agree that climate change has the potential to seriously degrade marine habitats, decrease marine biodiversity, cause species distributional changes and reduce ocean productivity (Hobday et al. 2008; Hoegh-Guldberg and Bruno 2010; IPCC 2014). The long-term condition of marine ecosystems and the sustainability of the communities that they support are therefore threatened by the changes brought about by global warming and ocean acidification.

Tropical marine ecosystems, including coral reefs, are considered particularly at risk from climate change (Bellwood et al. 2006; Hoegh-Guldberg et al. 2007; Nicholls et al. 2007). More than 800 million people from 109 countries live within 100 km of coral reefs, which provide important sources of ecosystem goods and services for these communities (Donner and Potere 2007; World Resources Institute 2012). Changes to tropical marine ecosystems will therefore have serious implications for the millions of people that depend on them for food and livelihoods (e.g. Cheung et al. 2009; Bell et al. 2013).

For example, climate-driven thermal bleaching in 1998 resulted in 16% of the world's coral reefs being damaged (Wilkinson 2002) with consequences for reef fisheries observed in the western Pacific, Indian Ocean, Persian Gulf, Middle East and the Caribbean (Wilkinson 2002, 2008; Pratchett et al. 2004, 2008). Projections of increasing incidence of thermal coral bleaching are already evident with the largest coral bleaching event documented in many nations during the 2016 summer and the Great Barrier Reef experiencing two successive severe bleaching events in 2016 and 2017 (Normile 2016; Hughes et al. 2017). This trend is expected to continue with models predicting that some tropical nations will experience annual severe bleaching before 2040 (e.g. Cayman Islands, Samoa, Palau, Israel) and all Pacific nations will experience severe annual bleaching by 2050 under RCP8.5 (van Hooidonk et al. 2016).

Many Pacific Island countries and territories receive unprecedented economic benefits from tuna fisheries operating within their exclusive economic zones due to license fees from foreign fishing fleets, as well as tuna processing and national fishing fleets (Bell et al. 2015). Changes to Pacific Ocean temperatures and currents driven by climate change are projected to shift the distribution of skipjack and yellowfin tuna (the most targeted species in the region) due to changes in the locations preferred by these two species. Recent modeling (Lehodey et al. 2015; Nicol et al. 2016; Senina et al. 2016) projects that the average abundance of yellowfin tuna are expected to decline in the west and south of the Pacific region. While skipjack tuna are projected to decrease in abundance mainly in equatorial areas west of ~160^{o}E, with increases in abundance expected elsewhere. Modelling for two other large pelagic fish commonly caught by small-scale fishers – wahoo and mahi mahi – indicates that climate change is likely to cause a poleward migration of both species (Bell et al. 2017), with mahi mahi distribution most affected. These distributional shifts will have implications for the fishing fleets in that target tuna and other large pelagic fish, as well as the coastal communities that depend on the catch for food and livelihoods.

Similarly, projected changes to coastal fisheries catches in the Pacific, primarily by small-scale fishers, reflects the significant impacts of climate change as well as the heavy reliance on reef fish for food and artisanal income. Projected declines in coastal fisheries catches of as much as 30% in Kiribati, 28% in Tonga and the Marshall Islands, and 25% in Solomon Islands, Vanuatu, the Federated States of Micronesia, Nauru, New Caledonia and Northern Marianas Islands by 2100 under a high emissions scenarios (Bell et al. 2011b) demonstrate the critical need to better understand the drivers of these changes and the most vulnerable sectors to target adaptations. The effects of climate change on small-scale coastal fisheries are expected to exacerbate current pressures due to overfishing and poor management, and widen the gap between the amount of fish recommended for good nutrition and sustainable harvests. To optimise the contributions of small-scale fisheries to food security in Pacific nations, adaptations are needed to minimise fisheries declines and provide alternative sources of protein (Bell et al. 2017).

1.3 A novel quantitative vulnerability assessment approach

This thesis postulates that it is possible to design a criteria-based vulnerability assessment method that can meet the challenges marine managers face and transform theory into practice to inform management decision-making. Importantly, the method combines lessons from different approaches and can be tailored to specific circumstances. The design of a decision-support tool for practitioners would need to fulfill the following criteria:

(1) Identify management objectives, attributes to assess vulnerability, and appropriate spatial/temporal scales,

(2) Provide robust and semi-quantitative results,

(3) Use available data (published and expert knowledge),

(4) Be multi-sectoral and multi–disciplinary,

(5) Integrate socio-ecological factors using science-based indicators,

(6) Address sources of uncertainty,

(7) Be accessible to practitioners, and

(8) Facilitate planned rather than reactive adaptation by prioritising targets for action.

The vulnerability assessment tool developed in this body of work aims to address these needs, minimise the limitations of past methods, and provide a clear pathway for adaptation in the face of climate change. Importantly, it merges ecology and society into one framework by including indicators for 'adaptive capacity' that encompass physiological tolerances, epigenetic and genetic effects, as well as governance and leadership that support social adaptive capacity. The work described in this thesis has contributed to new knowledge by taking a conceptual model of climate change vulnerability, adapting it and developing indicators with criteria that integrate ecological and social data to quantify results that clearly identify the source of vulnerability and provide a clear pathway for targeting adaptation actions.

The method was developed through a series of case studies that applied the approach to different systems and each contributed to the learnings and evolution of the method. Development began with the theoretical review of the vulnerability framework and how it could be conceptually linked to resilience and adaptation actions. These qualitative reviews considered the main drivers of change in marine and coastal ecosystems and the policy and planning context that management operates in to determine what type of tool would be most useful (Chapters 2 and 3). It was through these reviews that it was identified that due to resource and data limitations, a rapid approach that didn't require new data collection was needed. In addition, the theoretical analysis identified the importance of linking social and ecological factors through an integrated method to inform adaptation.

With these learnings came the recognition that while the vulnerability assessment framework had utility and was universally recognised (Schroeter et al. 2005; Schneider et al. 2007), in order to provide certainty for management, there needed to be indicators that linked climate variables with system components and integrated socio-ecological factors to assess vulnerability (Chapter 4). While the theoretical reviews considered coastal and marine ecosystems more generally, the evaluation of assessment indicators focused on marine fisheries and supporting habitats due to their importance for food security and livelihoods as well as there being available data.

A challenge facing practitioners in this field is the lack of simple methodologies or agreed frameworks for conducting vulnerability assessments and targeting resilience-based actions. Based on lessons from previous research (e.g. Füssel and Klein 2006; Glick et al. 2011; Cinner et al. 2013; Hay and Mimura 2013; Tonmoy et al. 2014; McLeod et al. 2015), Chapters 5 and 6 of this thesis deliver a practical Semi-quantitative Vulnerability Assessment (SQA) method that uses evidence-based indicators to assess vulnerability and prioritise management actions. The application of the semi-quantitative approach focused further on SES centred around marine fisheries in specific locations where they are both significantly important to local communities and economies, as well as where there are management policies and plans for sustainable management. The development and application of the SQA has therefore been consistent in that it focused on SES where fisheries are important and management actions are needed. It was also spatially variable to test its utility in different locations since climate change is known to be spatially variable and therefore to have differential impacts on SES in different locations. Having developed a method and tool that is robust under different climate change projections, and tested its utility for integrated SES, its use is now being expanded to other locations and resources (e.g. Maynard et al. 2018).

The method that has been developed is framed around clearly articulated management objectives that define the values or resources of concern and the spatial and temporal boundaries. Importantly, the SQA method uses available data and expert judgement to rank relative vulnerability, making it rapid, participatory and accessible to practitioners for decision-making. It is a relatively easy method to implement and communicate to stakeholders, and can be applied to the local context of any socio-ecological system; advancing theory into practice.

Ultimately, this body of work over 10 years has designed and tested a novel criteria-based vulnerability assessment method that integrates socio-ecological factors and transforms theory into practice to inform decision-making and resilience-based management. It provides an assessment approach for focusing local action on supporting the resilience of ecosystems by reducing the stresses of human activities.

1.4 Thesis focus and research objectives

This is a PhD by *prior publication* under the James Cook University HDR procedures. Thus all of this work was published prior to thesis submission, and the thesis document has been produced from the publications and manuscripts. The synthesising theme is that *marine socio-ecological systems can adapt to climate change using vulnerability assessments to target resilience-based management*.

The objectives of this thesis are to:

(1) Evaluate climate change implications on ***marine socio-ecological systems***.
(2) Demonstrate that with climate change knowledge, marine socio-ecological systems ***can adapt***.
(3) Conceptualise how indicators of vulnerability and resilience ***to climate change*** can inform decision-making.

(4) Develop a novel semi-quantitative ***vulnerability assessment*** tool focused on integrating socio-ecological factors at management-relevant scales.
(5) Demonstrate how the application of this tool in six different locations can inform decision-making ***to target resilience-based management***.

The thesis contains five data chapters each of which aims to address a specific research focal area or need. Each chapter begins with a brief introduction to the publications and their key messages relative to the thesis objectives and includes the publications in full. Each chapter is anchored by one journal publication, except Chapter 2 that is based on two published book chapters. Supporting supplementary publications that strengthen my contribution to the field of work in each chapter are included in Appendix 1 as further reading on each topic.

Chapter 2

This chapter is foundational in that it reviewed and synthesised the climate change implications for tropical marine ecosystems using a qualitative vulnerability lens. In particular, the chapter focused on whether the social and economic implications of climate change can be integrated with ecological components, particularly in nations with high resource-dependence, such as the Pacific Islands region. The chapter provides an application of the IPCC vulnerability assessment framework in a qualitative manner, to broadly identify what adaptation options and policies are needed to minimise vulnerability to climate change.

Chapter 3

The qualitative assessment of vulnerability using a structure approach provides broad targets for action, however, a more quantitative method was the objective of this work. Therefore understanding the current state of knowledge for climate change adaptation that relates to marine socio-ecological systems, and how SES have demonstrated adaptations to change key to informing the development of assessment criteria. This chapter documented the current scientific information on marine SES adaptation, and critical discussed how it can be used in conservation science and management practice to inform and support adaptation of marine socio-ecological systems. Importantly, this chapter provided boundaries for adaptive capacity that were used to inform the criteria and indicators developed for the SQA method.

Chapter 4

This chapter critically examined the structured approaches for assessing the vulnerability of coupled socio-ecological systems to climate change, and the utility of the IPCC framework for marine ecosystems. Using marine capture fisheries as an example, the work considered how the vulnerability assessment could be applied, and what factors would need to be included in order to conduct a semi-quantitative assessment. Ultimately, the chapter determined that science-based indicators designed using vulnerability and resilience concepts could provide a semi-quantitative lens to a structured assessment framework to inform management and adaptation.

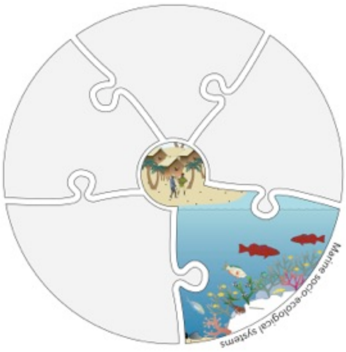
Chapter 5

This chapter provides the first full application of the vulnerability framework in a semi-quantitative assessment. Working with a single sector in a socio-ecological system that is data rich for some components and data poor for others, the research applied an optimized method to rapidly assess climate change vulnerability and quantify the results to support marine conservation and management. It demonstrated how results of the semi-quantitative vulnerability assessment (SQA) can empirically inform local conservation and management decision-making.

Chapter 6

The final research chapter of the thesis provide a series of case studies that applied the SQA tool at different spatial and temporal scales to validate that the method does deliver results that can inform practical management that integrates ecological and social goals. The application to different SES and locations very deliberately sought to understand how boarding the tool could be applied and its utility to a range of natural resource managers. It was demonstrated that the assessment results can inform prioritised resilience and adaptation actions to maximise socio-ecological benefits across different scales.

The thesis concludes with Chapter 7, which provides an overview of my research and novel assessment approach that demonstrates strong outcomes that justify future practical applications.



Chapter 2

Climate change implications for marine socio-ecological systems

This chapter includes two substantial bodies of work that cover spatially extensive assessments of the implications and qualitative vulnerability to climate change of marine ecosystems in the Great Barrier Reef (Johnson et al. 2013a; Publication 1) and Pacific Island region (Johnson et al. 2017; Publication 2). This work was based on emerging frameworks that aim to assist resource managers understand the implications of and deal with the uncertainty of climate change (Schroter et al. 2004; Schneider et al. 2007). Chapter 2 addresses Objective 1: Evaluate climate change implications on marine socio-ecological systems, and is based on two published chapters where I am the lead author.

My contribution to Publication 1 was to prepare the chapter structure and draft the first complete version, and then request focused contributions from all co-authors for specific sections. Maynard provided input on the sections pertaining to cumulative impacts and exposure to disturbances, including providing exposure maps from a Great Barrier Reef Marine Park Authority project we were co-investigators on with van Hooidonk and Puotinen (Maynard et al. 2015b). The remaining co-authors contributed to the sections pertaining to their field of expertise: Devlin to impacts of episodic events, Wilkinson to catchments and pollutant loads, Anthony to resilience, Yorkston to shipping, and Heron to thermal stress. Editors and reviewers of the *Reef Water Quality Scientific Consensus Statement* provided insightful comments, as did colleagues who authored other chapters in the publication.

My contribution to Publication 2 was to prepare the chapter structure and draft the first complete version, and then request focused contributions from all co-authors for specific sections. Bell provided input on the section pertaining to the importance of fisheries and aquaculture in the tropical Pacific, as well as adaptations for all sectors from a Pacific Community (SPC) project we were co-investigators on (Bell et al. 2011a,b, Johnson et al. 2013b). The remaining co-authors contributed to the sections pertaining to their field of expertise: Allain to impacts on oceanic food webs, Hanich to the economic valuations for tuna, Moore to status of coastal fisheries, Nicol to status of tuna fisheries, and Pickering to aquaculture, while Lehodey and Senina provided updated tuna modeling data and biomass projection maps. Editors and reviewers of the book *Climate Change Impacts on Fisheries and Aquaculture: A Global Analysis* provided insightful comments.

The main findings in Chapter 2 are:

- Climate change is a significant driver of changes in tropical marine ecosystems, undermining resilience now and into the future due to increasing surface temperatures, ocean acidification, sea-level rise, more intense storms, and more extreme rainfall and flood events.
- Impacts from climate change and variability are already being observed in the Great Barrier Reef (GBR) and Pacific region, and include habitat degradation and loss, species distributional shifts, reduced calcification, local eutrophication and declining productivity.
- The Pacific region has a vast ocean area and as a result, the greatest dependence on marine resources in the world for economic development, food security and income to support livelihoods. Climate change impacts therefore pose a critical threat to Pacific nations and their people.
- While many impacts from climate change drivers have been documented, the potential for additive and synergistic effects will be more severe than indicated from studies of individual stressors.
- The recent cluster of severe cyclones and wet seasons in the Pacific region (including the GBR) have caused spatially extensive and cumulative impacts and reduced the recovery time for ecosystems between disturbances. Such cumulative impacts are likely to continue, as more severe disturbances combined with deteriorating conditions become the norm, leading to further ecosystem-wide declines.
- Recent downward trends in many indicators of ecosystem health (e.g. coral cover, seagrass meadow extent) highlight critical questions about whether the system will be resilient enough to sustain ecosystem functions, biodiversity and populations into the future under continued global, regional and local pressures.
- Knowledge about which disturbances or impacts represent perturbations with limited influence on resilience *per se* and which represent threats to resilience is critical as management and conservation work to support ecosystems in the face of climate change.
- The transition from documenting potential impacts to finding ways to integrate ecological and social factors to support practical adaptations is essential in the face of climate change, particularly in nations and communities with high resource-dependence.

2013 Scientific Consensus Statement

Chapter 2
Resilience of Great Barrier Reef marine ecosystems and drivers of change

Johanna Johnson, Jeffrey Maynard, Michelle Devlin, Scott Wilkinson, Ken Anthony, Hugh Yorkston, Scott Heron, Marji Puotinen, Ruben van Hooidonk

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The Pacific Island Region: Fisheries, Aquaculture and Climate Change

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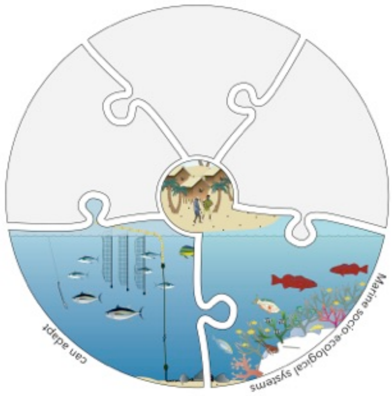
Chapter 3



Understanding climate change vulnerability enables actions to adapt

This chapter includes a journal article that synthesised the available science about climate change impacts in Australian marine ecosystems and analysed how it can inform conservation management (Johnson and Holbrook 2014; Publication 3). This research used a systematic approach to critically analyse how the current understanding of climate change impacts, thresholds, and responses of marine ecosystems can enable “no regrets” adaptations now and under future accelerating climate change, addressing Objective 2 of the thesis.

My contribution to Publication 3 was to conduct all synthesis and analysis, draft the first complete version, and then request focused contributions from my co-author. Holbrook provided general input on the style and language and minor edits, with a primary focus on ensuring complementarity with a companion publication we co-authored on climate change impacts and adaptation of commercial marine fisheries in Australia (Holbrook and Johnson 2014). Editors and reviewers of the *International Journal of Ecology* provided comments and useful edits.

The main findings in Chapter 3 are:

- The challenges that climate change poses for marine ecosystems are already manifesting in impacts at the species, population, and community levels, exacerbating current pressures and significantly increasing the challenge for marine management.
- Keystone species that form the foundation of marine habitats, such as coral reefs, kelp beds, and temperate rocky reefs, are projected to pass critical thresholds with subsequent implications for communities and ecosystems.
- As climate change places additional pressure on already degraded marine ecosystems, management needs to consider ecological resilience, cross-sectoral integration, long-term ecological stability, and facilitate cooperation between jurisdictions.
- A new management paradigm is needed that includes climate-aware objectives that are not underpinned by a return to historic baselines but rather knowledge about climate impacts, ecosystem responses and potential future climate scenarios.

- Understanding the sources of climate change vulnerability of integrated marine ecosystems therefore provides a focus for “no-regrets” adaptations that can be implemented now and refined as knowledge improves.

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Review Article

Adaptation of Australia's Marine Ecosystems to Climate Change: Using Science to Inform Conservation Management

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The challenges that climate change poses for marine ecosystems are already manifesting in impacts at the species, population, and community levels in Australia, particularly in Tasmania and tropical northern Australia. Many species and habitats are already under threat as a result of human activities, and the additional pressure from climate change significantly increases the challenge for marine conservation and management. Climate change impacts are expected to magnify as sea surface temperatures, ocean chemistry, ocean circulation, sea level, rainfall, and storm patterns continue to change this century. In particular, keystone species that form the foundation of marine habitats, such as coral reefs, kelp beds, and temperate rocky reefs, are projected to pass thresholds with subsequent implications for communities and ecosystems. This review synthesises recent science in this field: the observed impacts and responses of marine ecosystems to climate change, ecological thresholds of change, and strategies for marine conservation to promote adaptation. Increasing observations of climate-related impacts on Australia's marine ecosystems—both temperate and tropical—are making adaptive management more important than ever before. Our increased understanding of the impacts and responses of marine ecosystems to climate change provides a focus for "no-regrets" adaptations that can be implemented now and refined as knowledge improves.

1. Introduction

Australia's marine ecosystems are typically areas of high biodiversity and important for the ecosystem services they provide to marine industries (e.g., fisheries, aquaculture, and tourism) and people, as well as being iconic features of Australia's national identity. Climate change poses significant challenges for sustainably managing marine species, communities, and ecosystems. Already impacts are being observed in Australia's marine ecosystems due to extreme climate events such as heat waves [1], tropical cyclones [2–4], and flooding [5, 6]. Further, climate change projections suggest extremes are likely to increase in the future [7, 8]. The magnitude of impacts on marine ecosystems and whether they can adapt depend on the rate and magnitude of change, the response of marine species and ecosystems, and their resilience to future climate change [9]. Some marine species and ecological communities will be able to respond, while others will require support in order to adapt to increasing climate-related stressors.

The current condition of marine ecosystems plays an important role in determining how they will respond to climate-related disturbances (both acute and chronic) and whether they are able to cope with an increasing rate and magnitude of change. This natural capacity to withstand and recover from disturbances, or resilience [10, 11], is often described as the maintenance or return to a stable state [12]. Some projected climate-related changes are within the historic range of variability experienced by marine species. However, the global rate of change is projected to exceed this historic exposure [13]. Natural adaptation and resilience may, therefore, not be sufficient to cope with projected changes and may need to be supported by appropriate strategic conservation. The range of strategies available to managers to enhance resilience of marine ecosystems will vary spatially and temporally depending on (i) the response of species, communities, and ecosystems to climate change, (ii) their current condition, (iii) trade-offs with other socioeconomic imperatives, and (iv) existing governance arrangements and management paradigms.

This review provides a synthesis of recent scientific studies relevant to climate change impacts and adaptation of Australia's marine biodiversity and ecosystems and how these can inform conservation management. Adaptation of marine ecosystems to climate change can be reactive or anticipatory, planned or autonomous [14, 15], and occur at a range of scales from individuals to complex ecosystems. For most natural systems, adaptation is inherently autonomous. However, adaptation can be assisted by interventions that maximise resilience and reduce harm [16] or realise opportunities associated with the consequences of climate change. Management can influence adaptation and resilience of marine ecosystems in two ways: by acting to reduce the exposure of ecosystems to climate change that reduces condition and undermines resilience or by supporting autonomous adaptation of ecosystems [17]. Conservation management is now undertaking vulnerability assessments to better understand the sources and scales of climate-related impacts and to inform response strategies that build adaptive capacity and enhance resilience [6, 18–20]. Implementing planned adaptations to elicit strategic change in anticipation of a variation in climate requires management regimes that take a systems perspective, particularly across sectoral and jurisdictional boundaries; embraces diversity and change, particularly through accountability, transparency, and being inclusive; and includes coordinated governance [21].

Specifically, this review considers recent climate change science—impacts and thresholds of response for marine species and ecosystems—and how this can focus conservation management on ecosystem-based approaches and planned adaptations. It represents the key findings of a larger initiative to determine whether the research priorities identified in Australia's National Climate Change Adaptation Research Plan for Marine Biodiversity and Resources [22] are being addressed that included a review of marine fisheries [23]. This review provides a synthesis of climate change implications for conservation management and what research focus is needed to inform future management under a changing climate.

2. Observed Impacts of Climate Change

The impacts of climate change on Australia's marine ecosystems are already being observed in southeast temperate regions (e.g., [24–26]), the southwest [1, 27], and the tropical north (e.g., [28–30]). Recent research has documented impacts in southeast Australia on marine species in response to changing climate drivers, including a decline of giant kelp (*Macrocystis pyrifera*) by up to 95% at some sites [31]; a poleward range extension of the long-spined sea urchin (*Centrostephanus rodgersii*) into Tasmania [32], poleward shifts of seaweed species along Australia's east and west coasts since 1940 [33], and tropicalization of fish communities [34]. In the southwest, reduced resilience of kelp to disturbances at the northern limit of their range has been documented [35], a marine heat wave in 2011 led to a range contraction in the habitat-forming seaweed *Scytothalia dorycarpa* [27] and a subsequent shift in community structure towards a depauperate state, as well as a tropicalization of fish communities [1].

Australia's temperate marine regions have high rates of species endemism (e.g., [36]) and with the observed [37] and projected [38] accelerated warming of Australia's southeast marine waters and Tasman Sea, some temperate species are already showing southward (poleward) distributional shifts, while other endemic species will be unable to shift their distribution further south as available habitat is limiting. The expansion of the long-spined sea urchin (*C. rodgersii*) into Tasmanian waters from New South Wales is altering benthic habitats critical for local species, such as rock lobster and abalone [32]. Southward distributional shifts, attributed to warming temperate oceans, have also been documented for 45 species of fish in southeast Australia since the late 1800s [25] and 16 species of Tasmanian invertebrates [24].

Observed impacts have also been documented in tropical Australia, such as a decline of 11.4% in coral calcification on the Great Barrier Reef since 1990 [39], declines in fish diversity after climate-related habitat disturbances [40], and reduced adult foraging and chick provisioning of some seabird species during heat waves and after tropical cyclones [41–43]. Stochastic climate-related disturbances, for example, tropical cyclones, floods, and excessive and/or prolonged marine heat waves, have been documented to cause declines in the condition of tropical marine ecosystems. These include documented declines in coral cover on the Great Barrier Reef from 28% to 14% since 1985 [28] and declines in seagrass meadows since 2009 with 94% of sites surveyed classified as being in "poor" or "very poor" condition [29].

Ocean acidification, coupled with local stressors, is expected to impact coralline algae biomass and recruitment, an important component of temperate and subtropical near shore communities [44], with consequences for habitat structure. Reduced calcification will also affect temperate invertebrates, such as early life history stages of sea urchins, compounded by the negative effects of increased temperature on embryo development [45]. Many marine invertebrates are "keystone species" and any impacts on their populations will have consequences for habitat structure and other species that rely on that structure [46].

During the past 15 years, several spatially extensive coral bleaching episodes have occurred on the Great Barrier Reef (GBR) as a consequence of marine heat waves [47, 48]. These climate-related impacts have also been observed in other tropical ecosystems in Australia with marine heat waves causing the first-ever reported bleaching on reefs in the Torres Strait in 2010 [49] and at Ningaloo Reef in Western Australia in 2011 [1]. The ability of coral reefs to recover from bleaching events varies between coral species and among regions, but there is only limited evidence to date that corals can adapt to the projected rate and magnitude of increasing sea temperatures combined with ocean acidification [50]. Marine heat waves have also been observed to cause mortality and reduce reproductive success in intertidal and estuarine seagrass species (e.g., [29, 51]).

A long term decline in coral calcification documented on the GBR is postulated to be due to the combined effects of increasing temperature stress and a declining saturation state of seawater aragonite, with a threshold reached in the late 20th century [52]. Further, studies of coral reefs surviving in naturally low pH waters of 7.8–8.1 due to volcanic CO_2 seeps in Papua New Guinea have documented reductions in coral diversity, recruitment, and abundance of framework building corals, as well as benthic invertebrates and fish [53]. They also documented shifts in competitive interactions between taxa as pH declines from 8.1 to 7.8 (the change expected if atmospheric CO_2 concentrations increase from 390 to 750 ppm [53]). However, coral cover remained constant between pH 8.1 and ~7.8, as massive *Porites* corals dominated (despite low rates of calcification) resulting in a low diversity reef, and reef development ceased below pH 7.7.

Other tropical species are also experiencing the effects of climate-driven changes in habitats, for example, breeding seabirds that have lost suitable nesting islands due to rainfall changes impacting vegetation and increasing inundation from more intense storms [54, 55], and declines in fish diversity after coral bleaching and tropical cyclone induced habitat disturbances [40]. Impacts on important marine turtle nesting islands are increasingly becoming evident, with elevated sand temperatures biasing hatchling gender ratios toward more females or exceeding thermal mortality thresholds [56, 57]. Habitat range changes have also been documented for coral reefs in Japan, where examination of 80 years of data shows a poleward range expansion of tropical coral species [58].

3. Ecological Thresholds of Response

The value of recent observations of climate change impacts is that they can provide insight into thresholds where a relatively small change in external conditions causes a significant change in an ecosystem. When such an ecological threshold has been passed, the ecosystem may no longer be able to return to a stable state and this can lead to rapid declines in ecosystem health [59]. It is for this reason that conservation management is starting to focus on enhancing ecosystem resilience as a key strategy for sustaining marine systems and avoiding these “tipping points” or thresholds of irreversible change. Understanding the environmental conditions that drive thresholds to be crossed and identifying specific communities or habitats that are on the brink of crossing a threshold are critical for being able to successfully manage for resilience.

Studies of ecological thresholds use a range of approaches, including long term studies of ecosystem condition and response [50]; investigations of historic reconstructions using paleorecords [60], ice cores [61], and coral cores [62]; experimental manipulation of environmental conditions to detect thresholds of change [63]; and monitoring of bioindicators coupled with models of ecosystem responses to changing conditions [59]. Most of the recent work on critical thresholds for marine ecosystem change has focused on the impacts of single parameters—in particular, temperature—rather than multiple stressors. The potential for additive, negative, and deleterious synergistic effects will be more severe than indicated from studies of individual stressors [64]. However, for some species antagonistic effects (or reduced stress) are also possible; for example, benthic invertebrate biomass in southeast Australia increased as a result of the interacting effects of fishing, ocean warming, and acidification [65].

An examination of historic climate data and coral reef responses worldwide has shown that mass coral bleaching causing mortality in geographically extensive locations started when atmospheric CO_2 concentrations exceeded 320 ppm (with associated ocean warming), and bleaching became sporadic but highly destructive in most reefs at ~340 ppm. Coral reefs are projected to be in rapid and terminal decline at 450 ppm (2030–2040 at current rates) from multiple synergies of mass bleaching, ocean acidification, and local environmental impacts [64].

Corals live within 1-2°C of their upper thermal limit [66] and the warming of oceans has raised the baseline sea surface temperature closer to their thermal bleaching threshold, so that natural variability is more likely to exceed this threshold [67]. Tropical coral reefs exist in ambient waters of 28.2–34.4°C [68] and therefore have higher bleaching thresholds than subtropical corals along Australia’s east coast, whose bleaching threshold ranges from 26.5 to 26.8°C [69]. Hence, subtropical reefs may be more susceptible to marine heat waves [69] in a region of eastern Australia that is projected to experience accelerated ocean warming.

Recent modelling of increasing air and sea temperature impacts on marine turtle nesting in northern Australia projects that hatchlings will be primarily females at three north Queensland nesting sites by 2070 (Moulter Cay, Milman Island, and Bramble Cay) and by 2030 at Ashmore Island (WA) and Bare Sand Island (Northern Territory). These latter two sites are projected to regularly exceed the upper egg thermal incubating threshold (33°C) by 2070, resulting in deformed hatchlings and severe mortality [56].

There is a growing body of work using experimental studies that demonstrate the interactions between multiple climate stressors on abalone and sea urchins [45, 63], corals [70, 71], and forams [72]. Studies on the interactive effects of warming and acidification on abalone (*Haliotis coccoradiata*) and sea urchin (*Heliocidaris erythrogramma*) found deleterious effects on development (e.g., number of spines produced and skeleton formation) with increasing acidification (pH 7.6–7.8). An interactive effect between stressors was also documented for sea urchins, with +2°C warming reducing the negative effects of low pH but the developmental thermal threshold was exceeded at +4°C [63]. A review of marine invertebrate thresholds more broadly shows that all development stages are highly sensitive to warming and larvae are particularly sensitive to acidification [45].

In addition, the proposal that elevated nutrients can lower coral bleaching thresholds [73] has been demonstrated experimentally by Wiedenmann et al. [74] who showed that nutrient enrichment (via imbalances) can increase the susceptibility of reef corals to bleaching. This synergistic effect of nutrients and temperature on bleaching response demonstrates the importance of managing local stressors as an effective management strategy to increase the resilience of corals to marine heat waves.

The consequence of passing a critical threshold is that ecosystem condition declines and may not be able to return to a stable state [75]. However, such phase shifts have been shown to be less common than expected [76] or transient [77], demonstrating the dynamic nature of resilient reefs and the need to understand ecological thresholds better. Although, for some marine species and ecosystems, ecological thresholds have been identified, there are limited examples of an Australian marine ecosystem passing such a threshold and undergoing a complete phase shift. International examples of marine phase shifts exist [78]. However, there is still debate whether marine ecosystems operating under a dynamic equilibrium are more likely to exhibit phase shifts (a change in community composition in response to a persistent change in environmental conditions) or exist in alternative stable states (more than one state occurring in the same place and under the same environmental conditions at different times) [79] and if in fact crossing a threshold is necessary to cause such a shift [80].

Adaptive management will be facilitated if the ecological processes with nonlinear behaviours and/or threshold responses to changes in climate drivers can be identified [59, 81]. Further research on critical thresholds for marine ecosystems and methods for measuring ecosystem dynamics and processes is required for a range of marine ecosystems in Australia, particularly for species of conservation concern and keystone species where climate change impacts have already been observed (Table 1).

4. Climate Change Implications for Marine Conservation Management

Current conservation management uses a number of strategies for managing marine resources in Australia, including legislation for extractive activities, regulation of fisheries, international agreements, and marine reserves or marine protected areas (MPAs). Marine reserves (that include no-take areas) can have great benefits for mobile species [82], benthic communities (e.g., [83]), biodiversity conservation [84], and protection of genetic diversity for future adaptation [85]. However, their utility for protecting marine ecosystems from changing climate pressures has been strongly debated. A recent study near Maria Island off Tasmania's east coast showed that marine reserves have the potential to build ecological resilience through mechanisms that promote species and functional stability and resist colonisation by warm water vagrants [34].

The Australian Government has established a system of marine reserves in offshore waters to contribute to the long term conservation of Australia's marine ecosystems, protect marine biodiversity, and maintain resilience. One of the guiding principles when establishing these reserves was to accommodate climate change as far as practicable, using design principles and zoning that promote resilience and adaptation, in particular, accommodating latitudinal or longitudinal movement in ecosystem or species distributions and changes in oceanography, anticipated in response to climate change [86]. The addition of these areas has expanded the total size of Australia's marine reserve estate to 3.1 million km^2, making it the largest system of marine reserves globally [86]. However, criticism about the location of these new marine reserves in areas that naturally have low exposure to impacts due to their remoteness or low commercial utility questions their contribution to the real goals of nature conservation, that is, to avoid threats and protect biodiversity [87].

Current marine management clearly identifies the need to protect marine ecosystems in the face of climate change and allow for changing ocean conditions, distributional shifts, and natural adaptation. The utility of MPAs in the face of climate change, therefore, will depend on their location and their ability to protect ecosystem connectivity and promote recovery after climate disturbance. However, the return period of disturbances will be an extrinsic factor that can undermine resilience, and spatial factors strongly influence connectivity. Simulations of coral reef ecosystem connectivity show that climate change is expected to reduce population connectivity by reducing average larval dispersal distance, with naturally fragmented habitats likely to be at higher risk [88]. This study suggests that future conservation efforts consider habitat fragmentation and connectivity when designing MPAs, placing reserves closer together to retain connectivity patterns. As populations become smaller and more isolated due to climate-related habitat loss and fragmentation, it may also be necessary to increase the size of reserves to ensure viable populations are maintained within their boundaries. MPA networks that connect source and sink reefs and consider their role in promoting recovery after climate-related impacts and enhancing resilience to climate change risks will be critical under an uncertain and changing future [89].

In addition, modelling shows that protection of and connectivity to areas expected to have lower exposure to climate drivers are important for enhancing the adaptive capacity of corals, as is protecting genetic diversity [90], which can promote ecosystem recovery post-disturbance [16]. Promoting the conditions that allow for phenotypic adaptation to thermal stress may provide some options for future conservation management, an ability documented in southeast Asia after a significant coral bleaching event in 2010 [91]. However, the rate of projected climate change means this is only a short term option, and long-lived species are unlikely to have the phenotypic plasticity to "keep pace" in the medium- to long term [92].

Whether, in fact, MPAs can offer "climate protection" to marine ecosystems remains to be seen since they are not designed with large-scale distributional shifts, phase shifts, and changing ocean currents in mind. Graham et al. [82] suggest that they offer only limited resilience to climate impacts that are global in scale, since MPAs primarily protect

Table 1: Summary of key observed impacts of climate change in Australian marine ecosystems, (locations of these impacts have been documented), main climate driver(s) implicated, and current management options available to support adaptation.

Observed impacts	Location of documented impacts	Climate driver	Management to support adaptation
Giant kelp decline by up to 95%	Eastern Tasmania	Increasing ocean temperature	Maintain ecosystem connectivity; interventions to replant communities
Changed structure of nearshore zooplankton communities	Eastern Tasmania	Increasing ocean temperature	Maintain ecosystem connectivity
Poleward range extension of the long-spined sea urchin causing habitat changes	Eastern Tasmania	Increasing ocean temperature	Interventions to rehabilitate degraded habitats; removal of locally invasive species; artificial habitats for displaced species
Poleward shifts of seaweed species	SE Australia, SW Australia	Increasing ocean temperature	Maintain ecosystem connectivity
Reduced resilience of kelp to disturbances at the northern limit of their range	SW Australia	Increasing ocean temperature	Maintain ecosystem connectivity; reduce other stressors on kelp communities
Range contraction of habitat-forming seaweed and decline in habitat condition	SW Australia	Increasing ocean temperature	Maintain ecosystem connectivity; reduce other stressors on habitats in decline
Tropicalization of fish communities	SW Australia, Tasmania	Increasing ocean temperature	Maintain ecosystem connectivity
Decline of 11.4% in coral calcification since 1990	Great Barrier Reef, northeast Australia	Ocean acidification and increasing ocean temperature	Maintain ecosystem connectivity
Declines in fish diversity after climate-related habitat disturbances (coral bleaching and storms)	Great Barrier Reef, northeast Australia	Marine heat waves and more intense storms	Maintain ecosystem connectivity; reduce other stressors on affected fish populations during recovery
Reduced adult foraging and chick provisioning of some species of tropical seabirds	Great Barrier Reef, northeast Australia	Marine heat waves and more intense storms	Reduce other stressors on tropical seabird populations and breeding activities
Loss of primary seabird nesting islands	Great Barrier Reef, northern Australia	Altered rainfall patterns and more intense storms (future sea-level rise)	Reduce other stressors on seabird nesting islands; rehabilitate degraded islands; provide artificial nesting sites
Declines in coral cover from 28% to 14% since 1985	Great Barrier Reef, northeast Australia	Marine heat waves and more intense storms (and crown-of-thorn starfish)	Maintain ecosystem connectivity; reduce other stressors on coral reefs
Declines in seagrass meadows since 2009 with 94% of sites surveyed classified as being in “poor” or “very poor” condition	Great Barrier Reef, northeast Australia	Extreme rainfall events and more intense storms	Maintain ecosystem connectivity; reduce other stressors on seagrass meadows; rehabilitate severely degraded habitats
Reduced coralline algae biomass and recruitment	Temperate and tropical Australian reefs	Ocean acidification	Maintain ecosystem connectivity
Reduced calcification of benthic invertebrates	Experimental—projected Australia-wide	Ocean acidification	Maintain ecosystem connectivity; reduce other stressors on benthic invertebrates
Coral bleaching and mortality, and resultant habitat declines	Great Barrier Reef, northeast Australia; Ningaloo Reef, northwest Australia; Torres Strait, northern point	Marine heat waves	Maintain ecosystem connectivity; reduce other stressors on coral reefs

Table 1: Continued.

Observed impacts	Location of documented impacts	Climate driver	Management to support adaptation
Marine turtle nesting failures	Northern Australia	Increasing sand temperature and inundation (greater storm surge and sea-level rise)	Reduce other stressors on turtle nesting islands; relocate nests; provide artificial shade at nest sites

exploited fish and motile invertebrates but their effects on genetic diversity and connectivity are variable and unquantified.

A study of coral reefs in the Seychelles after the 1998 thermal bleaching event showed that reefs in MPAs were most strongly affected by bleaching mortality and that recovery was slow with some sites having <5% coral cover seven years after the event [93]. In Australia, bleached reefs on the GBR showed no difference in recovery rates between protected and unprotected areas over a 6- to 10-year period [94]. Similarly, no differences were found in recovery in the seven years following the 1998 bleaching event as a function of protection status [95]. These case studies show that MPAs have had only a limited role in ecosystem recovery from climate-driven disturbances to date, despite their positive effect in promoting recovery from other perturbations, such as crown-of-thorn starfish outbreaks [96]. Therefore, the current spatial and temporal design of MPAs does not appear to provide any advantage to impacted ecosystems recovering from climate-related disturbances, and the location of MPAs will be critical to their contribution to recovery. Protecting source reefs that are naturally more resilient is a strategy most likely to afford greater recovery potential for themselves and adjacent reefs following disturbances [97]. A more flexible and dynamic approach will need to be part of a suite of tools that can enhance resilience in an uncertain future under a more extreme and variable climate [82, 98].

While MPAs may have utility as reference areas to assess future climate change impacts and document new ecosystem structures and function [99], they may also act to enhance resilience [34]. The magnitude of other anthropogenic effects combined with climate change will further test the resilience of marine ecosystems to climate change. For example, the interaction between declining coastal water quality and recent climate-related extreme events (floods and storms) in the GBR has resulted in a deterioration of coastal seagrass meadows since 2009 and species that depend on them, such as dugong and green turtles [100]. Ultimately, effective implementation of MPAs as a resilience strategy will depend on the conservation objectives, the condition of sites, and the future risk of climate impacts [101]. In addition, the complementary management of local and/or regional pressures on marine ecosystems as well as optimal spatial and temporal design of dynamic MPAs to maximise connectivity will also need to be considered if conservation management is to support adaptation to climate change [64, 102].

There are many current management strategies employed in Australia to protect marine ecosystems by minimising other human pressures that impact directly marine ecosystem condition and have chronic influences that undermine resilience. These include mining and exploration, shipping and port development, catchment activities that influence marine water quality (urban centers, industry, and agriculture), fishing, and tourism, all of which are managed under different legislative and government levels. At present, management of these pressures is not coordinated or integrated, something that will need to change as the pervasive impacts of climate change increase [102, 103].

5. Adapting Conservation Management under a Changing Climate

Management of Australia's marine biodiversity under future climate change will require an ecosystem-based approach to conservation [104], explicitly considering the cumulative effects of multiple pressures [44], dynamic ecosystem interactions [105], and ecosystem function [106] as they interact to reduce resilience. For example, the effects of fishing and climate interact because fishing can reduce the biodiversity of marine ecosystems, making them more sensitive to additional stresses, such as ocean warming [107]. Addressing local pressures on marine ecosystems is critical for maintaining healthy marine ecosystems, in order to build resilience to climate change and secure future adaptation options [17, 102]. Adaptations that address other impacts in the short term and climate change in the long term ("no regrets" or win-win adaptations) [108] provide a response that can be implemented immediately and revised as new information becomes available. Management will therefore need to be coordinated and integrated across sectors to reduce current stressors from deteriorating water quality, overexploitation of marine resources, pollution, and shipping [64, 109, 110].

The importance of addressing nonclimate stressors is supported by modelling that projects that, even under low CO_2 emissions scenarios (e.g., ~540 ppm), local management maintains and/or restores resilience and increases the chance of reefs remaining coral dominated [111]. Managing marine ecosystems to avoid or reverse such undesirable phase shifts therefore requires an integrated approach through reforms of scientific approaches, policies, governance structures, and management goals [75]. Iwamura et al. [112] used a resource allocation algorithm to prioritise conservation investment that incorporates the stability of ecological regions under future climate change. While focusing on terrestrial ecosystems, their governance approach of accounting for ecological stability to target funding in stable regions and avoid phase shifts provides a functional way of incorporating climate change into conservation planning. Essentially, this is a resilience-based approach that advocates protecting the "strong," while improving understanding of ecosystem dynamics to support ecosystem-based management [75, 113]. Progress is being made in this arena, with a trial in the southern GBR using a series of indicators to identify resilient reefs to prioritise management effort and operationalize a range of local resilience strategies [114], providing a plausible framework for future conservation.

New generation ecosystem models (e.g., multispecies and coupled biophysical) can provide skillful predictions of ecosystem responses to multiple pressures for management and provide information for integrated ecosystem-based management. Models are currently used to focus actions taken by marine management; for example, predictions of marine heat waves known to cause coral bleaching (e.g., [115–117]) can trigger responsive management (e.g., [118]), and more such applications will be essential under an uncertain and changing future. The results of recent modelling of ecosystem responses to climate-driven food web changes [119, 120] could be incorporated into future ecosystem-based approaches that use strategies to focus on locations where declines in primary productivity or communities are predicted.

Although the implications of cascading processes on ecosystem function and resilience remain uncertain, lessons learnt from systems that have lost key functional groups such as top predators [121] and herbivores [122] suggest the need for ecosystem-based approaches that include a food web perspective. Consideration of ecosystem structure and function will likely maximise adaptation to climate change as reductions in marine biodiversity (due to local and regional drivers) can lead to compromised ecosystem resilience to climate change [123].

Marine reserves can protect habitat-specific predator-prey dynamics and have been demonstrated to reinstate trophic dynamics and increase resilience to climate-driven phase shifts in Tasmanian waters [83]. However, recent studies have shown that MPAs do not afford benthic communities protection from climate-related coral bleaching impacts [76, 95]. Their future design should therefore consider both spatial and temporal drivers of change and accommodate inherent uncertainty through greater flexibility. Further, in Australia, where overfishing is not a significant factor that undermines resilience or recovery, the widespread application of MPAs as a response to climate change will need to be complemented by management of chronic nonclimate stressors.

Dynamic MPAs that are designed to be mobile (both spatially and temporally) would allow for climate-related changes in marine environments, with mobile MPAs proposed as an option for protecting species as distributions change [124]. Although there are legal implications of a more flexible conservation approach, many jurisdictions already have the legal frameworks in place to begin to promote and implement actions now with the ability to amend or enact new instruments as experience and knowledge increase [125]. Guidelines for incorporating connectivity into MPAs have been developed [84, 126] that outline optimum size, spacing, shape, risk spreading (representation and replication), and connectivity for designing MPA networks that may be more robust in the face of climate change. Although being a legislatively daunting task, the coordinated management of spatially large and connected protected areas that are temporally dynamic and act across sectors is becoming the new paradigm for effective MPAs [126–128] as part of a range of conservation tools [82].

Conservation management will also need to prioritise effort in the face of climate change, and decisions need to be made whether areas of high biodiversity [129], high genetic diversity [92, 106], high stability [112], high resilience [75], or unique ecosystems [106] should be protected. However, it is postulated that the speed at which climate change is impacting marine ecosystems leaves little opportunity for evolutionary processes and survival will be highly dependent upon the natural resistance already in gene pools and the management interventions that can increase resilience [64].

6. Future Research Needs

Recent climate change science has sought to better understand how Australia's marine ecosystems are being impacted and are projected to be impacted by climate change and what adaptation strategies are available [130]. However, conservation managers need more information to anticipate the phenology and movements of individual species in response to climate change as well as potential changes to biological communities [131]. Future research needs to support ecosystem-based management by defining critical thresholds and designing methods for measuring ecosystem dynamics and processes, such as phase shifts. This will inform where adaptation management should focus (spatially) on enhancing resilience and employ active conservation to minimise the risks of climate impacts.

While MPAs have utility for conserving important marine resources by reducing extractive activities, their utility as tools for addressing climate change impacts on marine ecosystems is only likely to enhance resilience if complemented by strategies that minimise other pressures, such as deteriorating water quality. The recent consensus for the GBR is that although climate drivers will exacerbate water quality issues, existing pressures need to be addressed to halt the decline of marine ecosystem condition [103]. Science and modelling have a role in developing methods to select the most effective suite of possible strategies and understanding of the spatial and temporal drivers affecting connectivity of marine habitats. Research also needs to investigate whether improving networks of MPAs can connect source and sink reefs to promote recovery after climate-related impacts and if these will actually be effective in reducing long term climate change risks. Improvements in the coupled dynamic representation of the biophysical, economic, and social components of systems and major environmental and anthropogenic drivers will bolster modelling of critical processes whose characteristic spatiotemporal scales span many orders of magnitude (from microbes to ocean basins) [98].

Separating marine conservation management from other sectors that impact marine resources, such as catchment and fisheries management, is a paradigm that we need to move away from. Such an integrated approach is being widely applied in the Pacific region through the Ridge to Reef initiative, that aims to integrate water, land, forest, and coastal management to preserve biodiversity and ecosystem services [132]. Ultimately, single sector management is unlikely to see major challenges like climate change addressed and critical research gaps exist to identify and inform multisector integrated management approaches. These gaps are not new; information on multistressor thresholds, multiscale analyses, and synergistic effects has long been identified as challenges for conservation biologists [131].

7. Conclusions

Australia's marine ecosystems are areas of high biodiversity, providing important ecosystem goods and services to marine industries and people. These ecosystems are at risk from climate change, and impacts are already being observed in many species and ecological communities around Australia. Recent research efforts reflect the importance of these ecosystems and issues to Australia. However, research gaps still exist and targeted research is needed to inform "no-regrets" adaptations that adopt robust solutions that allow for potential uncertainties together with adaptive approaches that involve monitoring and review as circumstances, conditions, and knowledge change.

A new management paradigm is needed. Climate-aware conservation requires the development of objectives that are not underpinned by a return to historic baselines [124] but rather acknowledge that current equilibrium assumptions are no longer valid. Climate change acts at a range of scales—cellular, genetic, species, population, and ecosystem—and managers will need to respond to this by acting over different spatial and temporal scales. The focus of conservation will need to shift from historic species assemblages to an ecosystem-based approach and active adaptation based on potential future climate scenarios [133]. The increasing tropicalization of Australia's east and west coasts will have implications for conservation management, making spatial flexibility, high connectivity, larger management units, and integrated ecosystem-based management essential.

In summary, marine conservation management needs to take an ecosystem-based approach that integrates across sectors and jurisdictions. The temporal and spatial features of MPAs will need to be more dynamic and flexible to consider the observed and projected impacts of climate change such as distributional shifts, habitat declines, and phase shifts. Climate change impacts on Australia's marine ecosystems are currently manifesting in the southeast, southwest, and the northern tropics but are expected to be widespread, increasing the challenge for conservation management.

Climate change provides an unprecedented opportunity to challenge the conventional thinking and evaluate conservation management with a different perspective and a longer-term view. While science is providing important insights into the impacts of climate change on marine resources, effective management strategies need to be responsive, bold, and multilateral. As climate change places additional pressure on already strained marine ecosystems, a new management paradigm needs to consider ecological resilience, cross-sectoral integration, long term ecological stability, and facilitate cooperation between jurisdictions. Ultimately, conservation management will need to be ecosystem based and implement "no regrets" adaptations based on the available information in order to sustain Australia's marine ecosystems into the future.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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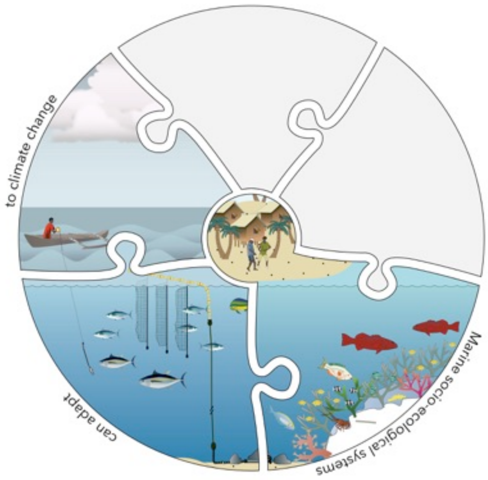
Chapter 4



Indicators for a structured framework to assess vulnerability to climate change

In chapters 2 and 3 I demonstrated that climate change is impacting marine socio-ecological systems, which will continue under future projections. While a greater understanding of climate change vulnerability can inform and improve adaptation prospects, assessment frameworks for managers to apply in a local context have been largely qualitative. This chapter includes a journal article that evolved the approach to assessing vulnerability, moving beyond a purely qualitative application of the IPCC framework, I propose a structured approach with indicators for the elements of vulnerability – exposure, sensitivity and adaptive capacity – and explore its application to coupled human-environmental systems (Johnson and Welch 2010; Publication 4). With fisheries one of the most resource-dependent industries, and the majority of fisheries around the world in decline, this research critically examined the theoretical application of a semi-quantitative assessment using socio-ecological indicators to address Objective 3. We adapted the Allison et al. (2009) approach to encompass ecological and social measures of vulnerability and to allow for expert-based assessments that can accommodate data-limited situations to evolve the method to have broader and more immediate applications.

My contribution to Publication 4 was to conduct all synthesis and analysis, draft the first complete version, and request focused contributions from my co-author. Welch provided input on the current status of fisheries globally and how a structured framework with indicators for each vulnerability element could be applied in a fisheries context. Editors and reviewers of *Reviews in Fisheries Science* provided insightful comments and suggestions for improving the conceptual thinking.

The main findings in Chapter 4 are:

- Marine capture fisheries will be exposed to increasing sea surface temperatures, ocean acidification, sea-level rise, increasing storm intensity, altered ocean circulation, and changing rainfall patterns that will affect target species directly and indirectly.
- The sensitivity of fish stocks to these changes will determine the range of potential impacts on life cycles, species distributions, community structure, productivity, connectivity, organism performance, recruitment dynamics, prevalence of invasive species, and access to marine resources by fishers.
- A structured vulnerability assessment approach provides an objective lens to examine the level of vulnerability of different fisheries to climate change, and the factors that will confer resilience or temper vulnerability (e.g. capacity to adapt) and those that drive vulnerability (e.g. poor governance).
- Conceptual thinking about climate vulnerability was progressed to consider which indicators would represent the elements of vulnerability, how they could be quantified, and how the three elements combined to provide an overall assessment of vulnerability.
- A quantitative and objective approach is essential to prioritise sectors in greatest need of intervention, understand the drivers of vulnerability, and importantly, review current fisheries management with the view to develop management responses that will be effective in securing sustainable harvests under future climate projections.
- A regional and expert-based approach that incorporates both social and ecological variables is needed to assess the vulnerability of data limited fisheries (and other sectors).
- Analogies with resilience theory provide opportunities to progress application of vulnerability indicators to rank the relative vulnerability of sectors most at risk and inform decision-making.

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Marine Fisheries Management in a Changing Climate: A Review of Vulnerability and Future Options

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Marine capture fisheries are an important source of protein globally, with coastal and oceanic fish providing a rich source of essential fatty acids, vitamins, and minerals. Fisheries also support economies and important social structures in many nations, particularly developing nations (Allison et al., 2009). Marine fisheries are under increasing threat from climate change, with climate change now identified as the latest threat to the world's fast declining fish stocks (UNEP, 2008; Cochrane et al., 2009). Marine fisheries will be exposed to increasing sea surface temperatures, ocean acidification, sea level rise, increasing storm intensity and altered ocean circulation, and rainfall patterns that will affect target species through a range of direct and indirect mechanisms. The sensitivity of fish stocks to these changes will determine the range of potential impacts to life cycles, species distributions, community structure, productivity, connectivity, organism performance, recruitment dynamics, prevalence of invasive species, and access to marine resources by fishers. Many fisheries are already experiencing changes in target species diversity and abundance, species distribution, and habitat area, as well as loss of fishing effort due to intensifying storms (Johnson and Marshall, 2007; Hobday et al., 2008; UNEP, 2008). Using a vulnerability assessment framework, we examine the level of vulnerability of marine fisheries to climate change and the factors that will temper vulnerability, such as adaptive capacity. Assessing fisheries vulnerability to climate change is essential to prioritize systems in greatest need of intervention, understand the drivers of vulnerability to identify future research directions, and more importantly, to review current fisheries management with the view to develop management responses that will be effective in securing the future sustainability of marine fisheries.

Keywords vulnerability, adaptation, climate change, marine ecosystems, marine fisheries

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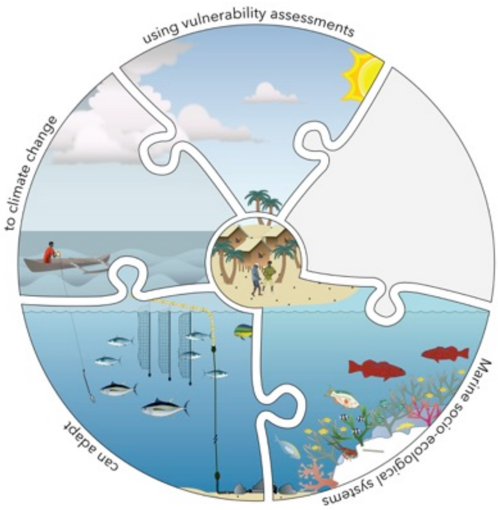

Chapter 5

Vulnerability assessments as a tool to enhance resilience of socio-ecological systems

Having conceptualized a quantitative vulnerability assessment approach, my research progressed to develop a semi-quantitative tool that focused on integrating socio-ecological factors to inform decision-making and management (Objective 4). This chapter is based on a journal article that documented the first application of the semi-quantitative method for assessing vulnerability to climate change (Johnson and Welch 2016; Publication 5). This research developed new indicators for the elements of vulnerability – exposure, sensitivity and adaptive capacity – with criteria to score each indicator, and an equation to calculate the relative vulnerability of 15 fisheries in Torres Strait. The approach integrated ecological and social factors through the indicators to deliver results that could inform adaptation and management.

My contribution to Publication 5 was to jointly develop the vulnerability assessment indicators and criteria, jointly develop the assessment equation and conduct the assessment, and draft the first complete version. My co-investigator and co-author, Welch provided input on the current status, exposure and sensitivity of fisheries in Torres Strait and application of the semi-quantitative calculations in a fisheries context. Editors and reviewers of *Climatic*

Change provided insightful comments and suggestions for improving the application of the semi-quantitative approach, and analysing and representing the results.

The main findings in Chapter 5 are:

- Integrating ecological and social indicators of exposure, sensitivity and adaptive capacity was effective at linking species and ecosystem responses with social practices and conditions.
- The assessment successfully ranked the vulnerability of 15 very different fisheries (e.g. finfish, crustaceans, sea cucumbers and dugongs), and using a standardization step, identified species with high, medium and low vulnerability to projected climate change in 2030, and the main drivers of vulnerability.
- A separate prioritisation process that considered the cultural and economic value of species identified three high priority species for future management focus.
- The novel assessment method uses existing data (for climate projections and scoring indicators) with expert elicitation, making it accessible to all managers and regions.
- The semi-quantitative results provide targets for fishers and managers to prepare for the effects of climate change by either minimizing exposure or sensitivity, or enhancing adaptive capacity.
- The decision-support utility of the semi-quantitative approach can be tailored to the local and/or regional context, and provide adaptation targets over future timescales.

Climatic Change
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Climate change implications for Torres Strait fisheries: assessing vulnerability to inform adaptation

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Abstract Climate change impacts on marine fisheries are being observed in tropical regions, including northern Australia and the Pacific. In the Torres Strait, Islanders have a long association with their sea country that holds significant cultural, social and economic importance. Future impacts of climate change on marine fisheries stocks and supporting habitats will affect Torres Strait Islander communities. We assessed the relative vulnerability of 15 key fishery species in Torres Strait using a semi-quantitative framework modified from the Intergovernmental Panel on Climate Change that integrated both ecological and social indicators of exposure, sensitivity and adaptive capacity. The assessment identified species with high, medium and low vulnerability to projected climate change in 2030. The species assessed as having the highest vulnerability were: *Holothuria whitmaei* (black teatfish), *Pinctada margaritifera* (black-lipped pearl oyster), *Dugong dugon* (dugong), and *Trochus niloticus* (trochus). A separate prioritisation process that considered the cultural and economic value of species identified three high priority species for future management focus: *D. dugon*, marine turtles (principally *Chelonia mydas*) and *Panulirus ornatus* (tropical rock lobster). These results can inform fishers and managers to prepare for the effects of climate change and minimise impacts. The relatively healthy condition of most fisheries in the Torres Strait is likely to assist successful adaptation.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-015-1583-z) contains supplementary material, which is available to authorized users.

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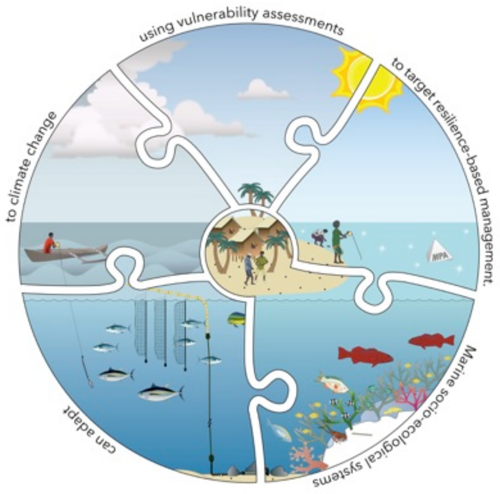

Chapter 6

Quantifying vulnerability to target resilience-based management

As climate change impacts accelerate, natural resource managers need a vulnerability assessment tool that can be applied at management-relevant scales and answer specific management questions. This chapter explored how the semi-quantitative assessment tool can be applied to different questions to inform decision-making and target adaptation actions (Objective 5). The chapter is based on a journal article that documented the complete new 10-step method for semi-quantitatively assessing vulnerability to climate change and provided different examples of its application (Johnson et al. 2016; Publication 6). This publication provided guidance in selecting and applying the method, and demonstrated how structured vulnerability assessments have moved from theory to practical decision-support. The paper provided two case applications as examples: (1) food security in Pacific Island nations under climate-driven fish declines, and (2) fisheries in the Gulf of Carpentaria, northern Australia.

My contribution to Publication 6 was to develop the 10-step process and analysis, draft the first complete version, and request focused contributions from my co-authors. Welch provided input on the 10-step process in light of his experience using the method, and input to the Northern Territory case study. Maynard provided support with visualising the 10-steps and how they best support decision-making, Bell provided input to the Pacific food security case study, Pecl and Robins provided general style and readability input, and Saunders

provided input to the Northern Territory case study. Editors and reviewers of *Marine Policy* provided insightful comments and feedback.

The main findings in Chapter 6 are:

- Understanding vulnerability ensures managers can target actions to reduce the impacts of climate change on socio-ecological systems.
- Quantitative assessments of vulnerability are rare because available frameworks are complex and lack guidance for dealing with data limitations and the complexity of integrating across scales and disciplines.
- The semi-quantitative assessment method developed integrates socio-ecological factors to address management objectives and support decision-making.
- The method applies a framework first adopted by the Intergovernmental Panel on Climate Change using a novel 10-step process.
- The steps include: setting objectives; selecting components to assess; deciding on indicators for the exposure, sensitivity and adaptive capacity elements of the framework; and then setting criteria for low, medium, and high to score indicators.
- After gathering data, scores for each framework element are normalized and multiplied to produce a vulnerability score and then the assessed components are ranked from high to low vulnerability.
- Sensitivity analyses determine which indicators are most influencing the analysis and the resultant decision-making process so data quality for these indicators can be reviewed to increase robustness of the analyses.
- Prioritisation of components for management considers other economic, social and cultural values with vulnerability rankings to target actions that reduce vulnerability by decreasing exposure or sensitivity and/or increasing adaptive capacity.
- The step-wise process outlined can be applied to any socio-ecological system or location, and can be undertaken with minimal resources using existing data, thereby having great potential to inform adaptive natural resource management.
- Ultimately, it is the flexibility, coupled with the participatory and multi-disciplinary features of the approach that are its greatest strengths for supporting decision-making and local adaptation actions.

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Assessing and reducing vulnerability to climate change: Moving from theory to practical decision-support

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A R T I C L E I N F O

Keywords:
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Assessment framework
Climate adaptation
Socio-ecological systems
Decision support

A B S T R A C T

As climate change continues to impact socio-ecological systems, tools that assist conservation managers to understand vulnerability and target adaptations are essential. Quantitative assessments of vulnerability are rare because available frameworks are complex and lack guidance for dealing with data limitations and integrating across scales and disciplines. This paper describes a semi-quantitative method for assessing vulnerability to climate change that integrates socio-ecological factors to address management objectives and support decision-making. The method applies a framework first adopted by the Intergovernmental Panel on Climate Change and uses a structured 10-step process. The scores for each framework element are normalized and multiplied to produce a vulnerability score and then the assessed components are ranked from high to low vulnerability. Sensitivity analyses determine which indicators most influence the analysis and the resultant decision-making process so data quality for these indicators can be reviewed to increase robustness. Prioritisation of components for conservation considers other economic, social and cultural values with vulnerability rankings to target actions that reduce vulnerability to climate change by decreasing exposure or sensitivity and/or increasing adaptive capacity. This framework provides practical decision-support and has been applied to marine ecosystems and fisheries, with two case applications provided as examples: (1) food security in Pacific Island nations under climate-driven fish declines, and (2) fisheries in the Gulf of Carpentaria, northern Australia. The step-wise process outlined here is broadly applicable and can be undertaken with minimal resources using existing data, thereby having great potential to inform adaptive natural resource management in diverse locations.

1. Introduction

Understanding vulnerability to climate change provides insight into which parts of social-ecological systems are most likely to change, what is driving this potential change, and how conservation and management actions can minimise impacts and maximise resilience. Assessing the vulnerability of species, ecosystems and resource-dependent industries to climate change is a critical step to identify effective adaptations and prioritise management that enhances resilience. Vulnerability is the degree to which a system or species is susceptible to, or unable to cope with, the adverse effects of climate change [1], and depends on exposure (extrinsic factors), sensitivity and adaptive

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capacity (intrinsic factors). The Intergovernmental Panel on Climate Change (IPCC) has provided an approach to understanding vulnerability and its elements that has become a universally recognised vulnerability assessment framework [2]. In the IPCC framework, exposure and sensitivity determine potential impacts, which are tempered by adaptive capacity to yield vulnerability to climate change.

In this framework, exposure is defined as the degree to which the component assessed (e.g. species, ecosystem or resource-dependent industry or community) is likely to experience climate change at the local scale, given their preferred habitats, ranges, behaviour and mobility. Sensitivity is the degree to which a component can be directly altered by a change in climate or indirectly altered, for example, by a change in a species' habitat. Adaptive capacity is the potential to reduce exposure or adjust sensitivity so as to maximise fitness and moderate or cope with the detrimental effects of climate change [1]. These terms are commonly used when assessing vulnerability and are consistent with existing approaches [see 3,4,5]. Assessing the vulnerability of complex socio-ecological systems (SES) to climate change can identify effective adaptation options and help construct targets for resilience-based management [6].

There has been an evolution in thinking on climate change vulnerability over the last 15 years [7–9] and a range of approaches to assess vulnerability have been proposed and applied [e.g. 4,10,11,12]. Central to all existing approaches is understanding and accounting for the complexity and uncertainty associated with: climate change and other global stressors, the integration of social and ecological data, and SES thresholds of change [13]. These are multi-faceted challenges typically addressed with resource-intensive methods that require significant data and/or expertise, e.g. multi-dimensional models [14], fuzzy cognitive mapping [15], paleo-ecological reconstructions or scenarios as proxies [16]. Management uptake of these approaches has been limited, creating a niche for a relatively simple, robust semi-quantitative approach to assess vulnerability to climate change.

In response, criteria-based approaches have emerged that use indices for social and ecological factors or 'indicators' and then integrate scores or classifications for indicators to produce a relative assessment of either vulnerability or resilience [17–21]. In addition, for many developing countries, although national assessments of vulnerability to climate change are available they cannot be easily downscaled and localized assessments that provide species-, community- or location-specific information are required.

2. Method

The framework described here for semi-quantitatively assessing vulnerability to climate change builds on this recent thinking to provide a framework for local assessments. The framework has evolved through applications by the author team to ecosystems [22–24], national industries and economies [25,26], fisheries [17,27,28], resource-dependent communities [20,26,29], and aquaculture [30]. This evolution has refined techniques for identifying and selecting indicators and for quantifying ecological responses. The result is a broadly applicable assessment framework and step-wise process, and a practitioners guide is provided in the Supplementary Material. The process uses available data and expert judgment to generate results on relative vulnerability for practical decision-support targeting management and conservation.

2.1. Semi-quantitative assessment method

The semi-quantitative assessment (SQA) method involves a customisable 10-step process that directs the assessment focus and application of results, particularly for targeting management (Fig. 1). Glick et al. [31] outlined the key steps for assessing vulnerability to climate change, with the vulnerability assessment results informing broader adaptation planning. Building on this concept, the SQA method presented here includes clear steps to assess climate change vulnerability (steps 2–8) as well as applying results to inform adaptation (steps 9 and 10). All 10 steps may not be applicable in all circumstances, and selecting which steps to complete is part of customising the process to the study context. In particular, 'review and reassess' (step 8) may not be required depending on the results of the sensitivity analysis. Similarly, 'prioritisation' (step 9) may be skipped if the selection of components (in step 2) already considered values and importance. The SQA method is designed for application by decision-makers seeking transparent support for managing natural resources, conservation areas, community-based actions and climate change impacts (see practitioners guide in the Supplementary Material). Including participation by local experts, stakeholders and communities throughout the process ensures the results are robust and maximises uptake, delivering direct translation to management actions [32,33].

The described framework has already been applied by tailoring the 10 steps to assess the vulnerability of ecosystems and communities in tropical SES's. Two of these applications are summarised in detail as case examples of applying the 10 steps: (1) Pacific Island food security from fisheries [17,25]; and (2) Gulf of Carpentaria fisheries [28], in Section 3 and a third application – Torres Strait fisheries [20] – is used to demonstrate the method in each step of the SQA method and in Fig. 1.

2.1.1. Step 1: set management objectives

This step involves managers and stakeholders determining the core objectives and scope of the assessment and how the results will inform decision-making. The objectives will determine the management needs, scale (spatial and temporal) of the assessment, components to be assessed, and ultimately the focus of any identified management actions. Determining the scale of the assessment includes which climate projections and impacts are most relevant for the management objectives, in terms of future timeframes and emissions scenarios. For example, the objectives of the Pacific Island food security SQA were to identify: (1) which nations were most vulnerable to climate-driven declines in fish supply by 2035 under a high emissions scenario, and, (2) which fisheries adaptations can support filling the gap between demand and supply [17,25].

2.1.2. Step 2: set vulnerability assessment focus

This step involves selecting the SES components to assess (e.g. species, habitats, resource-dependent industries or communities) and the type of sensitivity analyses to conduct in partnership with local experts and stakeholders. This step also requires identifying situation-appropriate indicators and criteria. The case applications outlined in this paper used a workshop brainstorming session to choose a representative suite of components that are relevant to the management objectives. The selection can be based on specific criteria, for example: (1) conservation, social, economic and/or cultural importance; (2) known or expected sensitivity to climate change; and/or (3) data availability [28]. A review process with a wide group of stakeholders is used to validate the selected list of components to assess. Stakeholder engagement should be as inclusive of different stakeholder types as possible but guided by the stakeholders likely to be most affected by climate change, similar to that described by Heenan et al. [33].

2.1.3. Step 3: identify and select indicators

The SQA uses known biology, ecology and responses to climate variation to develop a series of indicators for: (i) exposure, (ii) sensitivity and (iii) adaptive capacity. Indicators for exposure are based on climate projections. Sensitivity indicators are based on known tolerances or responses to environmental variables [e.g. 27]. Indicators for adaptive capacity are based on research that identifies which characteristics (or traits) of species/systems support recovery and ultimately confer resilience [e.g. 34–38]. The exposure, sensitivity and adaptive capacity indicators for assessing vulnerability should be customised to the spatial and temporal context, and the components being assessed (see Table 1 for example indicators). Relevant and appropriate indicators can be identified using known responses to climate drivers, or expert judgement. Indicators are generally more situation-appropriate if developed and reviewed with local experts [13] to develop a final suite that are applicable to the components being assessed.

Exposure indicators are based on the specific environmental variables predicted to be important for the components being assessed, and the criteria for scoring these are developed to reflect the local or regional conditions (see step 4). Appropriate indicators for exposure will depend on whether the assessment is focusing on coastal, marine or terrestrial species, a particular industry or a resource-dependent community. For each emissions scenario used (e.g. 2030 RCP8.5), the exposure indicators are developed specifically for the model projections that corresponded to that particular future scenario and location. For example, the assessment of Pacific Island food security included exposure indicators for 'reef fish available (kg) per person per year', and the 'expected shortfall in fish (kg) per person per year' (see Supplementary Table 2).

Sensitivity is complex to conceptualize because part of a species' or system's response to exposure to the effects of environmental change can be attributed to the extent of its environmental specialisation [39]. Pecl et al. [27] provide a detailed explanation of the development of sensitivity indicators for temperate fisheries based on different aspects of species' population and life history characteristics likely to be affected by climate change – abundance, distribution and phenology. For habitats, resource-dependent industries or communities, sensitivity indicators are based on known responses and tolerances to environmental variables or dependencies on environmental services. Sensitivity indicators applied in the Gulf of Carpentaria fisheries SQA include 'reliance on environmental drivers' and 'early development duration (dispersal capacity of larvae/young)' (see Table 1).

Adaptive capacity (AC) includes two facets: the ability of species or habitats to cope with changes (ecological or autonomous adaptation), or the ability of resource-dependent industries and communities to cope with or influence changes (socio-economic or planned adaptation). AC indicators are developed for both of these facets. However, vulnerability assessments of ecological components of a system can focus on indicators related to governance and management of pressures, as these will influence responses to disturbance and recovery. On the other hand, assessments of resource-dependent industries and communities should include indicators that encompass the adaptive capacity of people, industries or communities. Such indicators will significantly influence how people and communities adjust to and persist in the face of change. Possible indicators include measures of ecological status – fishery stock status or replenishment potential (see Table 1) – or social indicators of health, education, economy size and governance (see Supplementary Table 1). It is particularly important that industries and communities that will be affected by changes be involved in the development of appropriate socio-economic indicators [33].

2.1.4. Step 4: define criteria for scoring indicators

Criteria are developed for scoring each indicator taking a risk-based approach using ecologically relevant triggers and relationships. Ideally, categories for scoring each indicator are empirically based. However, known thresholds for such criteria are rare and expert-based thresholds are usually required. The low-medium-high scale used in this SQA scoring system reduces a common tendency to focus on having 'precise values' for each attribute. This is especially helpful when data are limited, and allows the system to be used by a wide range of experts [e.g. 27]. Indeed, the purpose of criteria- or trait-based approaches is to provide a rapid assessment of the relative vulnerability of a large number of species. Undertaking detailed quantitative analysis to

Table 1
A sub-set of the indicators applied in the Gulf of Carpentaria fisheries assessment to demonstrate examples for exposure, sensitivity and adaptive capacity indicators and the scoring criteria developed and refined during an SQA (Adapted from Welch et al., 2014).

INDICATORS		Low=1	Medium=2	High=3
Exposure (2030 A1FI/ RCP8.5 projections)	Sea surface temperature increase +0.3 to +0.9 °C	Adult spends < 50% of time in surface (< 25 m) waters	Adult spends 50–80% of time in surface (< 25 m) waters	Adult spends 80–100% of time in surface (< 25 m) waters
	Changing rainfall patterns & more extreme rainfall events	Spends no time in estuarine or freshwater habitats during any life history phase	Spends < 50% of time in estuarine or freshwater habitats; no critical (larvae, juvenile, spawning) life history phase in these habitats	Spends > 50% of time or has critical (larvae, juvenile, spawning) part of life cycle in estuarine or freshwater habitats
Sensitivity	Reliance on environmental drivers	No correlation to environmental variable	Weak correlation to environmental variable	Significant correlation to environmental variable
	Early development duration (dispersal capacity of larvae/young)	> 8 weeks	2–8 weeks	< 2 weeks or no larval stage
Adaptive capacity	Fishery stock status	Overfished or on the verge of overfishing	Undefined or fully exploited	Sustainably fished
	Replenishment potential	Late maturing (> 6 years), slow growth or few young	Matures at 3–6 years, moderate growth or moderate numbers of young	Early maturing, fast growth or many young
	Fishery resource dependence	No alternate species and/or significant gear/ modifications required to target other species	Some alternate species that could be targeted with minor gear/practice modifications	Multiple alternate target species that could be targeted without any gear/practice modifications

determine specific thresholds is not in the spirit of the rapid assessment approach and is usually time or cost-prohibitive. Consistent application of set criteria (see example scoring criteria in Table 1) is important as this avoids arbitrary classification into the low, medium, high categories. This is especially problematic when uncertainty is high (e.g. in estimating thresholds of response, see [14]). A weakness of the 3-point scoring system recommended (low-medium-high) is that there can be a 'central tendency' to the classifications, especially when based on expert-judgment; in that assessors often avoid the extremes (low and high). This can be avoided through, as describe above, setting and then *strictly* adhering to the criteria for the scoring classifications. Alternately, for a data-rich assessment, a 5-point Likert-scale system can be used, requiring criteria be set for 'medium-low' and 'medium-high', to avoid excessive use of the central tendency medium answer. In most cases, data availability and expert judgment will necessitate use of a 3-point scale only, emphasising the importance of the process of setting the scoring criteria.

The criteria for scoring exposure indicators are based on the likelihood of experiencing a change in that variable. Criteria for scoring sensitivity indicators are based on known relationships and tolerances and, for adaptive capacity indicators, scoring criteria are based on inherent resilience characteristics. In each instance, criteria have to be set that are inclusive of the full range of data or judgments possible for each indicator. This ensures there is no ambiguity when classifying the components into the agreed-upon relative scoring categories (i.e. low, medium, high) for each indicator. In step 4, criteria can also be set for two (i.e. low and high) or three (i.e. low, medium and high) classifications of confidence (or uncertainty) for each indicator. Such criteria could be based on the quality and quantity of quantitative data available or experts' confidence in their judgments. A side benefit of concurrent assessments of confidence/uncertainty when scoring is that it enables assessment coordinators to identify the components of the framework for which uncertainty is greatest. Consequently, lists can be readily developed of knowledge gaps and research priorities. Well-chosen criteria for indicator and confidence/uncertainty scoring provide a transparent and repeatable mechanism for scoring (example indicators and criteria are provided in Table 1).

2.1.5. Step 5: data collection

A key benefit of the SQA method is that it draws on and collates existing empirical data, including climatologies, projections, species and habitat thresholds and response, status and trends, demographics, available modelling and expert knowledge. There are three sources of data that can inform the assessment: (1) existing data, (2) expert judgment, and (3) critical data collection to filling knowledge gaps (if required). Structured expert elicitation offers a semi-quantitative way to estimate exposure, sensitivity and adaptive capacity [40], particularly when limited empirical data exists. Expert judgement is especially valuable when assessing the impact of climate change in data-poor areas. As described above, the level of confidence in scoring is determined by the quality and quantity of data inputs.

In some cases, it may be necessary to collect or re-analyse specific data that are essential for completing an assessment. For example, if the physiological thresholds for a key species are unknown, correlations between available biological and environmental data from similar species can fill this gap [28], or new data can be collected if it is deemed critical. Where data are lacking it is suggested that a category is scored higher (i.e. more sensitive to climate change, as per [27]) consistent with applying the precautionary principle and follows established risk assessment practice [e.g. 41].

2.1.6. Step 6: vulnerability metric: analysis and ranking

A vulnerability metric has been developed to quantify results so that SES components are systematically ranked based on their relative vulnerability to climate change. Scores are assigned for each indicator (from step 3) using a 3-point scale (or 5-point Likert scale) based on the criteria developed in step 4, and whereby low scores represent low vulnerability.

An index is calculated for each element (i.e. exposure, sensitivity and adaptive capacity) by averaging the indicator scores. Since interactions among the different assessment elements and the relative importance of different indicators are not well understood [35], indicators are generally given equal weighting. Also, the relative importance of each vulnerability element – exposure, sensitivity and adaptive capacity – can vary by region, and can be difficult to determine. For these reasons, the elements are given equal weighting except where it can be demonstrated that they should be differentially weighted.

The Potential Impact (PI) index is determined as the product of E and S Indices (PI=*S). The calculation of PI is based on the synergy (or multiplicative nature) of E and S since these factors interact rather than being additive. Although some analyses have used an additive approach [e.g. 18], the interaction of E and S are synergistic, and there is very little difference in the ranking outcomes between averaging (additive) and multiplicative approaches when estimating vulnerability using the same framework approach [35]. A comparative analysis using the Torres Strait and Gulf of Carpentaria data confirmed the Allison et al. [35] findings, and multiplying E and S scores has been used in the case applications presented in Section 3.

Since vulnerability is the degree to which a system or species is susceptible to or unable to cope with the adverse effects of climate change, the PI measured by the framework assumes a negative direction (i.e. high scores represent high potential impacts due to high exposure and sensitivity). However, some consequences of high E and high S can sometimes have positive outcomes for specific components. For example, skipjack tuna are projected to increase in abundance in the tropical eastern Pacific by 2035 due to high exposure and sensitivity to increasing ocean temperature, resulting in higher catches for fisheries in the central and eastern areas of the Western and Central Pacific Ocean [23]. To represent these potential positive effects, a 'Direction of impact' coefficient of −1 is applied only to components that are expected to benefit: $PI=(E^*S)^*-1$. This transformation inverses the PI score, resulting in negative vulnerability scores that are re-set to zero (low or no vulnerability), and eliminates spurious high vulnerability scores for components that will benefit.

Since adaptive capacity (AC) tempers exposure and sensitivity (i.e. high AC reduces vulnerability), the AC Index is standardized to a value between 0.0 and 1.0 (by dividing by the maximum score), and then inverted: AC index=1−AC.

The vulnerability (V) index is then calculated using the metric: $V=(PI\times AC\ index)+1$.

Due to the effect of standardization, 1 was added to avoid zero values, which could be misinterpreted as zero or 'no' vulnerability. Therefore, the species with the lowest relative vulnerability had a score of 1.00. The components are then ranked from highest to lowest relative vulnerability.

2.1.7. Steps 7 and 8: sensitivity analysis and review and reassess

A sensitivity analysis is conducted to determine the importance of the different indicators to the final vulnerability ranking. The sensitivity analysis identifies: (1) the indicators most influencing the rankings (overall), and (2) the indicators that have the most influence on the higher rankings, which are the components most likely to be targets for management actions. Each input (indicator) is systematically excluded to examine the effect on the output values (vulnerability ranking) using a bootstrapping approach. Data or expert judgments for the indicators most influencing the vulnerability rankings can be reviewed and re-assessed to maximise analysis robustness. For example, sensitivity analysis of the Torres Strait fisheries SQA results found that AC indicators were the most influential on vulnerability rankings. Five of nine AC indicators affected > 50% of rankings, and influenced some movement of species between high and moderate vulnerability categories (referred to as category substitutions) (see Fig. 1). Consequently,

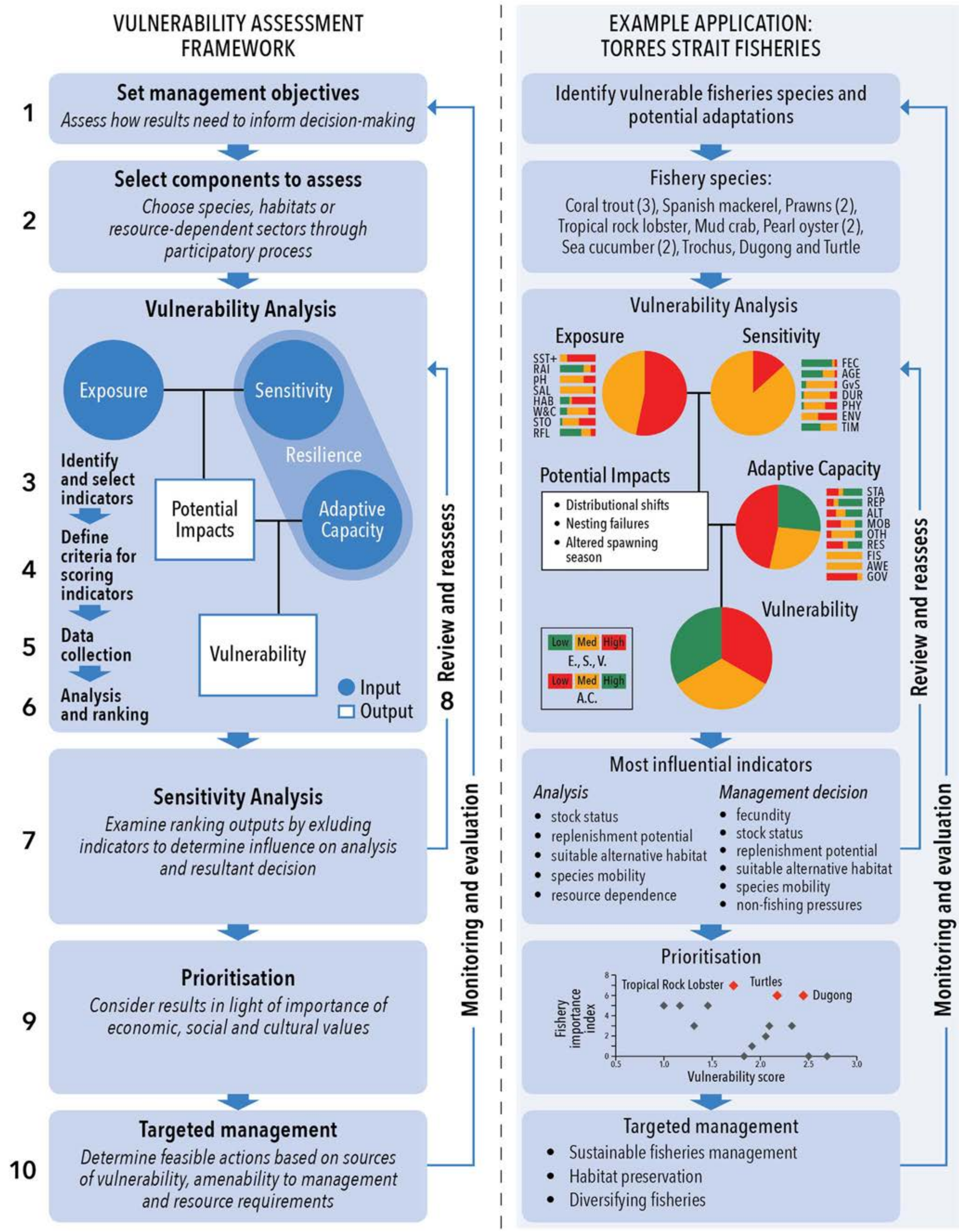

Fig. 1. (a) The 10-steps for applying the Semi-quantitative Assessment (SQA) method, and (b) Application of the SQA to Torres Strait fisheries, showing the results of each step (Welch and Johnson 2013, Johnson and Welch, 2015). The Torres Strait fisheries assessment objective was to identify which fish stocks and fisheries were most vulnerable to climate change under the A1FI SRES emissions scenario in 2035, to inform management actions and adaptation. Fifteen fishery species were assessed using E, S and AC indicators and criteria developed and reviewed by local experts. Low AC contributed significantly to high vulnerability of species. Indicators that most influenced the analysis results as well as possible management decisions were identified. After prioritisation based on economic and cultural values, three species were assessed as having the highest vulnerability: tropical rock lobster, dugong and turtles. Targeted management should focus on sustainable fisheries, marine habitat preservation (particularly seagrass), and diversifying species targeted by fisheries.

step 8 reviewed those data inputs for the Torres Strait SQA as a quality control step prior to finalising the analysis. Under Step 4, the value of concurrently assessing confidence/uncertainty when determining indicator scores is explained. It will be especially important to review and reassess indicators found during the sensitivity analysis to be strongly influencing rankings that also have low confidence/high uncertainty. This way, reviewing and reassessing can increase the robustness of the assessment and confidence among all parties involved that the assessment both reflects state-of-art understanding and objective assessments of uncertainty.

2.1.8. Step 9: prioritisation based on vulnerability results

The relative vulnerability rankings (i.e. outputs from Steps 2–8) identify the species, habitats or resource-dependent industries and communities with highest vulnerability to climate change. In many cases, components with high vulnerability will be priorities for management responses because a first step towards adaptation is reducing vulnerability and exposure to climate change [42]. However, relative vulnerability will rarely be the only consideration when prioritising components for management focus. The relative 'importance' of components should also be taken into account. Importance or 'value' scores can be calculated for each component using known conservation, economic, social, recreational and/or cultural values. The determination of values includes intrinsic values (e.g. conservation or culture) and therefore is not limited to fiscal calculations. This step requires stakeholder participation to determine values (particularly non-monetary values) specific to the location. The prioritisation step will adjust the rankings since components with high vulnerability scores combined with high importance scores are higher priorities for management or conservation. For example, in the Torres Strait, Johnson and Welch [20] plotted vulnerability against 'importance' for each component and used Euclidean distances to identify the highest combination of scores, and therefore highest priority components (species). In their SQA, dugong and turtle were ranked as the 3rd and 5th most vulnerable species but increased to the top two species after prioritisation as a consequence of their cultural importance as an indigenous fishery [24]. Further, weightings can be applied to different values as deemed appropriate in the calculation of overall importance values [see 20].

2.1.9. Step 10: targeted management

Managers can reduce climate vulnerability by reducing exposure or sensitivity or increasing adaptive capacity [43]. Step 10 involves managers and relevant stakeholders identifying the management actions most likely to reduce climate vulnerability. This is achieved by targeting the indicators from step 6 that contribute most to high vulnerability, focusing on components that were identified as high priority in step 9, and selecting actions that management can influence within reasonable resource requirements (Fig. 2). Additionally, the SQA may have identified indicators that are locally important and relevant but have high uncertainty. A key action for these indicators would be collecting essential data to enable a re-assessment. Step 10 includes monitoring and evaluation of the outputs against the management objectives (set in step 1) to assess the validity and performance of the assessment in terms of broader adaptation planning.

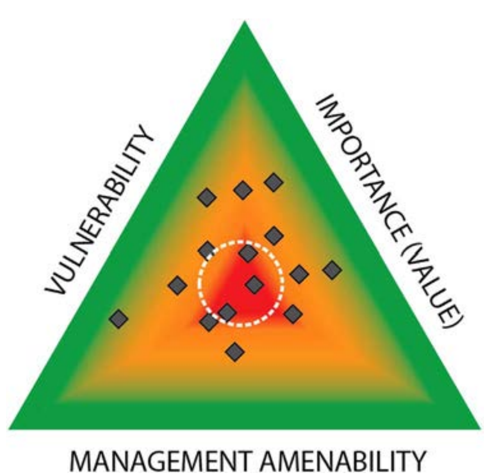

Fig. 2. Decision-support for selecting the assessment components for targeted management action. The centre (red) area represents components with high vulnerability to climate change, high importance (value) and high management amenability (cost effectiveness). Targets for management can focus only on those components circled or trade-offs among these three that are most aligned with management objectives.

3. Results and applications

This SQA method has been applied to different ecosystems and communities in Oceania using steps customised to each study context. Two case studies are summarised below that provide contrasting applications of the method (further details for each study are available in the Supplementary material and references cited).

3.1. Case 1: vulnerability of Pacific Island nations to climate-driven food security issues

The vulnerability of 22 Pacific Island countries and territories (PICTs) to climate-driven declines in fish for food was assessed using the SQA method (Fig. 3) [44]. The objectives and focus of this SQA (steps 1 and 2) were to determine the coastal communities in PICTs where fish demand is projected to exceed supply by 2035 under the A2 SRES emissions scenario.

The SQA used situation-appropriate indicators for all assessment elements (steps 3 and 4) using data from an earlier phase that assessed fisheries vulnerability (step 5) (see Supplementary Tables 1 and 2). Exposure (E) was calculated using an index based on the availability per person (kg) of: (1) demersal fish, non-tuna nearshore pelagic fish and shallow subtidal and intertidal invertebrates in proportion to their contributions to the estimated production of 3 t per km^2 per year, and (2) freshwater fish based on current national catches [45], given future projected population growth. The availability of all reef-associated fish and invertebrates, and freshwater fish, was modified by the projected changes to their production under future climate change [17]. The resulting total availability of fish per person was then deducted from the 35 kg per person required for good nutrition to estimate the exposure of each PICT.

Sensitivity (S) was estimated as the recommended level of fish consumption for good nutrition (35 kg per person per year; [46,47]), or higher national levels of consumption where these occur [45,47].

Potential impact values (PI=E*S) were >1 and varied widely, so were normalized to range from 0 to 1, with higher values representing greater potential impact. No PICTs were expected to benefit from the average climate-driven changes and therefore the 'Direction of Impact' coefficient was not applied.

To assess adaptive capacity (AC), four indices were combined – health, education, governance and the size of the economy – on the assumption that PICTs with higher levels of human and economic development are in a better position to undertake planned adaptation. Health was estimated as a weighted combination of infant mortality rate (0.33) and life expectancy (0.66). Education was measured as the combination of the literacy rate for people up to 24 years of age (0.66) and the percentage of students enrolled in primary education (0.33). The World Bank governance index was used to amalgamate six equally weighted aspects of governance: political stability, government effectiveness, regulatory quality, rule of law, voice and accountability, and corruption. To indicate the size of the economy and purchasing power, parity GDP per person was used. The AC index for food security (the capacity of PICTs to adapt to shortages in the supply of fish) was

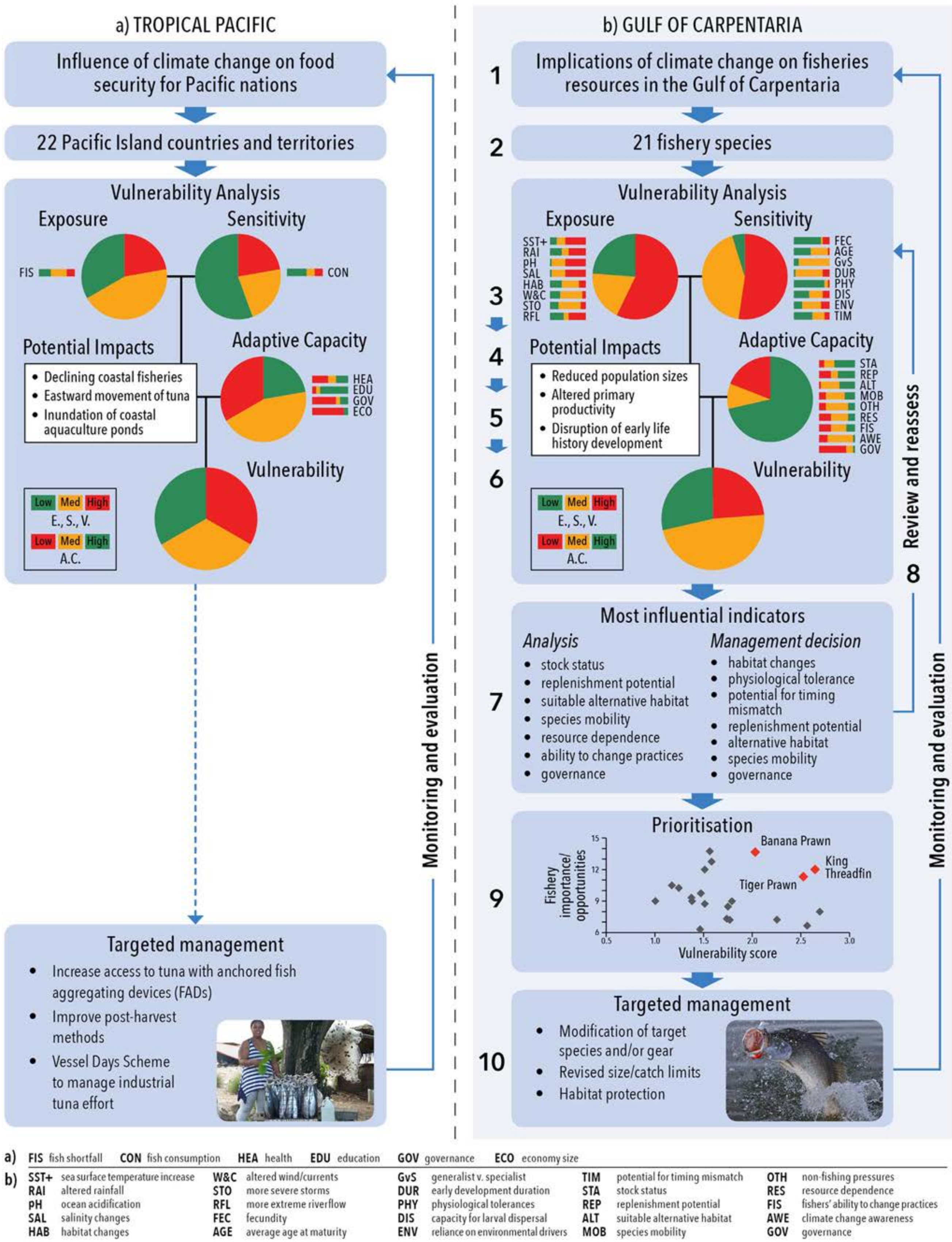

Fig. 3. Two contrasting case studies showing the application and results of the SQA method: (a) Pacific island countries and territories' vulnerability to climate-driven declines in fish for food security (Bell et al., 2011a, 2011b), and (b) Gulf of Carpentaria fisheries and supporting habitats. These example applications demonstrate how the SQA can be customised to the specific objectives and context of a study, and the steps tailored to address the management question.

estimated by weighting the values for the size of the economy (purchasing power) by 0.5, and the indices for health, education and governance by 0.167 (Supplementary Table 1). These weightings were based on the absence of plans to provide greater access to other sources of fish, thereby purchasing power plays a greater role in allowing individuals to acquire fish for food.

Nine PICTs were identified (of the 22 assessed) that will experience a gap between projected fish supply under future climate change and the recommended level of fish consumption for good nutrition (Supplementary Tables 1 and 2). Since all nine PICTs will require support to address this shortfall in fish supply, prioritisation (step 9) was not necessary to prepare a comprehensive suite of adaptations and policies for managers and governments [48].

The results have been disseminated through a participatory process with Pacific Island countries and development partners who have launched plans and initiatives to combat the food security problem (step 10). These include: the installation of nearshore fish aggregating devices to increase access by communities to tuna, protection and restoration of coastal habitats that support fisheries, distribution of bycatch and tuna from industrial fleets to urban areas, and improved post-harvest methods [26,44].

3.2. Case 2: vulnerability of Gulf of Carpentaria fisheries to climate change

The vulnerability of fisheries in the Gulf of Carpentaria under the A1FI SRES scenario by 2030 was assessed using the SQA method (Fig. 3) [28]. The project objective was to identify which fish stocks, and which fishery sectors, were likely to be impacted by climate change to prioritise species for action and identify potential adaptations (step 1).

The assessment of 21 fishery species targeted by commercial and recreational fishers (step 2) used E, S and AC indicators modified to the local context (steps 3 and 4) and assessed relative vulnerability using existing data and new data correlations (step 5) and the vulnerability metric (step 6). Generally, inshore species were assessed to be more exposed and sensitive to future climate change, and as a result the species in the inshore finfish fishery were ranked as having the highest vulnerability. Some species were identified that may benefit from climate change [28], with higher population sizes predicted due to projected increases in rainfall (e.g. banana prawns).

The sensitivity analysis (step 7) identified a suite of indicators that influenced both species' rankings and substitutions of the high vulnerability species, which are those most likely to be targeted by management. Eight indicators affected >50% of overall rankings, and seven indicators affected substitutions between the high and moderate rankings (see Fig. 3). Therefore, opportunities for future research should consider the information requirements for these indicators to enable a repeat assessment (step 8).

Prioritisation (step 9) resulted in a reduced focus on some inshore finfish species and an increased focus on highly valuable commercial species, such as tiger prawns. The assessment applied a highly participatory expert-driven process, with multiple structured expert elicitation sessions, and extensive stakeholder consultation during the final steps. The presentation of future scenarios to stakeholders allowed for identification of potential adaptation options (step 10). This proved to be an effective mechanism for delivering robust results and collective learning throughout the process, enabling a pathway for action through engaged stakeholders [28].

4. Lessons learned and future applications

Application of the SQA method presented here, as described above in the practical cases, has increased utility of the framework and method for management. There are considerations when implementing the approach that will maximise confidence in the results and focus outputs on management objectives. One general limitation of using indices and scores that should be considered before implementing this approach is that they do not provide direct measures of the expected impacts. That is, they do not quantify the magnitude of change (e.g. the size of range reductions or population declines, see [14]). If the primary management objective is to answer a specific hypothesis on the magnitude of change, then a vulnerability assessment of any kind is unlikely to be the appropriate method. All of the following are important to consider when implementing the SQA method: spatial scale of assessment, participation, weighting indicators, uncertainty and validation.

4.1. Spatial scale of assessment

A critical consideration when beginning a vulnerability assessment is to define attributes and the spatial and temporal scales of interest [49]. Place-based analyses that focus on a defined site or region but recognise nested scales and the dynamic nature of SES are recommended. The spatial scale of the assessment needs to be determined in step 1, and should assimilate scales of analysis with feasible scales of action. A limitation of multi-species climate change vulnerability assessments is that they can on occasion deliver spurious results for migratory species [50] or species with spatially extensive ranges. Application of this framework to such species should incorporate indicators and criteria (steps 3 and 4) that encompass connectivity and migration pathways. Conservation and migratory status are also considerations during prioritisation (step 9).

4.2. Participation

An integral part of this SQA method is effective participation with stakeholders, including decision-makers and communities, throughout the process. Effective participation maximises the quality of assessment outputs and uptake of results by stakeholders [33,51,52]. Thus, for the assessment to be successful it should: (i) draw upon diverse knowledge; (ii) be inclusive of all known perspectives; and (iii) build political will. Participation of stakeholders should be based on a human rights and human development approach to achieve gender equality, maintain relevant traditional customs and culture, and empower youth [53]. Improving the rigour and transparency of engagement with stakeholders during multiple steps of the assessment (e.g. in steps 1, 2, 3, 4, 6 and 9) will facilitate better multi-disciplinary integration and build support for the actions identified during step 10 (and beyond).

4.3. Weighting indicators

The SQA method outlined here and applied in different regions differentially weighted indicators in some cases. One benefit of criteria-based assessments is the ability to incorporate weightings if it is determined that some indicators are more important than others in determining climate change vulnerability. This is unlike trait-based assessments that typically do not include weightings [14]. Scientifically sound aggregation approaches that recognise and incorporate non-linearity and key drivers of vulnerability are essential for producing assessments that are valid and consistent [49]. The Pacific Island food security assessment provided such an application, where AC indicators were weighted based on known interactions between health and economic factors with adaptation of food security policy and communities. Expert participation provides an opportunity to determine if such weightings are necessary and which indicators and criteria should be weighted and how (steps 3 and 4).

4.4. Uncertainty

The most common sources of uncertainty in vulnerability assessments originate from the choice of criteria, parameterisation of thresholds of change, gaps in knowledge [54] and from assumptions of linearity in the relationship between indicators and vulnerability to climate change [49]. There is also a range of approaches for combining indicators (e.g. aggregated, averaged) and the weighting of these that would result in different outputs. The ordinal scoring approach described here, where particular characteristics are evaluated as increasing or decreasing the impacts of climate change rather than quantifying direct measures of vulnerability, addresses some of those concerns. By using science-based indicators and criteria applied consistently to all components being assessed, some of these sources of uncertainty can be addressed [49,55]. As examples, steps 3 and 4 should use qualitative and quantitative research when identifying indicators to reflect the processes that drive vulnerability to climate change and apply the scoring criteria consistently to minimise uncertainty. The sensitivity analysis and review (steps 7 and 8) aim to identify which indicators most influence rankings – reviewing and reassessing influential indicators for which confidence is low can help reduce uncertainty – this process emphasises the value of setting criteria for confidence scoring at the same time as setting criteria for indicator scoring (i.e. during step 4; as per [56]). Confidence scores can also be produced for each element index such as exposure or sensitivity [54], or for the final assessment results [56]. However, confidence scores are *most easily* developed as relative classifications of confidence or uncertainty (i.e. low, medium and high) for each of the indicators included, as described in step 4. Concurrently assessing uncertainty when determining indicator scoring increases the transparency of the results. This way, the final vulnerability classifications enable targeting of management actions to the major drivers of climate change vulnerability for which confidence is highest (or uncertainty is lowest).

4.5. Validation

Finally, validating the accuracy and precision of this SQA method is important for refining the approach and ensuring results are accurate and robust. Sensitivity analysis and review (steps 7 and 8) provide one avenue for checking if particular inputs (indicators) are especially influential and warrant further review. Comparisons of assessment results with observations, particularly under variable climate conditions, provide another avenue for validation. This type of validation is most appropriate during the monitoring and evaluation phase, where vulnerability results can be compared to the original management objectives (set in step 1) to verify if objectives are being met.

5. Conclusions

The SQA method described here overcomes many of the challenges of assessing vulnerability of complex SES, in that it can: (1) address specific conservation, socio-economic and environmental management objectives; (2) be implemented by decision-makers using available data and expert knowledge; (3) be customised to any context (spatial or temporal); (4) integrate social and ecological factors; (5) rank relative vulnerability of a range of SES components; (6) identify knowledge gaps critical to justifying actions or increasing analysis confidence, and (7) provide decision-support for managers enabling actions to be targeted to reduce climate vulnerability. The practical applications demonstrate the flexibility of the SQA method in that it can be applied to species, ecosystems or resource-dependent industries and communities anywhere. Once assessments are complete, they can be iteratively refined, particularly as new information becomes available. Through monitoring and evaluation, the analysis inputs and outputs can be regularly reviewed and the assessment repeated. This way, future assessments can either measure the progress made in reducing climate vulnerability and/or include new data or improved understanding of vulnerability drivers. Importantly, the results of a semi-quantitative vulnerability assessment can lead to a more transparent process for evaluating the trade-offs between short-term priorities and longer-term adaptation plans.

Data accessibility

All data for this paper and the semi-quantitative assessments are available in published reports available at ResearchGate (DOI 10.13140/2.1.4002.3846).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2016.09.024.

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Chapter 7

Discussion

Climate change is a suite of acute and chronic stressors that are impacting socio-ecological systems, ultimately affecting the millions of people that live in coastal and island environments and are dependent on the oceans for food and income, as well as the industries that support national economies. While abatement and reduction of greenhouse gas emissions is critical for addressing climate change, even with such mitigation there is inertia in the climate system that change would still continue for some decades. In addition, influencing mitigation is largely out of the scope of local managers so the current paradigm is to support the resilience of ecosystems, mostly through reducing stress caused by local anthropogenic activities. The challenge for managers lies in determining which actions to implement and where to target those actions to maximise site and system resilience.

Informed adaptation thus remains a priority for future decades even with effective global mitigation action. Scientists and conservation managers continue to search for effective methods to identify, prioritise and select adaptation responses to support socio-ecological systems in the short- to medium-term. A decade ago, research focused on whether ecological systems can autonomously adapt in time or if gene selection was possible. While managers focused on supporting the general resilience of natural systems so they could cope with future change. This research set out to develop a vulnerability assessment approach that answered specific management questions, identified the main sources of vulnerability and the components of the system that most needed support, and identified adaptations to minimise key vulnerabilities.

The concept of vulnerability has emerged as a key dimension in the climate adaptation field over the last two decades (FAO 2015). As ecological responses and thresholds of change have become evident, important and sensitive habitats and regions are focal points for determining pathways to adaptation that supported future sustainability. In Australia, the Great Barrier Reef became the first focal location for a multi-disciplinary qualitative vulnerability assessment (Johnson and Marshall 2007) using the Intergovernmental Panel on Climate Change (IPCC) vulnerability framework (Schneider et al. 2007). In the tropical Pacific Island region, the high dependence on fish for food security, livelihoods and national economies, meant assessments had to move beyond detailing potential impacts on ecosystems to understanding how climate change would affect resource-dependent communities and importantly, the national plans and policies in place to derive benefit from marine resources (e.g. The Pacific Plan 2007, The Vava'u Declaration on Pacific Fisheries Resources 2007). Informed adaptations were needed and the structured IPCC vulnerability framework provided a mechanism for identifying targets for action to reduce impacts and prepare for the projected changes and variability (Bell et al. 2011a,b; Bell et al. 2013).

The five objectives of this thesis were addressed as follows, through the learnings in each chapter and the development and refinement of the SQA method:

(1) A systematic review of experimental and field research, as well as projections in the fields of species distributions and socio-economic dependencies documented the range of potential impacts of climate change on marine ecosystems (Chapter 2) and provided expert value judgments of these climate change implications on ***marine socio-ecological systems***. Findings demonstrated that marine habitats, species and dependent societies and economies are expected to be impacted by climate change, and these implications will require support in the form of management policies and plans that facilitate adaptation.

(2) Understanding species ecology and responses, and observing systems that are already experiencing changing climate conditions confirmed that marine socio-ecological systems ***can adapt*** (Chapter 3), and provided insight into how science can inform adaptation actions.

(3) Moving from theory to development of a vulnerability assessment approach, Chapter 4 conceptualised socio-ecological indicators of vulnerability ***to climate change*** and postulated how the results of regional, expert-based assessments can inform decision-making. Importantly, the example application of the semi-quantitative approach identified key areas of focus for the method, as integrated social and ecological indicators and the inclusion of direct effects of climate change on societies through adaptive capacity indicators.

(4) The first full application of the SQA method, used a novel semi-quantitative ***vulnerability assessment*** tool that integrated socio-ecological factors at management-relevant scales, weighted variables as a measure of their importance and likelihood, and delivered ranked outputs that directly informed fisheries management investment and effort (Chapter 5). The results demonstrated that data limitations could be overcome but further work was required to understand how positive responses could be analysed, and the utility of the method to other sectors and systems.

(5) The final evolution of the SQA method in this thesis, applied the tool in six different locations to determine how robust the method and results were for different sectors

and contexts (Chapter 6), and whether results were still useful to inform decision-making ***to target resilience-based management***. While a wholly terrestrial system was not tested, the utility was demonstrated for a range of coastal and marine sectors and contexts.

7.1 What the research means for theory in this field

Application of the IPCC vulnerability framework to criteria-based assessments provided an evolution of methods for understanding vulnerability of social and ecological systems (e.g. Johnson and Marshall 2007; Allison et al. 2009; Marshall et al. 2010; Bell et al. 2011a; Doubleday et al. 2013; Foden et al. 2013; Pecl et al. 2014; Beaugrand et al. 2015), although few have been quantitative. Results of these applications have provided valuable insight and lessons on integrating social and ecological factors, and tailoring the framework to specific local and regional contexts. Initial attempts to integrate socio-ecological factors conducted a two-step approach (Figure 2) where the first assessed ecological vulnerability, and then a replicated step used the results of the ecological assessment as input data to the 'exposure' of social systems to assess their vulnerability (Cinner et al. 2013a,b). However this approach was complex and still provided two separate results – one for the ecosystem and the other for the resource-dependent community – thus not fully integrating the assessment.

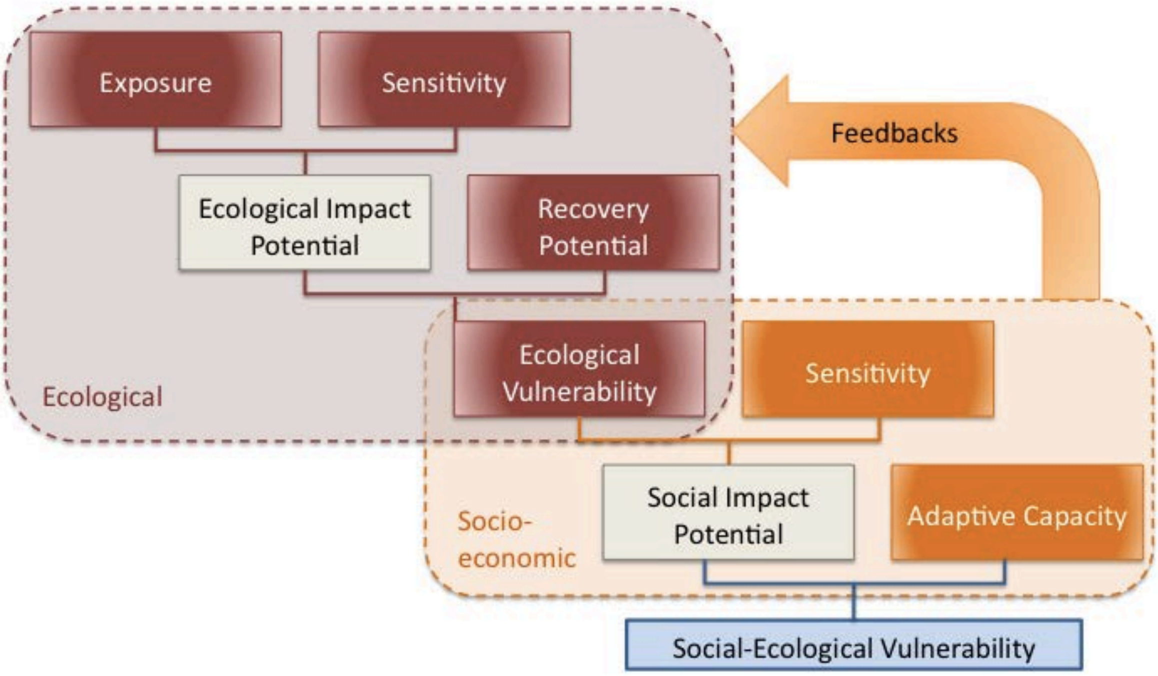

Figure 2. Two-step framework for linking social and ecological vulnerability (adapted from Marshall et al. 2010).

A recent review of vulnerability assessment methods (Pacifici et al. 2015) found that in general, a *correlative* approach is appropriate when the only data available are those on species' occurrence, for example, to project future climatic suitable areas for a species, at local to global scales. While *mechanistic* models are good at assessing extinction probability driven by climate change, they require substantial data inputs and are therefore limited to a few species of conservation interest. Risk-based approaches that consider Management Strategy Evaluation (MSE) are effective for data-rich single species (Plaganyi et al. 2013) but perform poorly when applied to complex multi-species systems with limited data. Another recent review focused on vulnerability assessments as a tool to improve the targeting and effectiveness of adaptation actions for people, activities, places or hazards (FAO 2015) and concluded that methods needed to embrace the complexity of the issue and selecting the type of vulnerability assessment (e.g. scale, methods, data) should be determined by the purpose of the assessment, available resources, time, expertise and data.

Further, an examination of the results of a global vulnerability assessment found that the relative ratings for small-island states depended critically on the choice of methods and data (Monnereau et al. 2017). For example, there were vastly different vulnerability scores depending on whether data for number of fishers were given as raw numbers or scaled by population size, and depending on the definition of "fishers." These method reviews consistently identify key factors needed for an integrated and standardised vulnerability assessment tool; the method needs to articulate the management objectives (purpose) of the assessment, normalize the data, and consider the local available resources and context in order to provide practical and consistent results.

This thesis addressed these issues by:

- Delivering a standardised and simple method that has application at a range of spatial and temporal scales and to different local and regional contexts.
- Delivering a single-step for integrating ecological and social factors using indicators and criteria to score all factors that contribute to vulnerability.
- Using available knowledge and data about climate projections, species and community responses to quantify and rank vulnerability.
- Using normalized data to score indicators as an objective mechanism to identify the main drivers of vulnerability and target adaptation actions.
- Ranking system components in order of vulnerability and identifying the main sources of vulnerability that can be used to inform resilience-based management.
- Including a sensitivity analyses to determine which indicators most influence the results and whether the data quality for these indicators needs to be reviewed to increase analysis robustness.

- Prioritising results using economic, social and cultural values to focus adaptations on the most vulnerable and important components of the system.

7.2 Current practical applications of the research

The key climate drivers of change for marine socio-ecological systems include ocean acidification that is causing a steady decline in ocean pH, rising sea temperatures, more intense storms, sea-level rise, altered rainfall patterns, changing ocean currents and salinity changes. The resultant changes to biophysical conditions in global oceans, and marine habitats are of growing concern for the species and resource-dependent industries and communities that rely on these important marine resources. Importantly, impacts can be spatially extensive and delayed, and therefore adaptations that are practical and targeted are essential for maintaining sustainable industries and supporting food security and livelihoods of communities.

This body of work represents over 10 years of research, where a range of assessment methods were reviewed, ultimately adapting the IPCC vulnerability framework that had been applied in a qualitative way and had prospects for application to dynamic and complex systems. The semi-quantitative assessment (SQA) method described in this thesis has evolved from a conceptual vision (Johnson and Welch 2010) to be a practical tool applied initially at an ecosystem scale then to regions, species, habitats and resource-dependent communities and nations. The SQA method was developed to be robust, applicable to different socio-ecological systems using locally relevant indicators, to integrate socio-ecological factors and provide semi-quantitative results in order to identify the main sources of vulnerability and determine which adaptation and resilience actions will be the most effective. Importantly, the approach provides a practical tool that managers can apply in resource and data limited situations and provides local targets for adaptation that support sustainability under a changing climate.

A key factor in operationalising vulnerability concepts to support resilience-based management has been the development of tailored indicators and criteria to conduct a semi-quantitative assessment. The indicators and criteria are tailored to each local context based on known species and ecosystem ecology, responses to climate drivers and resource-dependence, to score and rank vulnerability using existing data. The benefits of such an approach is that it can integrate social and ecological data, the relative vulnerability rankings identify the main sources of vulnerability, and adaptations can be tailored to highly vulnerable components, supporting resilience-based management. The integration of socio-economic and ecological factors provides decision-support that targets adaptations most likely to succeed in building resilience of socio-ecological systems to future climate change (Metcalf et al. 2015).

Managers, experts and stakeholders who have participated in assessments understand the concepts and support a tool that is neither complex nor difficult to implement or communicate. The SQA method has already delivered practical outcomes for decision-makers, prioritising targets for climate change adaptation action in the Great Barrier Reef, Torres Strait and Pacific region for marine ecosystems, fisheries and aquaculture sectors, and resource-dependent industries and communities (Bell et al. 2011a; Welch et al. 2014; Johnson and Welch 2016; Johnson et al. 2016a,b; Johnson and Basel unpublished). While the sensitivity analysis tested the influence of individual indicators on results and identified any disproportionate effect of a single indicator, the influence of different experts has not be tested in the same way. Each application of the SQA method aimed to include a range of experts from relevant fields to minimise the influence of any single person. Further testing of this could be conducted by having several focus groups with different experts from the same region conducting the assessment.

The design of the structured SQA method had to fulfill the following criteria: (1) deliver semi-quantitative results, (2) utilise available data (published and expert knowledge), (3) capacity to assess relative vulnerability of multiple components to multiple stressors, (4) integrate socio-ecological factors, (5) applicable to any local context, and (6) provide flexibility so emerging data can be added to rerun the assessment. The results inform targeted adaptation actions that can effectively minimise or address the sources of vulnerability and enhance resilience.

The clear step-wise approach has utility for socio-ecological systems anywhere at different spatial and temporal scales, and provides guidance for practitioners to use available information to prioritise adaptation actions. For example, understanding climate change vulnerability of Pacific oceanic fisheries has enabled progress on adaptations to tuna fisheries by-catch practices to improve food security in many nations. There has also been progress in some nations on allocating more tuna for local processing to benefit local economic development. Similarly, application of the SQA method to assess the vulnerability of reef-dependent coastal communities in 22 Pacific nations to the effects of ocean acidification on reef goods and services (e.g. food security, coastal protection, tourism livelihoods) has facilitated pilot projects to locally buffer acidification and minimise the consequences for communities and industries in the three most vulnerable locations (Johnson et al. 2016b).

Importantly, the SQA method can be used to systematically address management objectives by generating new knowledge and identifying appropriate management and community-based responses, which is a key benefit of vulnerability assessments (Rowland et al. 2011). Components assessed as having: high vulnerability, high importance, and sources of vulnerability (indicators) that are amenable to management can be addressed with available resources become targets for management action. The steps of ranking vulnerability to climate change then prioritising components based on social/cultural importance or economic value allows for management resources to be focused on specific components and target actions most likely to maximise site and system resilience.

7.3 Future applications and research

Climate change impacts are expected to accelerate in the future and are compounding challenges already facing ecosystems, industries and communities due to overexploitation, population growth, poverty and rural underdevelopment, and an inability to anticipate disturbances and adapt. Climate variability and change can therefore exacerbate ecosystem degradation, food insecurity and livelihood issues and effective adaptations are critical.

While adaptations at the household, community, sector and national levels to support resilience in a changing climate are being implemented they are not always targeted or based on an understanding of the main sources of vulnerability. For example, implementing ecosystem-based approaches to fisheries and aquaculture management provides a suitable road-map for adaptation and building resilience (Heenan et al. 2015). However it is a fundamental management principle that does not necessarily target the most climate vulnerable species, dependencies or sectors. Many such adaptations are no-regrets and are based on known best-practices that will have short-term benefits for the sector as well as long-term benefits in coping with future climate uncertainty and change. However, informed and targeted adaptations are needed and managers need the sort of information the SQA method can provide to support decisions on specific adaptations that focus on the most vulnerable components, locations and timeframes. Facilitating adaptation requires knowledge of current and future vulnerability, effective adaptation options, and the priorities for adaptation, as well as capacity to implement and fund long-term planning and actions. Therefore, there are many potential future applications of the SQA method for natural resources, sectors and communities worldwide.

The different contexts and management objectives that the SQA method can address vary substantially. For example, applying the SQA method to small island states (e.g. American Samoa, Puerto Rico, Seychelles) can systematically assess climate vulnerability and support long-term reporting and decision-making (Figure 3). Using a ‘traffic-light’ system, the SQA results can be used to show the contribution of different factors to vulnerability, the amenability of these factors to management, the cost of adaptation actions; ultimately informing forward-looking ‘Outlook’ reporting as the foundation for resilience-based management. A recent such application to coral reefs in Hawaii (Maynard et al. 2018) delivered a baseline Outlook Report that combined the results for each element of vulnerability to spatially map overall reef vulnerability based on ecological and human indicators. The results were further analysed to examine social vulnerability specifically, i.e. a community’s reliance on natural resources and ability to adapt to changes in their natural and social environment (Figure 4), thereby providing clear targets for management.

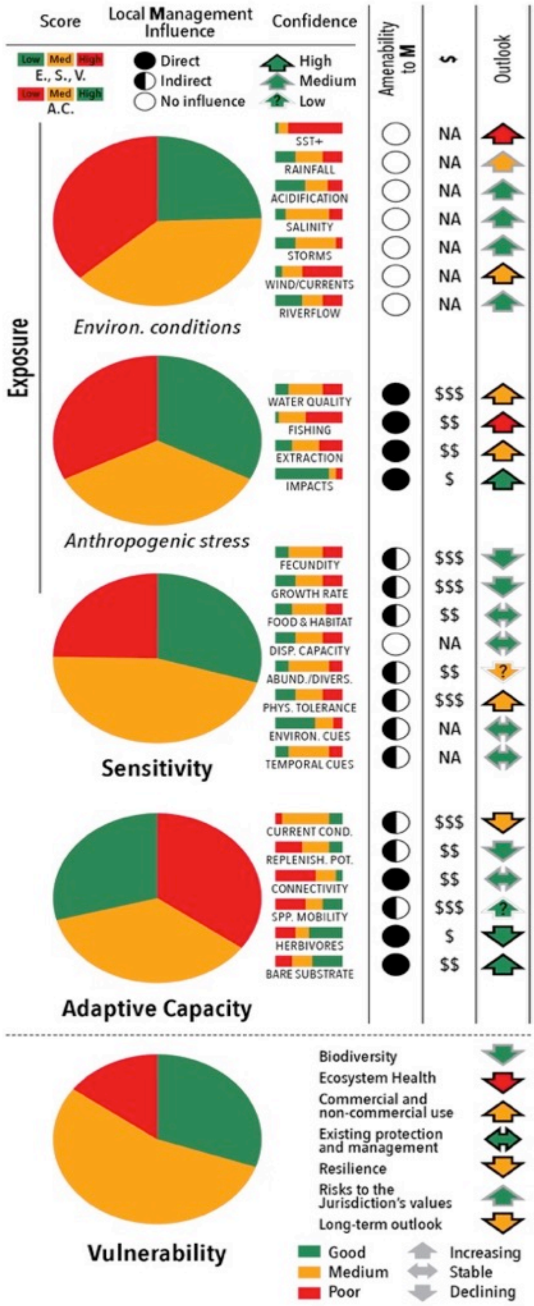

Figure 3. Application of the SQA results for targeted decision-making and Outlook reporting (adapted from Maynard et al. 2017).

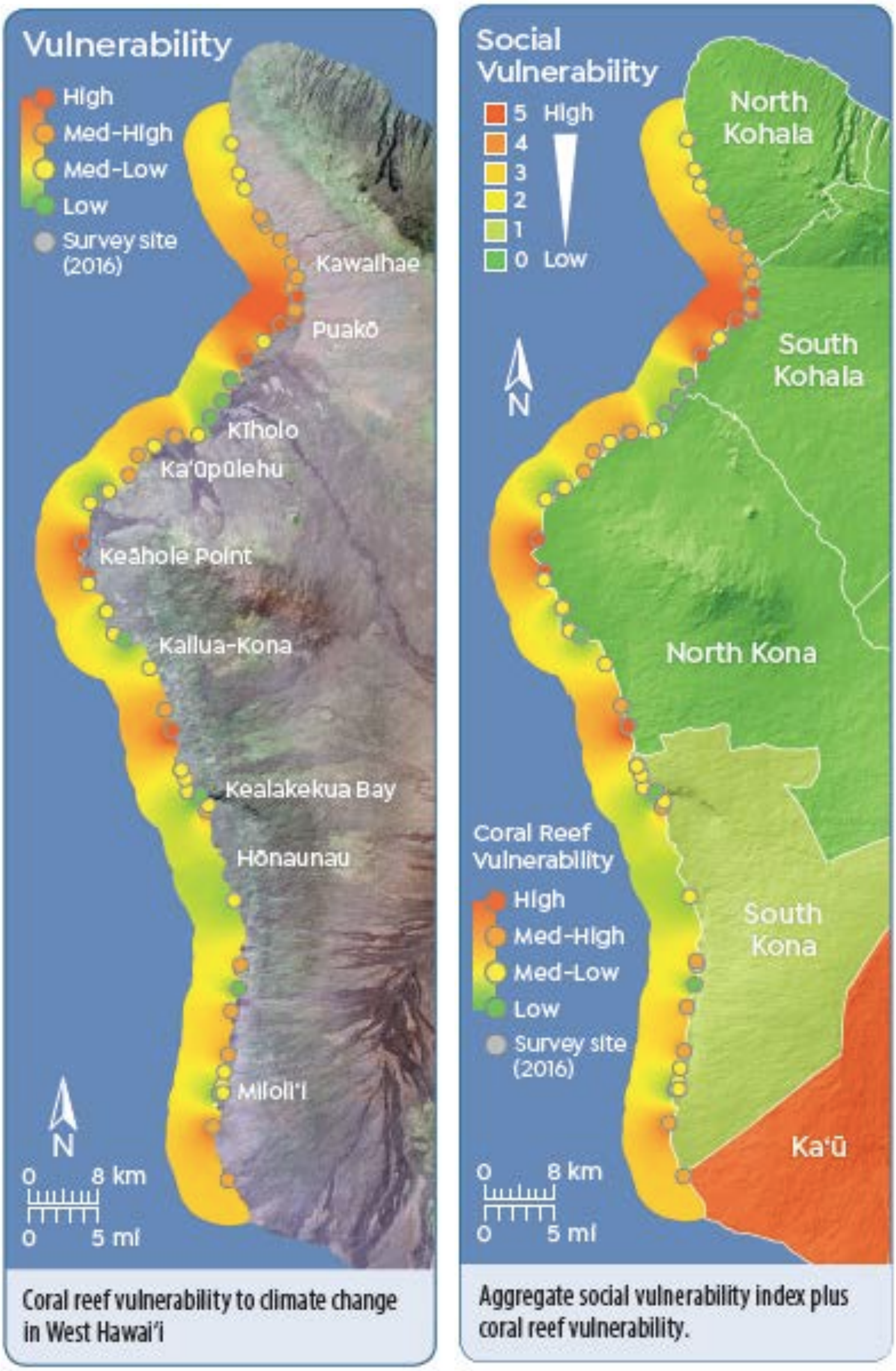

Figure 4. Spatial mapping outputs of the SQA method used in West Hawai'i to assess coral reef vulnerability and social vulnerability to climate change (Maynard et al. 2018).

Such Outlook reports rank indicators for each vulnerability component (low, medium or high), plus include a measure for local management influence (direct, indirect or no influence) and confidence (low, medium or high). The results are mapped and 'outlooks' produced for key components of the system. The main goals of using the SQA method to produce Outlook Reports is to: (1) improve decision-makers access to and capacity to incorporate information on climate change impacts into decisions and, therefore, (2) increase capacity of management to target effective and affordable adaptations that minimise vulnerability to climate change.

The SQA method has evolved into a framework that has utility for a range of locations, systems and contexts, particularly where data is limited. However, there are still limitations. The integration of social and ecological indicators in the assessment does not include social indicators throughout or weight their importance or influence on SES resilience, as this is generally unknown. However, it could be possible to include social indicators of sensitivity and weight them if the system being assessed has information on responses to climate variables for both social and ecological components. In the same way that the step-wise separation of social vulnerability (see Figure 2) imposes a weighting on indicators by the very nature of the approach, specific weighting of indicators could be explicitly examined in further research for the SQA tool.

This research has demonstrated that vulnerability assessments can be applied at a range of spatial and temporal scales, to different species, habitats and sectors, and with limited data. The SQA method includes participatory steps, and has utility for engaging with resource-dependent communities, incorporating non-technical but highly valuable local knowledge, and being able to rapidly inform practical social-ecological adaptations. Results provide insight into the main drivers of vulnerability, the priority components or locations to focus, and the adaptations that are most likely to effectively minimise vulnerability.

The SQA 10-step method has also been designed so it can be customized to any local context to assess vulnerability and address specific management objectives. The approach is suitable in data limited situations, is rapid and easy to use, making it accessible to decision-makers. The results provide an objective and practical mechanism for identifying key source of vulnerability, prioritising components and targeting adaptation and resilience-based initiatives. Ultimately, the SQA method has wide utility and can be applied at minimal cost using existing data so has great potential to inform adaptive natural resource management in any context. To this end, a guide for practitioners is in preparation outlining the 10-step method to be published as an FAO Fisheries and Aquaculture Circular (Johnson et al. in prep). As climate change continues to impact on marine socio-ecological systems, a tool that can be easily and rapidly applied to focus limited resources on effective adaptations will be key to supporting ecosystem resilience and sustainable communities.

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APPENDIX 1: Supplementary Published Material

Chapter 2:

Bell JD, **Johnson JE**, Hobday AJ, Ganachaud A, Gehrke P, Hoegh-Guldberg O, Le Borgne R, Lehodey P, Lough J, Pickering T, Pratchett M, Waycott M (2011a) Vulnerability of tropical Pacific fisheries and aquaculture to climate change: Summary for countries and territories. Secretariat of the Pacific Community, Noumea, New Caledonia.

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APPENDIX 2: Supplementary Material for Chapter 5

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Supplementary Information

Table S1: Vulnerability assessment indicators for Exposure, Sensitivity and Adaptive Capacity (grey shade – ecological indicators; blue shade – social indicators) and their criteria for semi-quantitative scoring of each fishery species.

		Low=1	Medium=2	High=3
Exposure	Surface temperature increase +0.62 to +1.27 °C	spends <50% of time in surface (<25 m) waters	spends 50-80% of time in surface (<25 m) waters	spends 80-100% of time in surface (<25 m) waters
	Rainfall change -2.97 to +6.27%	spends no time in estuarine or freshwater habitats during any life history phase	spends <50% of time in estuarine or freshwater habitats; no critical life history phase	spends >50% of time or has critical part of life cycle in estuarine or freshwater habitats
	pH decline 0.1 unit	open ocean or deep water species	continental shelf species	inshore or estuarine species or calcareous parts
	Salinity decrease -0.1 psu	open ocean or deep water species	continental shelf species	inshore or estuarine species
	Habitat changes (loss of productivity, structure or function)	species not habitat dependent	species dependent on pelagic or mangrove habitats	species dependent on seagrass or coral reef habitats
	Altered wind/currents	live young/egg bearers or no dependence on wind/current for larval dispersal	proximate dispersal of young not entirely dependent on wind/current dispersal	dispersal of young 100% dependent on wind/currents
	Tropical cyclone intensity +2 to +11%	deep water or highly mobile species	shallow water (< 25 m) and moderately mobile species	shallow water (< 25 m) or low mobility species
	More extreme river flow	spends no time in estuarine or freshwater habitats during any life history phase	spends <50% of time in estuarine or freshwater habitats; no critical life history phase	spends >50% of time or has critical part of life cycle in estuarine or freshwater habitats
Sensitivity	Fecundity – egg production	>20,000 eggs/year	100-20,000 eggs/year	<100 eggs/year or live young
	Average age at maturity	≤ 2 years	3-10 years	> 10 years

	Generalist v specialist (food & habitat)	reliance on neither habitat or prey	reliance on either habitat or prey	reliance on both habitat and prey
	Early development duration (dispersal)	> 8 weeks	2-8 weeks	< 2 weeks or no larval stage
	Physiological tolerance of stock	Threshold unlikely to be exceeded for any climate variable	Physiological thresholds unknown	Threshold likely to be exceeded for one or more environmental variables
	Reliance on environmental cues (for spawning, breeding or settlement)	No apparent correlation to environmental variable	Weak correlation to environmental variable	Strong correlation to environmental variable
	Reliance on temporal cues (duration of spawning, moulting or breeding)	Continuous spawning duration; >4 months	Moderate spawning duration; 2-4 months	Brief spawning duration; <2 months
Adaptive Capacity	Stock status	overfished or on the verge of overfishing	moderate fishing levels or status unknown	not overfished
	Replenishment potential	late maturing (> 6 yrs), slow growth or few young	matures at 3-6 yrs, moderate growth or numbers of young	early maturing, fast growing or many young
	Ability to range shift	low availability of habitat outside range or currently near northern edge of range	some availability of habitat outside range or currently near middle of range	high availability of habitat outside range and currently near middle of range
	Species mobility	low mobility; can travel <2 km/day	moderately mobile; can travel 2-10 km/day	highly mobile; can travel >10 km/day
	Non-fishing pressures on stock	multiple chronic pressures (e.g. poor water quality, disease)	some acute pressures (e.g. cyclones, storms, floods)	no or minimal other pressures
	Resource dependence	no alternate species and/or significant gear/practice modifications required to target other species	some alternate species that could be targeted with gear/practice modifications	multiple alternate target species that could be targeted without any gear/practice modifications
	Willingness to change fishing practices	not willing to change	willing to change with support	willingness to change
	Climate change awareness	unaware	aware and no planning undertaken	aware and has taken preparatory action
	Governance	inflexible or non-existent	flexible or adaptive (not both)	flexible and adaptive

Table S2. Information sources used for scoring the Exposure, Sensitivity and Adaptive Capacity indicators for each species during the assessment process.

Species	Sources for scoring indicators
Brown tiger prawn	Expert judgement. Bell et al. 2011, Skirtun and Vieira 2012, Turnbull et al. 2009, O'Brien 1994, Loneragan et al 1994, Watson and Turnbull 1993, Somers 1987, Wassenberg and Hill 1987, Meynecke and Lee 2011, Penn and Caputi 1986
Blue endeavour prawn	Expert judgement. Bell et al. 2011, Skirtun and Vieira 2012, Watson and Turnbull 1993, Somers 1987, Meynecke and Lee 2011, Penn and Caputi 1986, Park and Loneragan 1999
Tropical rock lobster	TI surveys. Expert judgement. Bell et al. 2011, Woodhams et al. 2012, Pitcher et al. 2005, Moore and MacFarlane 1984, Smith et al. 2009, Dennis et al. 2001, Plagányi et al. 2009, 2011 Skewes et al. 1997, Jones 2009, Norman-López et al. 2012, Sachlikidis et al. 2010
Mud crab	Expert judgement. Duke et al. 2012, TSRA 2011, Bell et al. 2011, Hill et al. 1982, Ong 1966, Davis et al. 2004, Hill 1994, Heasman et al. 1985, Knuckey 1999, Hamasaki 2003, Ruscoe et al. 2004, Webley et al. 2009, Heasman 1980, Fielder and Heasman 1978, Loneragan and Bunn 1999, Robins et al. 2005, Meynecke et al. 2012, Helmke et al. 1998, Brown 1993, Meynecke et al. 2010
Gold-lipped pearl oyster	Expert judgement. Bell et al. 2011, Gervis and Sims 1992, Sims 1992, Torres Strait Fisheries Assessment Group 1999, Yukihira et al. 2000, Doroudi et al. 1999
Black-lipped pearl oyster	Expert judgement. Bell et al. 2011, Gervis and Sims 1992, Yukihira et al. 1998, Yukihira et al. 2000, Fournier et al. 2012, Doroudi et al. 1999
Trochus (topshell)	Expert judgement. Bell et al. 2011, Nash 1993, Castell 1997, SEWPaC 2012, Murphy et al. 2010, Nash 1985, Heslinga and Helman 1981, Bertram 1998
Spanish mackerel	Expert judgement. Bell et al. 2011, Buckworth and Clarke 2001, McPherson 1992, Buckworth et al. 2007, McPherson 1981a, 1986, Ovenden et al. 2007, Jenkins et al. 1984, Jenkins et al. 1985, McPherson 1981b, Williams and O'Brien 1998, Begg et al. 2006, Tobin and Mapleston 2004, McPherson 1993, Mackie et al. 2005
Common coral trout, Bar-cheek coral trout, Passionfruit coral trout	TI surveys. Expert judgement. Bell et al. 2011, Williams et al. 2008a, Woodhams et al. 2012, Williams et al. 2008b, Samoilys and Squire 1994, Samoilys 1997, Doherty 1996, Masuma et al. 1993, Leis and Carson-Ewart 1999, Light 1995, Lou et al. 2005, Wen et al. 2012, St John et al. 2001, Tobin et al. 2010, Pratchett et al. 2013, Munday et al. 2009
Sandfish	Expert judgement. Waycott et al. 2011, Bell et al. 2011, Murphy et al. 2011, Morgan 2000, Ramofafia et al. 2003, Mercier et al. 2000a, Conand 2006, Uthicke et al. 2004, Mercier et al. 2000b, Ramofafia et al. 1995, Battaglene 1999, Asha and Muthiah 2005, Plagányi et al. 2013
Black teatfish	Expert judgement. Bell et al. 2011, Murphy et al. 2011, Shiell and Uthicke 2006, Uthicke et al. 2004, Battaglene 1999, Asha and Muthiah 2005, Plagányi et al. 2013
Dugong	TI surveys. Expert judgement. Waycott et al. 2011, Sobtzick et al. 2012, Bell et al. 2011, Heinsohn et al. 2004, Marsh et al. 1984, 1997, 2004, Grayson et al. 2006, Lawler et al. 2007, Marsh and Kwan 2008, Meager and Limpus 2011, Gales et al. 2004, Limpus and Reed 1985
Turtle	TI surveys. Expert judgement. TSRA 2011, Waycott et al. 2011, Sobtzick et al. 2012, Bell et al. 2011, Plotkin 2003, Kennett et al. 2004, Harris et al. 1997, Arthur et al. 2008, Musick and

	Limpus 1997, André et al. 2005, Yntema and Mrosovsky 1982, Hawkes et al. 2009, Fuentes et al. 2010, Pike and Stiner 2007, Meager and Limpus 2011, Limpus and Reed 1985, Marsh and Kwan 2008

Table S3. Mean scores for Exposure, Sensitivity, DI, Adaptive Capacity (broken down into ecological and social components), and AC normalized for each species and their overall vulnerability score.

Species	Exposure	Sensitivity	Direction of impact	Adaptive capacity		AC standardized	Vulnerability
				ecological	social		
Black teatfish	2.13	1.71	+1	1.20	2.00	0.61	2.69
Black-lipped pearl oyster	2.00	1.86	+1	1.40	2.00	0.66	2.50
Dugong	1.88	2.29	+1	1.80	1.75	0.71	2.44
Trochus	2.25	1.86	0	1.80	1.50	0.67	2.33
Turtle	2.13	2.57	+1	2.20	1.75	0.81	2.18
Gold-lipped pearl oyster	2.00	1.71	0	1.80	1.50	0.67	2.09
Brown tiger prawn	2.13	1.71	+1	2.20	1.50	0.77	2.06
Blue endeavour prawn	2.13	1.57	0	2.00	1.50	0.72	1.91
Sandfish	2.13	1.71	0	1.80	2.00	0.75	1.83
Tropical rock lobster	2.50	1.71	+1	2.60	1.50	0.86	1.72
Coral trout – common	2.00	2.00	+1	2.40	2.00	0.90	1.45
Mud crab	2.63	1.71	-1	2.60	1.75	0.90	1.32
Coral trout – barcheek	2.00	1.86	0	2.60	2.00	0.94	1.17
Spanish mackerel	2.00	1.71	0	3.00	1.75	1.00	1.00
Coral trout – passionfruit	2.00	1.86	0	2.80	2.00	0.99	1.00

Table S4: Estimating fishery importance indices for each fishery species. Economic value scores were based on the fishery mean dollar value over the period 2011/12 and 2012/13 (Georgeson et al. 2014). Coral trout catch is reported as a species group therefore the fishery value is apportioned as a third of the total for each species. Cultural value was subjectively scored based on whether the species is harvested for subsistence purposes and the level of use for cultural activities, weighted double to reflect high cultural connections to marine resources.

Species	Economic value score	Cultural value score	'Fishery importance' index	Mean value AU$M (2012 & 2013)
Tropical rock lobster	3	2	7	18.10
Dugong	0	3	6	0
Turtle	0	3	6	0
Coral trout - common	1	2	5	0.12
Coral trout - barcheek	1	2	5	0.12
Spanish mackerel	1	2	5	0.59
Coral trout - passionfruit	1	2	5	0.12
Trochus	1	1	3	~0
Gold-lipped pearl oyster	1	1	3	~0
Mud crab	1	1	3	~0
Brown tiger prawn	2	0	2	4.94
Blue endeavour prawn	1	0	1	0.86
Black teatfish	0	0	0	0
Black-lipped pearl oyster	0	0	0	0
Sandfish	0	0	0	0

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APPENDIX 3: Supplementary Material for Chapter 6

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Supplementary Table 1. Indices used to assess the adaptive capacity of Pacific Island countries and territories (PICTs). All indices have been standardized and normalized (Source: Bell et al. 2011).

PICTs	Adaptive Capacity (AC)										
	Health			Education			Governance Index[c]	Size of economy		AC Index: Economic development[d]	AC Index: Food security[e]
	Infant mortality	Life expectancy	Index[a]	Literacy 15–24 years	Primary school enrolment	Index[b]		GDP per capita	Index		
Melanesia											
PNG	0.03	0	0.1	0.62	0.77	0.67	0.26	991	0.01	0.26	0.18
Solomon Islands	0.00	0.29	0.2	0.85	0.94	0.88	0.33	753	0	0.35	0.24
Vanuatu	0.67	0.56	0.6	0.87	0.93	0.89	0.59	2,127	0.05	0.53	0.37
Micronesia											
Guam	0.89	1	0.96	0.95	1.00	0.97	0.72	22,661	0.75	0.85	0.82
Kiribati	0.23	0.29	0.27	0.97	0.97	0.97	0.55	653	0	0.45	0.30
Nauru	0.33	0.72	0.59	0.99	0.60	0.86	0.56	2,807	0.07	0.52	0.37
CNMI	0.96	0.89	0.91	0.95	1.00	0.97	0.59	12,638	0.41	0.72	0.62
Polynesia											
American Samoa	0.89	0.77	0.81	n/a	n/a	n/a	0.76	6,995	0.22	0.45	0.37
Samoa	0.73	0.8	0.78	0.99	0.90	0.96	0.63	2,872	0.08	0.61	0.43

n/a = information not available/applicable; a = 1/3 infant mortality rate and 2/3 life expectancy; b = 2/3 literacy and 1/3 primary school enrolments; c = where a governance index was not provided by Kaufman et al. (2008) this index was estimated based on the index for a PICT with similar political and cultural circumstances; d = average of indices for health, education, governance and size of the economy; e = based on weighted average, where size of the economy is weighted 0.5 and the indices for health, education and governance by 0.167.

Supplementary Table 2. Vulnerability results for nine Pacific Island countries and territories (PICTs) (of 22 assessed) where coastal communities are expected to experience shortages of fish for food security under the A2 SRES emissions scenarios in 2035 (see Supplementary Table 1 for the calculation of adaptive capacity). E = exposure; S = sensitivity; PI = potential impact; AC = adaptive capacity. Fish is used broadly to include fish and invertebrates (Source: Bell et al. 2011).

PICT	Exposure Index (% change in catch)		Sensitivity Index (fish consumption per person)		Potential impact		AC Index	1 – AC normalized	Vulnerability
	Reef fish available per person (kg) each year	E = Shortfall <35 kg required			PI = E x S	PI index			
Melanesia									
PNG	8.00	27.00	35	**	945	0.54	0.24	0.76	0.41
Solomon Islands	28.00	7.00	35	**	245	0.12	0.18	0.82	0.10
Vanuatu	8.60	26.40	35	**	924	0.53	0.37	0.63	0.33
Micronesia									
Guam	2.79	32.21	35	**	1127	0.65	0.82	0.18	0.12
Kiribati[a]	86.00	5.00	91	*	455	0.25	0.30	0.70	0.18
Nauru	1.40	33.60	51	*	1713	1.00	0.37	0.63	0.63
CNMI	9.59	25.41	50	**	1271	0.74	0.62	0.38	0.28
Polynesia									
American Samoa	12.25	22.75	63	**	1433	0.83	0.37	0.63	0.52
Samoa	28.97	6.03	73	*	440	0.24	0.43	0.57	0.14

a = shortfall based on current fish consumption rates (calculated as an average of urban and coastal communities), which is greater than the recommended 35 kg per person per year (SPC 2008, Bell et al. 2009); *Average of information in Bell et al. (2009) and Gillett and Lightfoot (2001); **Estimates based on information in Gillett (2009).

The rationale for predicting that the nine Pacific Island countries and territories (PICTs) listed in Supplementary Table 2 will have a shortfall of fish is that the areas of coral reefs and other coastal habitats (mangroves and seagrasses) in these countries and territories do not have the potential to produce the fish needed for good nutrition of their populations by 2035. Moreover, several of these PICTs are already facing a large gap in the fish needed for good nutrition due to the present size of their populations (Bell et al. 2015). Solomon Islands is the exception, where present-day coastal fisheries production is estimated to supply 50 kg per person per year. However, by 2035 population growth and the effects of climate change are expected to drive a deficit in availability of coastal fish in Solomon Islands of ~9,000 tonnes (~9 kg per person). A gap for Kiribati also emerges in 2035, when the fish deficit is expected to be 900 tonnes (~5 kg per person), based on traditionally high per capita fish consumption of 67 kg per year in urban areas and 115 kg in coastal communities (Bell et al. 2009). The relatively high GDP per capita in American Samoa, Guam and CNMI means that many people in these PICTs will have the ability to purchase other sources of high-quality animal protein (provided such foods are readily available) and so they are unlikely to need 35 kg of fish per year for good nutrition.

Other PICTs fall into two groups with respect to future fish supply. In one group (comprised of New Caledonia, Marshall Islands, Palau, Cook Islands, Tokelau and Pitcairn Islands), coastal fisheries are expected to meet the increased demand for fish for the foreseeable future. This is due to the large areas of coral reef relative to population size in these countries and territories, and the prediction that population growth will be low or negative due to emigration in some of these PICTs. In the other group (comprised of Fiji, FSM, French Polynesia, Niue, Tonga, Tuvalu and Wallis and Futuna), the area of coral reef should be able to produce the fish needed in the future, but it will be difficult to distribute the potential harvests to the main population centres because of the distances between reefs and the main markets.

Supplementary Table 3. Vulnerability results for 21 species of Gulf of Carpentaria fisheries under the A1FI SRES emissions scenario in 2030. E = exposure; S = sensitivity; PI = potential impact; AC = adaptive capacity (Source: Welch et al. 2014).

Fishery species	Exposure Index	Sensitivity Index	Direction of impact	AC Index	1 – AC normalized	Vulnerability
Golden snapper	2.63	1.50	0.00	1.44	0.59	2.61
King threadfin	2.63	1.75	0.00	1.67	0.68	2.46
Sand fish	2.50	1.75	0.00	1.78	0.73	2.19
Mangrove jack	2.50	1.75	0.00	1.78	0.73	2.19
Black jew	2.38	1.50	0.00	1.67	0.68	2.13
Tiger prawn (esculentus)	2.88	1.50	1.00	2.00	0.82	1.97
Grey mackerel	2.38	1.50	0.00	1.89	0.77	1.81
Tropical lobster	2.13	2.13	1.00	2.11	0.86	1.75
Coral trout	2.00	1.63	0.00	1.89	0.77	1.74
Mud crab	2.63	1.88	-1.00	2.00	0.82	1.71
Red emperor	1.38	1.50	0.00	1.67	0.68	1.66
Barred javelin	2.38	1.50	0.00	2.00	0.82	1.65
Spanish mackerel	2.25	1.50	0.00	2.00	0.82	1.61
Blue threadfin	2.63	1.25	0.00	2.00	0.82	1.60
Barramundi	2.50	1.63	0.00	2.11	0.86	1.55
Banana prawn	2.63	1.75	-1.00	2.22	0.91	1.33
Pigeye shark	1.75	2.00	0.00	2.22	0.91	1.32
Billfish (Sailfish)	1.25	1.75	0.00	2.22	0.91	1.20
Scalloped hammerhead	1.25	2.13	0.00	2.33	0.95	1.12
Spot tail shark	1.38	1.88	0.00	2.33	0.95	1.12
Blacktip shark (limbatus)	1.25	1.88	0.00	2.44	1.00	1.00

Supplementary Table 4. Vulnerability results for 15 species of Torres Strait fisheries A1FI SRES emissions scenario in 2030. E = exposure; S = sensitivity; PI = potential impact; AC = adaptive capacity (Source: Johnson and Welch 2016).

Fishery species	Exposure Index	Sensitivity Index	Direction of impact	AC Index		1 – AC normalized	Vulnerability
				ecological	social		
Black teatfish	2.13	1.71	+1	1.20	2.00	0.36	2.69
Black-lipped pearl oyster	2.00	1.86	+1	1.40	2.00	0.32	2.50
Dugong	1.88	2.29	+1	1.80	1.75	0.27	2.44
Trochus	2.25	1.86	0	1.80	1.50	0.32	2.33
Turtle	2.13	2.57	+1	2.20	1.75	0.18	2.18
Gold-lipped pearl oyster	2.00	1.71	0	1.80	1.50	0.32	2.09
Brown tiger prawn	2.13	1.71	+1	2.20	1.50	0.23	2.06
Blue endeavour prawn	2.13	1.57	0	2.00	1.50	0.27	1.91
Sandfish	2.13	1.71	0	1.80	2.00	0.23	1.83
Tropical rock lobster	2.50	1.71	+1	2.60	1.50	0.14	1.72
Coral trout – common	2.00	2.00	+1	2.40	2.00	0.09	1.45
Mud crab	2.63	1.71	-1	2.60	1.75	0.09	1.32
Coral trout – barcheek	2.00	1.86	0	2.60	2.00	0.05	1.17
Spanish mackerel	2.00	1.71	0	3.00	1.75	0.00	1.00
Coral trout – passionfruit	2.00	1.86	0	2.80	2.00	0.00	1.00

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