Microeconomic Adaptation in Social-Ecological Systems

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Dedicated to all small-scale resource users trying to

live in harmony with our oceans.

Then God said, “Let the waters bring forth creatures having life, and let birds fly above the earth across the face of heaven’s firmament.” It was so. Thus God made great sea creatures and every living thing that moves with which the waters abounded, according to their kind, and every winged bird according to its kind. God saw that it was good.
— Genesis 1:20–21, *Septuagint*

The forest does not change its place, we cannot lie in wait for it and catch it in the act of moving. However much we look at it we see it as motionless. And such also is the immobility to our eyes of the eternally growing, ceaselessly changing life of society, of history moving as invisibly in its incessant transformations as the forest in spring.
— Boris Pasternak, *Doctor Zhivago*, 1957

The power of a theory is exactly proportional to the diversity of situations it can explain.
— Elinor Ostrom, *Governing the Commons*, 1990

Without dynamics, we must turn to correlations – circumstantial evidence. Inference from such information certainly has its weaknesses but provides a potent place to begin formulating hypotheses.
— Simon A. Levin, *Fragile Dominion*, 1999

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Contributions

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Conference Presentations

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Abstract

Social-ecological systems are becoming more volatile, as measured by the increasing frequency and severity of social and ecological perturbations. In the 21st century, impacts from global warming and other climatic changes will be a major source of volatility. Global warming affects ecosystems and the services and benefits that they provide to people in a wide variety of ways, with profound direct and indirect effects on human society. In many cases, microeconomic actors, such as firms and households, are on the frontlines of climate change. Whilst global policy action stalls, firms and households are already faced with needing to make adaptation decisions to confront the unfolding climate crises. My thesis seeks to understand microeconomic adaptation to climate change in social-ecological systems (SESs), and the ways in which public policy can support the adaptation process. I used a range of approaches to investigate feedback relationships between adaptive capacity, adaptive responses, and adaptation outcomes.

I specifically investigated coral reefs, and the tourism industry that depends on them, as a model system through which to understand adaptation dynamics. My empirical work focused on coral reef social-ecological systems within the Asia-Pacific Region, where reef-dependent livelihoods have already come under threat from severe climate disturbances (bleaching and tropical cyclones). I surveyed about a third (n = 231) of the reef tourism operators in 28 locations, spanning eight countries, that were highly dependent on reef tourism. I focused on disentangling some of the different concepts within the adaptation literature, through the use of a novel conceptual framework focused on adaptation dynamics and feedbacks. Using my conceptual framework I addressed five specific research gaps.

First, I used data from social media users to quantify the effect of climate disturbances (coral bleaching) on reef tourism visitor numbers and reef tourism satisfaction, through a case study on the Great Barrier Reef in Australia. Using time series and content analysis, I found

that declines in coral cover reduced demand for recreational ecosystem services but had no apparent effect on the benefits received from recreation. Further analysis suggested that adaptation by reef tourism operators could have mediated the anticipated negative impact of environmental change on recreational benefits. My findings emphasize the importance of human culture and perception as influences on human responses to environmental change, and the relevance of the more subjective elements of social systems for understanding social-ecological feedbacks.

Second, I reviewed the empirical literature on adaptation to climate change by microeconomic actors to address research gaps in my conceptual framework and to synthesize existing evidence for the relationships between adaptive capacity, adaptive responses, adaptation outcomes, and government policies implemented to support microeconomic adaptation. Based on my review analysis, I developed a novel categorization of adaptive responses, identified that three out the six domains of adaptive are under-represented, and concluded that the evaluation of adaptation outcomes is largely absent within the empirical adaptation literature.

Third, I tested the applicability of the microeconomic adaptive response typology to adaptation to climate disturbances by Australian reef tourism operators. I found that as in my reviewed studies, the most common adaptation types were ‘diversification within livelihood’ and ‘natural resource management’. Prominent responses to climate disturbances such as reef monitoring, restoration, and spatial diversification pointed towards an intensified relationship between commercial users and the natural resource on which they depend. For cyclone impacts, as compared to bleaching, product and livelihood diversification became more relevant and point towards decoupling from the ecosystem. My findings provide real-world evidence for how resource users are impacted by, and are adapting to, the loss of coral reefs.

Fourth, I tested whether a multidimensional (using tangible and intangible determinants) measure of adaptive capacity is a reliable proxy for adaptation to climate disturbance by reef tourism operators in the APAC Region. I used a combination of descriptive and multivariate statistical approaches to explore the relationships between adaptive capacity, adaptive responses, and contextual conditions. My findings indicate that a comprehensive operationalization of actor-specific adaptive capacity is not necessarily a reliable proxy for measuring potential adaptation to future climate change. The severity of impacts on individual operators was the major determinant of adaptive action. Adaptive capacity was, however, a reliable proxy for the likelihood that an operator would take transformative action as their primary response to a climate disturbance; several of my indicators of adaptive capacity had a meaningful effect size, in particular those within the adaptive capacity domain of social organization.

Fifth, I evaluated the relationship between APAC reef tourism operators' adaptive response to climate change and the outcomes they experienced one year after a disturbance in terms of perceived climate risk, perceived climate vulnerability, and economic, environmental, and social sustainability. I used several statistical tests to explore the relationships between adaptive responses, adaptation outcomes, and contextual conditions. Operators affected by a climate disturbance were significantly more likely to have experienced an increase in perceived climate risk and reduced economic and environmental sustainability. However, my findings indicate that that at least some adaptation responses were effective in promoting desirable outcomes, such as reductions in perceived risk and vulnerability.

In sum, I provided a theoretically-grounded and empirically applied conceptual framework to understand the consequential linkages between adaptive capacity (social barriers and determinants), adaptive responses (through a novel six-category categorization),

and adaptation outcomes. The importance of the dynamic aspects of human adaptation studies has been acknowledged widely, but seldom implemented and operationalized. My thesis makes a contribution to the emerging research stream focused on feedbacks within the climate change adaptation process. It also builds a bridge between climate change adaptation theory and social-ecological system resilience theory. Overall, adaptive responses were associated with efforts to remain economically viable despite environmental impacts from climate change, and these responses were only weakly associated with underlying levels of adaptive capacity. Transformative responses, associated with efforts to reduce risk and vulnerability, were meaningfully associated with the adaptive capacity domains of social organation, socio-cognitive constructs, and (on-the-ground) learning, while the effectiveness of a country's government was also important. My thesis thereby identified that government efforts to foster social capital and social networks might be most effective in terms of promotion bottom-up social-ecological transformation.

Keywords: social-ecological systems; resilience theory; climate change; adaptation; adaptive capacity; adaptation outcomes; adaptation dynamics; adaptation feedbacks; tourism; coral reefs; climate disturbance; climate events; coral bleaching; Asia-Pacific; Great Barrier Reef; Bali

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Chapter 1. General Introduction

This section begins with an overview of my problem of interest (Section 1.1) and a topical introduction of relevant theoretical literature (Section 1.2). In Section 1.3 I discuss the main research gaps, followed by my thesis aims and objectives (Section 1.4) and a summary of the conceptual model I use throughout my thesis (Section 1.5). I end this chapter by introducing my research setting (Section 1.6) and outlining the main pillars of my thesis (Section 1.7).

1.1 Background

The world is expected to experience temperatures 2–3°C above pre-industrial levels in the second half of this century (DNV, 2022; Randers et al., 2016). As a result, the impacts of climate change on both human and natural systems are expected to increase in magnitude (Pörtner et al., 2022). Global warming will affect ecosystems and the services and benefits that they provide to people in a wide variety of ways, with profound direct and indirect effects on human society. In this context of rapid and escalating change, the ability of human communities to cope with and adapt to climatic change is critical (Eisenack et al., 2014; Freeman et al., 2015). Adaptation describes the ability of a system to 'stay the same while changing'—that is, to retain its identity while altering or re-calibrating its structure and functions to cope with changes in its environment (Cumming et al., 2005). Adaptation to climate change is specifically linked to the adjustment process to actual or expected effects of climate change (Pörtner et al., 2022). Adaptation may occur at any scale and across the full range of social, ecological, and economic systems of relevance. Microeconomic adaptation to climate change involves households and firms responding to climate signals by changing their behaviour (Fankhauser, 2017). Microeconomic adaptation is important because microeconomic actors are on the frontlines of climate change. Whilst global policy action stalls, firms and households are already faced with needing to make adaptation decisions to confront the unfolding climate crises.

1.2 Theoretical Framework

In my thesis, I refer to microeconomic adaptation as being focused on adaptation that is done by individual households and/or firms. I used this term to clearly distinguish my focus area from adaptation done by macroeconomic actors such as government actors and/or multinational institutions. Within social-ecological systems (SES) theory, such microeconomic actors are often referred to as just ‘actors’, setting them apart from the ‘governance systems’ (e.g. McGinnis and Ostrom, 2014). My use of the word microeconomic does not imply that my thesis is limited to classical economic theory because I focused on a wider framing of adaptation that also captures more subjective, value-laden, and normative dimensions of behavior and preferences. Additionally, while my thesis is focused on adaptation from the microeconomic point of view, responses could include both self-interested changes and the mobilization of collective action by individuals for actions to support common benefits (e.g. ecosystem resilience), independent of whether actors have directly experienced loss related to climate impacts.

While adaptation to climate change has a longer history in fields ranging from human geography (Head, 2010) to anthropology (Crate, 2011; Mulder, 1978), these fields typically focused on the larger units of analysis such as the tribe, group, community, and/or village. By contrast, my thesis will take as a starting point the adaptation literature that is specifically focused on adaptation to contemporary climate change impacts by microeconomic actors.

1.2.1 Microeconomic Adaptation

Academic interest in microeconomic adaptation to climate change started in the early 1990s, focusing largely on the agricultural sector in the United States (US). A group of agricultural meteorologists, led by William Easterling, developed an agronomic approach to model the impacts of climate change on agricultural output in the US. The model first looked at the outcomes of what was referred to as a 'dumb farmer' scenario, which assumed farmers would not make any adaptations in response to climatic change (Easterling, McKenney, et al., 1992). A 'smart farmer' scenario included adaptations that were deemed as relatively inexpensive; for example, changes in land and crop use, harvesting methods, and fertilization (Easterling, Rosenberg, et al., 1992). In both cases, the model outcomes showed a substantial reduction in agricultural yields as a result of climate change. The agronomic modelling results attracted the attention of economists, who developed a climate adaptation model based on Ricardian economics (Mendelsohn et al., 1994). Ricardian economics describes how trade and markets lead different economic actors to specialize in activities in which they have a comparative advantage. Their results showed a smaller reduction in agricultural output as compared to the agronomists. When measuring results in changes in revenue instead of agricultural output, they found that climate change could have a slightly positive impact on US agriculture. This was explained by the relatively higher value of warm-weather crops, including cotton, fruits, vegetables, and rice as compared to colder-weather grains.

Academic research on microeconomic adaptation to climate change has shifted from primarily being the concern of agricultural meteorologists to that of economists, and is now dominated by the social sciences. A growing number of studies from across the social sciences question the ability of farmers and other economic actors affected by climate change to adapt to the extent that Ricardian models would predict. Research from many different disciplines, including sociology, psychology, (behavioural) economics, and political science, have identified potential limits to *efficient* adaptation (Adger et al., 2009; Biesbroek et al., 2013; Dow et al., 2013). For example, an influential paper in the *American Economic Journal* (Burke & Emerick, 2016) found empirical evidence for the lack of long-term adaptation of

American corn and soy farmers to climate change. They suggested that the farmers either lacked adaptation options or found them too costly to implement. With a growing body of evidence about such barriers to adaptation, a need arose for clustering the barriers into a framework.

1.2.2 Adaptive Capacity (barriers and determinants)

For more than a decade, researchers have tried to understand how to measure and predict whether people will be able to adapt to the rapid, unprecedented climate change that is expected in the 21st century (Diffenbaugh & Field, 2013). Three approaches have been widely adopted to evaluate societal potential for adaptation to future climate change: (1) assessing whether people have taken necessary preparatory action; (2) exploring people's intended (future) adaptation through experiments; and (3) measuring people's adaptive capacity. The first approach evaluates whether people are implementing preparatory and preventive measures to deal with future climate risks (Brouwer et al., 2007; van Valkengoed & Steg, 2019). Taking preventive measures does not necessarily lead to better adaptation to climate change, however, especially where there is high uncertainty about local climate impacts and the effectiveness of adaptation alternatives (Berkhout et al., 2006; Freeman et al., 2015). For example, in Ethiopia, uncertainties about future rainfall patterns make it difficult for farmers to adapt and invest in crops that may have the highest yields under future climate conditions (Conway & Schipper, 2011). The second approach focuses on likely responses: experimental studies are used to ask people how they would respond to potential future impacts from climate change (Cinner et al., 2011; Niemeyer et al., 2005). However, actual adaptation might differ from intended or stated adaptation because of the variety of unanticipated factors outside an experimental setting (Ajzen et al., 2011; Hausman, 2012; Niles et al., 2016).

Due to the limitations of the first two approaches, the third approach (people's latent capacity to adapt) has increasingly been used as a proxy for measuring potential adaptation to future climate change (Cinner et al., 2018; Lemos et al., 2013; Siders, 2019; Smit & Wandel, 2006; Yohe & Tol, 2002). The concept of 'adaptive capacity' as interpreted in a climate change context seeks to facilitate more replicable and accessible research by synthesizing empirical findings on the kind of factors that enable or impede efficient adaptation to climate change (Lemos et al., 2013; Smit & Wandel, 2006; Yohe & Tol, 2002). Adaptive capacity refers to "the conditions that enable people to anticipate and respond to change, to minimize the consequences, to recover, and take advantage of new opportunities" (Cinner et al., 2018, p. 117). Adaptive capacity as used in a climate change adaptation context was initially strongly focused on tangible factors such as economic resources, technology, information and skills, and infrastructure (Smit & Pilifosova, 2001; Yohe & Tol, 2002). Within social-ecological systems (SES) theory, adaptive capacity is defined more broadly and includes not just a system's ability to adapt to change but also its ability to reduce its exposure and sensitivity to perturbations, increasing its resilience (Gallopín, 2006; Walker et al., 2004). Recently, an SES-based framework for adaptive capacity has been developed based on a review of empirical and theoretical work on (social) adaptation in social-ecological systems (Cinner et al., 2018; Cinner & Barnes, 2019). The framework acknowledges the multidimensional nature of adaptive capacity (Adger et al., 2009; Engle, 2011; Smit & Wandel, 2006), and approaches adaptive capacity holistically through the assessment of six interdependent domains. The domains that are argued to represent adaptive capacity are assets (e.g. access to financial resources), flexibility (e.g. to switch between adaptation strategies), learning (e.g. capacity to generate, absorb, and process information about climate change), (social) organization (e.g. social networks, social capital), agency (e.g. the power and freedom to change), and socio-cognitive constructs. The domain of socio-cognitive constructs reflects so-called “second generation” theories on adaptive capacity, which have focused on the psycho-social factors that enable the mobilization of assets and other determinants (such as flexibility) to successfully adapt to climate change (Bechtoldt et al., 2021; Cologna & Siegrist, 2020; Grothmann & Patt, 2005; Mortreux & Barnett, 2017; van Valkengoed & Steg, 2019; Wilson et al., 2020).

1.2.3 Adaptation Outcomes (success)

Not every microeconomic adaptation that is implemented should automatically be considered appropriate in terms of its outcomes (Berrang-Ford et al., 2021; Maddison, 2007). The framework of Cinner and Barnes (2019) suggests that hypotheses about adaptive capacity can be linked to outcomes by investigating how each adaptive capacity domain, and their interactions, enables or impedes efficient adaptation measures. Theoretical discussions on measuring the success of adaptation originally had a strong focus on removing barriers that could impede people’s decision to adapt to climate change (Biesbroek et al., 2013; Fankhauser et al., 1999; Moser & Ekstrom, 2010). For example, timely recognition of an emerging problem, an incentive, and an ability to adapt were identified as major determinants of adaptation success (Fankhauser et al., 1999). With an increasing number of studies showing that people were already adapting to climate change (Berrang-Ford et al., 2021), new theories were needed to measure what made implemented adaptations successful, rather than just the causes of adaptation.

Adger et al. (2005) proposed a definition of adaptation success that focused on effectiveness, efficiency, equity, and legitimacy as dynamic success criteria. Effectiveness evaluates the ability of adaptation to achieve its objectives (e.g. risk reduction), while efficiency describes the ability of adaptation to provide benefits that significantly outweigh costs. Equity and legitimacy consider the fairness and distributional consequences of adaptation and the adaptation decision making process. Building on Adger et al. (2005), Doria et al. (2009) proposed a coherent and explicit definition of ‘adaptation success’ based on expert elicitation (Figure 1.1), as: “…any adjustment that reduces the risks associated with climate change, or vulnerability to climate change impacts, to a predetermined level, without compromising economic, social, and environmental sustainability.” (Doria et al., 2009, p. 817). Within this definition, risk is defined as the likelihood of a specific climate hazard occurring, while vulnerability is defined as exposure to impacts without having the ability to prevent negative outcomes. Sustainability was deliberately left undefined in the definition of adaptation success and can refer to either strong or weak sustainability (Doria et al., 2009, p. 815). The predetermined levels were argued to depend on actual and perceived climate risk and vulnerability levels, and it was argued that these levels should be determined by people evaluating the different adaptation alternatives (Doria et al., 2009, p. 815).

Figure 1.1

Climate Change Adaptation Success

Note. Successful climate change adaptation measures contribute to reducing climate risk and/or vulnerability to a pre-determined level without compromising economic, social, and environmental sustainability (Doria et al., 2009). Design by Eileen Siddins.

The definition by Doria et al. (2009) integrates the dynamic success criteria put forward by Adger et al. (2005); effectiveness is included in terms of reducing risk and vulnerability to a pre-determined level; efficiency is associated with economic sustainability (benefits outweighing costs); while equity and legitimacy are included through an assessment of the social and/or environmental externalities associated with adaptation. This definition captures the fact that not all forms of adaptation will have beneficial outcomes for all actors

(S. Eriksen et al., 2011); it is related to the fairness and distributional consequences of adaptation (Adger et al., 2005). Indeed, adaptation that compromises the economic, social, and/or environmental sustainability of other actors or groups in a community or society has been described as ‘maladaptation’ (Barnett & O’Neill, 2010; Schipper, 2020). It remains an empirical question whether all the domains of the adaptation success definition (Doria et al., 2009) can be achieved in parallel. There might be trade-offs between reductions in risk and vulnerability, and different forms of sustainability. Thus, it could be argued that adaptation success should be considered as a non-binary continuum because there are many intermediate outcomes between success and failure (Tubi & Williams, 2021).

1.2.4 Adaptation Dynamics

The outcomes of adaptation become visible over time; thus, analysis of the microeconomic adaptation process demands a dynamic perspective (Eisenack et al., 2014; Engle, 2011; Nelson et al., 2007; Schill et al., 2019; Vincent, 2007). There are sequential linkages between adaptive capacity, implemented adaptations, and adaptation outcomes. Over time, adaptation outcomes are expected to have an effect on a microeconomic actor’s adaptive capacity (Dilling et al., 2023). Microeconomic adaptation is thus best understood as a process involving several key social and ecological feedbacks that might positively or negative influence the adaptation process (Barnes et al., 2017; Fedele et al., 2020; Laborde et al., 2016). The importance of adaptation feedbacks have been emphasized in other studies (Onyango et al., 2016; Simpson et al., 2021).

A better understanding of the dynamic complexities and feedbacks within the adaptation process will provide key insights for policy making (Eisenack et al., 2014). Governments are often heavily focused on macroeconomic outcomes, and the adaptations made by microeconomic actors are among the determinants of these outcomes. However, the design and implementation of effective incentives and policies to facilitate microeconomic adaptation to climate change remains an understudied topic (Fankhauser, 2017). In order to know how best to support microeconomic adaptation, we need to know what adaptive actions are being taken in response to actual impacts from climate change, and what the broader outcomes of these actions are. Interventions to foster successful adaptation to climate change should take account of adaptation cycle dynamics and conflicting interests between microeconomic outcomes, social and environmental externalities, and resilience (risk and vulnerability) (Figure 1.1).

1.3 Research Gaps

We have limited empirical knowledge about whether, how, and for what reasons microeconomic actors are adapting to climatic change, and what barriers might impede their ability to adapt (Berrang-Ford et al., 2011; Linnenluecke et al., 2013; Mortreux & Barnett, 2017; Nordhaus, 2013; Pörtner et al., 2022). The adaptation literature has focused on identifying potential adaptation options and assessment alternatives (Ford et al., 2011), with adaptive capacity often assessed as a proxy for potential adaptation (Mortreux & Barnett, 2017; Siders, 2019). Recent work has also studied people's motivations, intentions and preparedness to adapt to climate change (van Valkengoed & Steg, 2019). Yet little is known about how preparedness, intentions, and specific adaptive capacity characteristics translate to actual (implemented) adaptations to experienced effects of climate change. The relationship between adaptive capacity and implemented adaptations in this context has been argued to be far from direct, and better theories are needed to understand underlying mechanisms (Barnes et al., 2020; Green et al., 2021; Mortreux & Barnett, 2017).

We also have very limited knowledge about the success of implemented adaptations to climate change. Not all implemented microeconomic adaptations should automatically be considered appropriate in terms of their outcomes (Maddison, 2007). From a microeconomic point of view, effective adaptation measures would be considered efficient in that they lead to the highest net benefit to a firm or household's income over a defined period in the future. However, a broader definition of adaptation outcomes is provided by Doria et al. (2009), who classify a successful adaptation as "any adjustment that reduces the risks associated with climate change, or vulnerability to climate change impacts, to a predetermined level, without compromising economic, social, and environmental sustainability." Social and environmental factors are strongly related to the economic notion of "market externalities" (Pigou, 1920). The factors explaining risk and vulnerability are linked to the concept of resilience in social-ecological systems (Engle, 2011), and are not usually part of a microeconomic approach.

Government policies or support from non-government organizations (NGOs) may help microeconomic actors to successfully adapt to climate change. However, it is unclear what kind of interventions and policies are most effective. Intervening successfully in "dynamic webs of barriers" (Eisenack et al., 2014) requires understanding of the complexities within the adaptation process. Governments aim to provide legal, regulatory, and socio-economic incentives to facilitate autonomous adaptation to climate change by microeconomic actors (Fankhauser, 2017; Fankhauser et al., 1999; Levin et al., 2013; Repetto, 2008; Urwin & Jordan, 2008). However, well-intended government interventions aimed at promoting adaptation can lead to negative rather than positive welfare effects (Bennett et al., 2016; Levin et al., 2013; Mendelsohn, 2000; Repetto, 2008). For example, public crop insurance programs have in some cases reduced the incentive for farmers to adapt to climate change (Mendelsohn, 2006; Repetto, 2008). Public policies can also be more influenced by power dynamics than by market failures, favouring the protection of the *status quo* and special interest groups rather than creating a level playing field for cost-efficient adaptation (Cinner & Barnes, 2019).

1.4 Thesis Aim and Objectives

The aim of my thesis is to better understand and to empirically assess the sequential linkages between different domains of adaptive capacity, specific adaptive responses, and multidimensional adaptation outcomes. In accordance with the principles of systems theory (Bertalanffy, 1950), analysing the microeconomic adaptation process from a dynamic and systems perspective has the potential to provide novel insights that could not have been derived from studying each part of the puzzle in isolation. Thus, the added valued of my thesis comes from studying adaptation from a dynamic, integrated perspective, rather than as a singular (one-off) process.

The central aim of my thesis is supported through several more specific research objectives, each of which is addressed in one or more chapters.

- RESEARCH OBJECTIVE 1: Develop a typology for common adaptive responses adopted by microeconomic actors that have already been affected by climate change (**Chapter 3**).
- RESEARCH OBJECTIVE 2: Synthesize existing evidence in the scientific literature about the relationship between (1) adaptive capacity and adaptive responses; (2) adaptive responses and their outcomes; (3) adaptation outcomes and post-disturbance adaptive capacity; and (4) government policies and adaptation (**Chapter 3**).
- RESEARCH OBJECTIVE 3: Empirically test the adaptive response typology developed under objective 1 through a case study in a social-ecological system that has been heavily impacted by climate change (**Chapter 5**).
- RESEARCH OBJECTIVE 4: Test whether adaptive capacity is a reliable proxy for adaptation to climate change (**Chapter 6**).
- RESEARCH OBJECTIVE 5: Evaluate the multidimensional outcomes associated with different ways of adapting to climate change (**Chapter 7**).

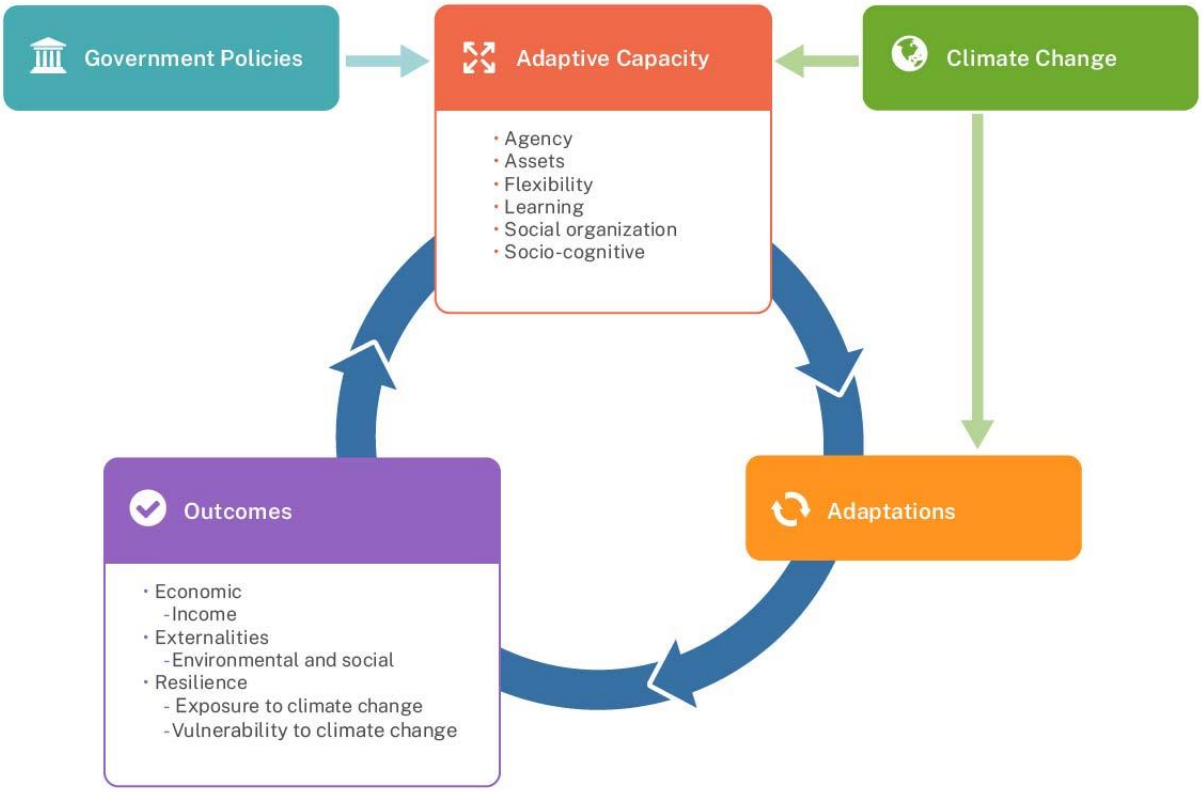
- RESEARCH OBJECTIVE 6: Assess the added-value of studying climate change adaptation as a dynamic process with sequential linkages between adaptive capacity, implemented adaptations, and adaptation outcomes (**Chapter 8**).

1.5 Conceptual Framework

My thesis builds on the most prominent recent extensions of the adaptive capacity (Cinner & Barnes, 2019) and adaptation outcomes (Doria et al., 2009) frameworks. I added an intermediate step between adaptive capacity and adaptation outcomes focused on how people adapt to climate change impacts. My conceptual model suggests a dynamic framework for climate change adaptation that is particularly focused on microeconomic actors (Figure 1.2). My conceptual model is helpful in understanding the consecutive linkages between adaptive capacity, adaptation, and adaptation outcomes. These linkages can be used to hypothesize about adaptation feedbacks. Adaptation outcomes might (over time) affect actors' adaptive capacity, which will then again affect how an actor will respond to future impacts. My initial conceptual foundations contained some gaps that I have progressively addressed throughout my thesis. For example, there is currently no adequate and empirically-grounded framework that categorizes how microeconomic actors respond to climate change.

Figure 1.2

Conceptual Framework: Microeconomic Adaptation to Climate Change



Note. This figure describes the inter-dependent relationships and consequential linkages between adaptive capacity, adaptations, outcomes, and government policies. Adaptive capacity domains adapted from Cinner and Barnes (2019), outcome indicators derived from Doria et al. (2009). The green (Climate Change), orange (Adaptations) and blue (Government Policies) boxes highlight knowledge gaps and missing elements within the microeconomic adaptation cycle, that my thesis addresses.

1.6 Research Setting

I studied the dynamic linkages between adaptive capacity, adaptive responses, and adaptation outcomes (Figure 1.2) within a coastal livelihood setting, within coral reef social-ecological systems, and specifically in the coral reef tourism industry. Coral reefs are one of the first, and most iconic, victims of climate change. The Intergovernmental Panel on Climate Change (IPCC) is highly confident that almost all tropical coral reefs will suffer significant losses even if global warming is limited to 1.5°C (Pörtner et al., 2022). Given that the world will most likely exhaust the 1.5°C carbon budget before the year 2030 (DNV, 2022), it is highly probable that extractive and service industries that depend on healthy coral reefs will be severely affected over the coming decades.

Coral reefs have already come under severe threat from elevated water temperatures and changes in disturbance regimes (Goreau & Hayes, 2021; Hughes, Anderson, et al., 2018). For example, the Great Barrier Reef (GBR) in Australia has been affected by mass coral bleaching events in 1998, 2002, 2016, 2017, 2020, and 2022, and has suffered substantial impacts from 10 category-three or higher cyclones between 2004 and 2018. Both the frequency and severity of coral bleaching (Hoegh-Guldberg, 1999; Lough et al., 2018) and tropical cyclones (Kossin et al., 2020) are driven by increasing sea temperatures and can lead to significant loss of coral reefs. Rapid degradation of coral reefs has implications for local resource users (Cinner et al., 2013; Ostrom, 2009) and consequently has wider socio-economic ramifications. To understand these, better theoretical frameworks and more information are needed about how resource users are impacted by, and are adapting to, the loss of coral reefs (Comte & Pendleton, 2018; Hoegh-Guldberg et al., 2019; Pendleton et al., 2016; Stoeckl et al., 2021).

The degradation of coral reefs will affect the tourism industry in a direct and immediate way (Figure 1.3). For example, the increasing trend in visitor numbers to the GBR in Australia levelled off after the severe bleaching event in 2016 and visitor numbers started a slow decline thereafter (GBRMPA, 2020).

Figure 1.3

Reef Tourism in the Okinawa Islands, Japan

Note. Photo shows tourists enjoying the coral reefs around Cape Maeda, one of the many reef tourism locations included in my thesis. The Ryukyu Islands (including Okinawa) were one of the many locations in the Asia-Pacific Region that were affected by a mass coral bleaching event in 2016. Credit: Henry Bartelet (2019).

The extent to which tourism will be impacted depends on the way dive and snorkel tourists respond to coral degradation from bleaching or other causes. For example, a survey of 194 Canadian and 109 Australian scuba divers (Verkoeyen & Nepal, 2019) revealed that the majority would change their behavior in response to declines in reef conditions. The most likely response was change of location, followed by decreasing dive frequency. Shifting baselines might reduce the strength of that behavioral change. After Phuket was hit severely by a tsunami in 2004, 85% of 124 recreational divers rated slightly to heavily damaged dive sites as having no damage (Main & Dearden, 2007). In Palau, however, 59 out of the 100 visiting divers who were questioned noticed the impacts of coral bleaching after the 1998 mass bleaching event. Bleaching had a significant impact on their satisfaction levels (Graham et al., 2001). Larger sample-sized studies are required to provide a more accurate understanding of tourists' perceptions of and behavioral changes to environmental changes on coral reefs, such as those caused by the impacts from climate change.

Besides behavioral changes by dive and snorkel tourists, the impacts from (climate-induced) coral reef degradation could be affected by the way that tourism operators adapt to the changes in the natural environment on which their livelihood depends. Prior studies on adaptation to climate impacts on coral reefs by resource users in the tourism industry have mainly been scenario-based rather than empirical (D. Biggs, 2011; D. Biggs et al., 2012; Evans et al., 2016). Business planning, diversification, and stewardship measures were identified as potential adaptation options (Evans et al., 2016), while some tourism operators indicated that they would consider exiting the reef tourism industry under scenarios of reductions in visitor numbers ranging from 10% to 50% (D. Biggs, 2011; D. Biggs et al., 2012). Given the severe effects from climate disturbances on coral reefs in recent years, empirical research can shed more light on the question of adaptation to climate change by reef tourism operators, among other resource users such as small-scale fisheries (Barnes et al., 2020).

My thesis is focused on adaptation by both reef tourism consumers (tourists) and reef tourism producers (tourism operators). From a microeconomic perspective, the goods and services that are produced and consumed in the case of reef tourism are cultural ecosystem services, and specifically recreational services. Most of the microeconomic literature is based on theoretical and empirical work that comes from agricultural settings (Chapter 1.2.1). There are differences (conceptual and material) in the climate sensitivity of agricultural produce (e.g., crops) as the goods produced by a farmer and how much such a farmer can affect their respective plot of land, as compared to tourism operators that rely on cultural ecosystem services produced by broader coral reef ecosystems. Tourism operators are not directly producing the ecosystem service that is affected by climate change, and they also do not necessarily have much control over the management of the ecosystem itself. Rather, tourism operators produce a service that is focused on giving others (tourists) access to the ecosystem (e.g., coral reefs), over which they only have limited influence as individual operators. Therefore, while agricultural actors in most cases (except when dependent on common irrigation systems) are more focused on their individual land/plot, reef tourism operators must manage a common resource through their individual and collective adaptive actions. Therefore, my thesis provides the opportunity to test whether adaptation frameworks based mostly on agriculture and other production settings are transferable to economic sectors that provide cultural ecosystem services.

1.7 Thesis Outline

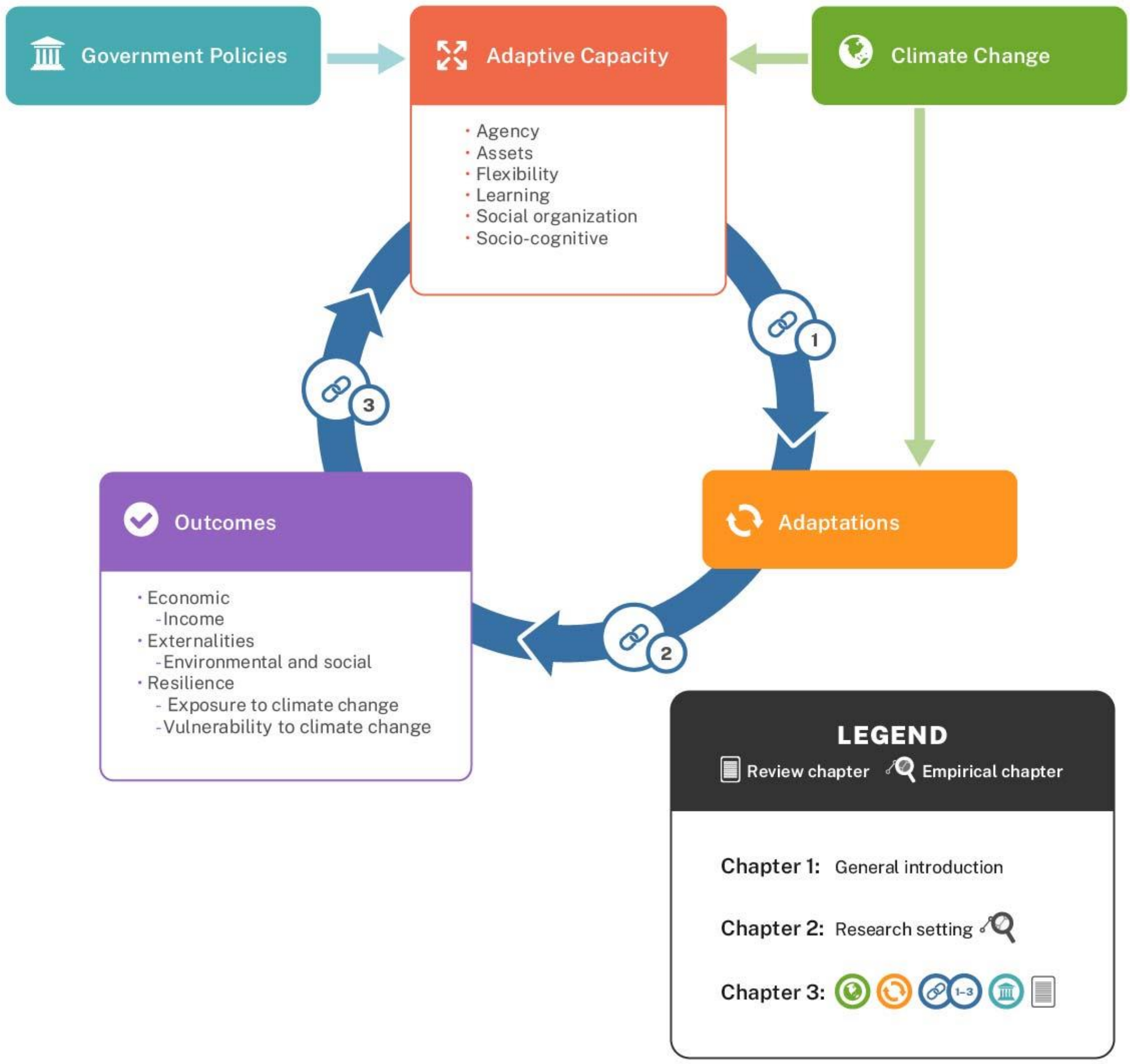
My seven thesis objectives are addressed through a literature review and four data-based chapters, all adapted from manuscripts published or prepared for peer-reviewed publication.

In **Chapter 2**, I introduce the relevance of the research setting used in my thesis. I explore, through a case study on the Great Barrier Reef in Australia, how climate change has already severely affected the reef tourism industry. Through the use of big data from social media (visitor reviews from TripAdvisor) I investigate how demand for and satisfaction with coral reef tourism are affected by the impacts from severe coral bleaching on coral reefs. Microeconomic actors include both consumers and producers. While the remainder of my thesis focused on adaptation to climate change by producers (reef tourism operators), my third chapter investigates adaptation from a consumers perspective.

In **Chapter 3**, I address RESEARCH OBJECTIVES 1 and 2 by providing a best-evidence synthesis of the empirical literature on microeconomic adaptation published between 1995 and 2020. In my review I address six specific research gaps (Figure 1.4) associated with the conceptual model used in my thesis (Figure 1.2). First, I identify the most common types of climate change to which microeconomic actors (in the published literature) are adapting. Second, I report all the different adaptation measures implemented in response to climate change, and develop a categorization of the most commonly used adaptive responses. I then synthesize the existing evidence for the relationships between adaptive capacity and adaptive responses, and between adaptive responses and their outcomes. I also evaluate whether there is any evidence for adaptation outcomes having a consequent effect on microeconomic actors' adaptive capacity, thereby closing the adaptation feedback loop. Finally, I identify the most common types of government policies that have been implemented to facilitate microeconomic adaptation to climate change, and synthesize their reported effects on adaptation.

Figure 1.4

Research Gaps Addressed in Review (Chapter 3)



Note. The specific gaps that are addressed include (1) common climate impacts; (2) common adaptation measures; (3) relationship between adaptive capacity and adaptation measures; (4) relationship between adaptation measures and their outcomes; (5) effect from adaptation outcomes on adaptive capacity; (6) common policies to facilitate adaptation.

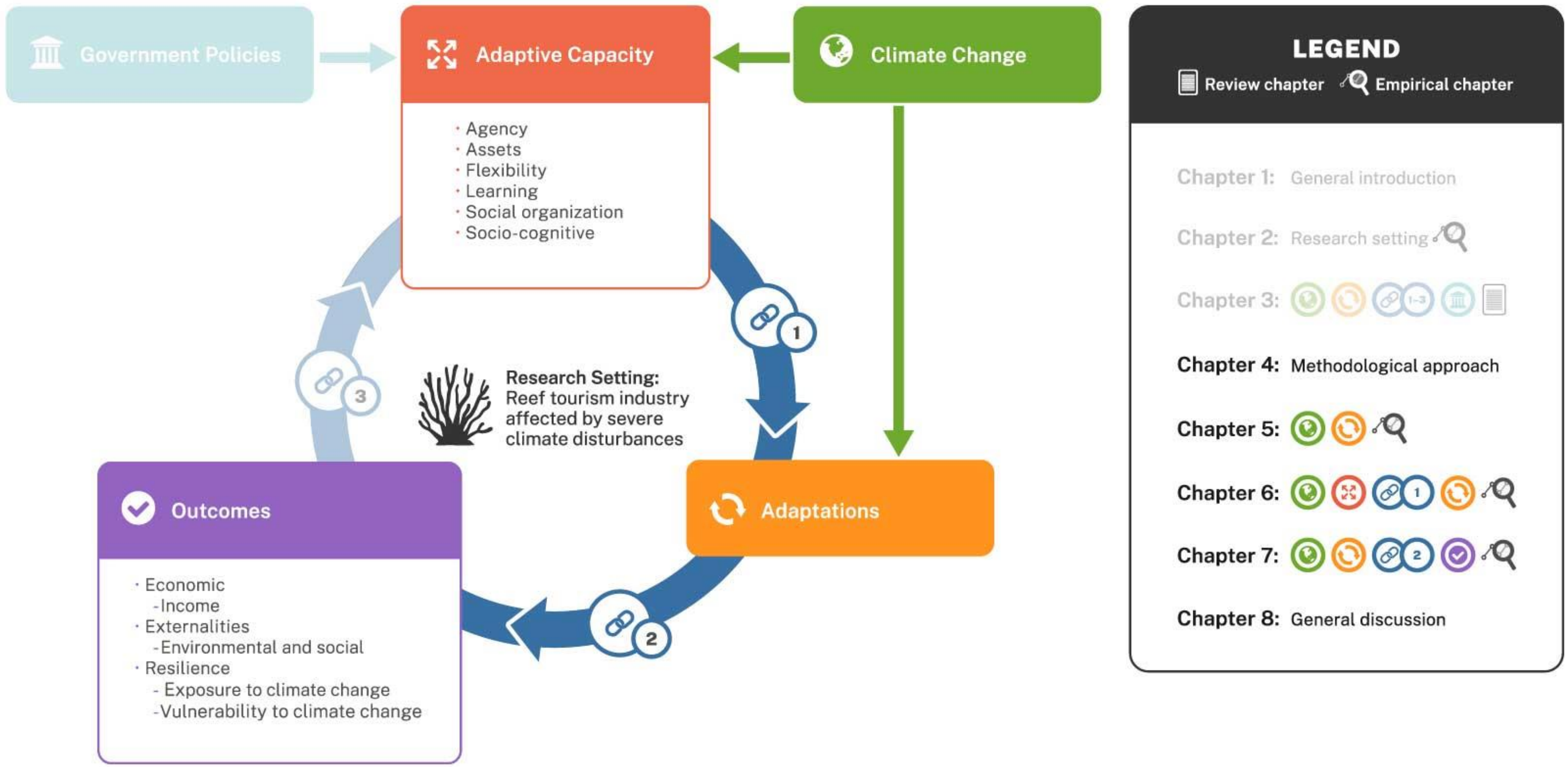
The remainder of my thesis follows the structure as presented in Figure 1.5, starting with an overview of the methodology used for my data chapters on coral reef tourism (**Chapter 4**), three data-based chapters (**Chapter 5** to **Chapter 7**), and a general discussion (**Chapter 8**).

In **Chapter 4**, I introduce the methodological approach for the remainder of my thesis chapters. Specifically, I present the research locations used in my study, the sampling method used, and the conceptualization and operationalizing of the adaptive capacity domains, the adaptive responses, and the adaptation outcomes in a reef tourism context.

In **Chapter 5**, I address RESEARCH OBJECTIVE 4 by testing the applicability of the categorization of adaptive responses to climate change that I developed in **Chapter 3** in the context of my case study: reef tourism. In this chapter I identify the most common adaptive responses to climate disturbances on coral reefs by Australian reef tourism operators, and test whether there are any responses that were adopted by reef tourism operators that could not be concisely included in the adaptive response categorization developed in **Chapter 3**.

Figure 1.5

Research Gaps Addressed in Empirical Data Chapters (4–7): Reef Tourism Adaptation to Severe Climate Disturbances



Note. The specific gaps that are addressed are shown in the Legend. The empirical chapters of my thesis do not include a study of the effect of adaptation outcomes on adaptive capacity and the effects of government policies because of time limitations, although I have collected data on these relationships during my thesis.

In **Chapter 6**, I address RESEARCH OBJECTIVE 5 by testing whether adaptive capacity is a reliable proxy for climate change adaptation in a reef tourism context. Specifically, I include indicators of adaptive capacity within all six domains of adaptive capacity (Cinner & Barnes, 2019) and explore whether they are meaningful predictors of the adaptive responses adopted by reef tourism operators.

In **Chapter 7**, I address RESEARCH OBJECTIVE 6 by evaluating the multidimensional outcomes that are associated with the adaptive responses adopted by reef tourism operators in response to severe climate disturbances. Specifically, I investigate whether particular adaptive responses were successful in terms of reducing perceived climate risk and/or vulnerability without compromising social, economic, and environmental sustainability (Doria et al., 2009).

Finally, in **Chapter 8**, I address RESEARCH OBJECTIVE 7 by discussing the contributions of my thesis and, specifically the added value of using my conceptual model (Figure 1.2), focused on the dynamics of microeconomic adaptation. Here I discuss what I have learned throughout my thesis and what theoretical contributions are provided by my thesis, as well as discussing limitations and future research needs.

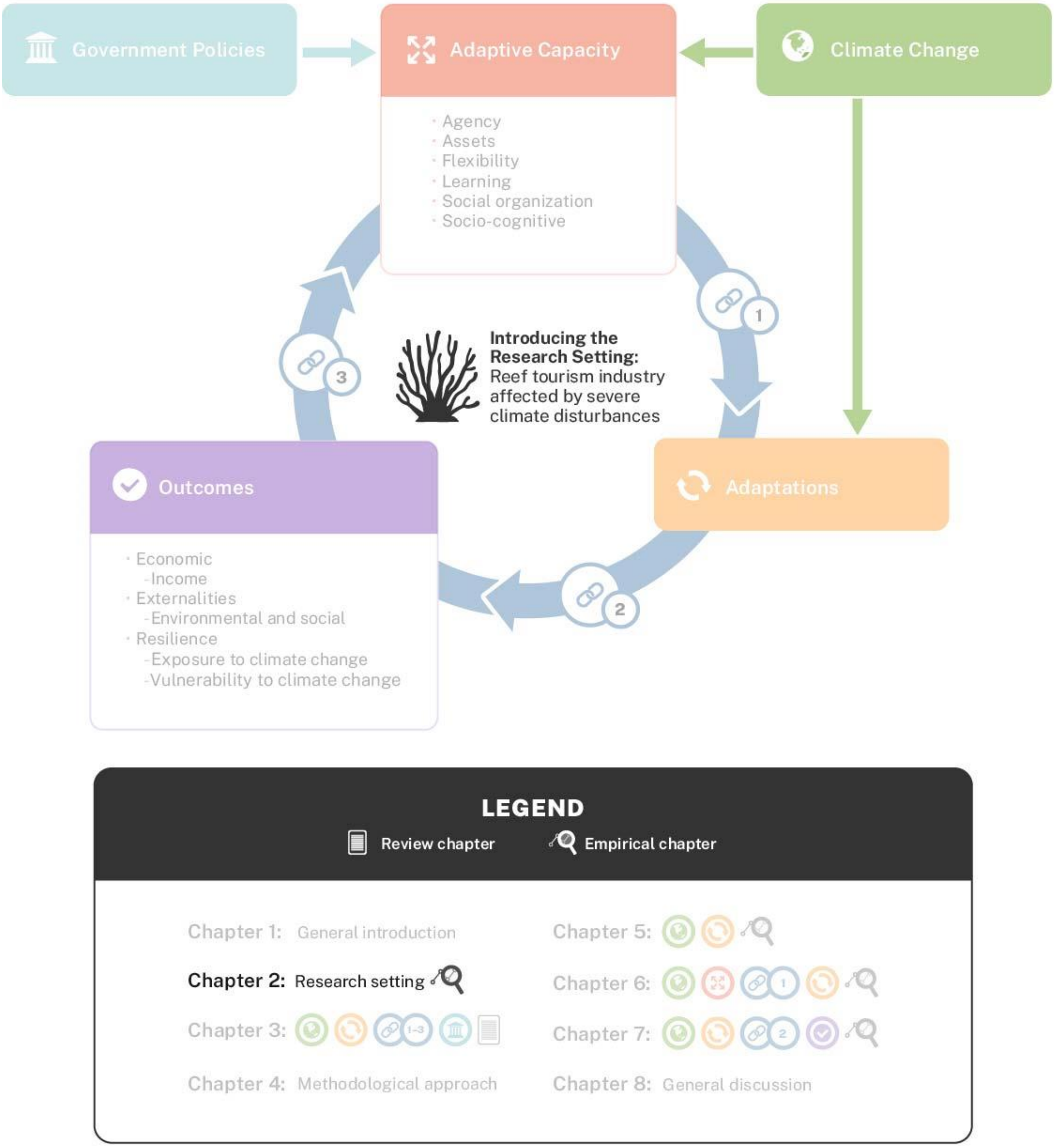
Chapter 2. The Effect of Coral Bleaching on the Recreational Value Derived From the GBR

Adapted from: Bartelet, H.A., Barnes, M.L., Zoeller, K.C., Cumming, G.S. (2022). Social adaptation can reduce the strength of social-ecological feedbacks from ecosystem degradation. *People and Nature, 4*, 856–865. https://doi.org/10.1002/pan3.10322

In my second chapter, I quantified the effect from climate disturbance-induced coral loss on the demand for and tourist satisfaction with coral reef tourism on the Great Barrier Reef in Australia. Before exploring adaptation to climate disturbances by reef tourism operators in the following chapters, this chapter provides evidence of tourist responses to coral loss as well as providing indications of some of the adaptive responses used by reef tourism operators to mitigate negative visitor impacts.

Figure 2.1

Research Setting Introduced in Chapter 2



Note. Chapter two introduces the relevance of my research setting. In subsequent chapters this research setting is used as model system to test the microeconomic adaptation framework. The relevance of the research setting is explored by a case study on the GBR focused on how climate disturbances have already affected the reef tourism industry. Based on this analysis, Chapter two provides some hypotheses about adapation by reef tourism operators that will be explored further in particular in Chapter 5.

Contributions

H.B. and M.B. conceived the manuscript, H.B. and G.C. developed methodological approach, H.B. ran the analyses and wrote first draft, M.B. and G.C. helped write and revise the manuscript. K.Z. provided expertise on cultural ecosystem services.

Abstract

Feedbacks between people and ecosystems are central to the study of Social-Ecological Systems (SES) but remain poorly understood. It is commonly assumed that changes in ecosystems leading to a reduction in ecosystem services will trigger human responses that seek to restore service provision. Other responses are possible, however, but remain less-studied. I evaluated the effect of environmental change, specifically the degradation of coral reefs, on the supply of and demand for a cultural ecosystem service (CES); i.e., recreation. I found that declines in coral cover reduced demand for recreational ecosystem services but had no apparent effect on the benefits received from recreation. While this finding seems counter-intuitive given previous experimental data that suggest ecosystem quality affects people's satisfaction, my analysis suggests that social adaptation could have mediated the anticipated negative impact of environmental change on CES benefits. I propose four mechanisms that may explain this effect and that require further research: spatial diversification; (service) substitution; shifting baselines; and time-delayed effects. My findings emphasize the importance of human culture and perception as influences on human responses to environmental change, and the relevance of the more subjective elements of social systems for understanding social-ecological feedbacks.

2.1 Introduction

Human responses to changes in ecosystems are the basis for a wide range of complex feedbacks within social-ecological systems. Understanding these cycles of causality, and particularly the ways in which adaptation by people mitigates the impacts of ecological change on human wellbeing, is becoming increasingly important as the scale and intensity of human impacts increases (Hughes, Barnes, et al., 2017). For example, the responses of fish communities to coral bleaching events, the knock-on effects on harvesting by humans, and consequent impacts on food security remain largely unknown (Eriksson et al., 2017). Globally, over the last century, ecosystems have declined while human well-being has increased (Raudsepp-Hearne et al., 2010); but it remains unclear how long this pattern can persist (Cumming et al., 2014). Presumably, global human wellbeing will decline rapidly due to famine and disease if a threshold is crossed in the production of provisioning and regulating services (Rockström et al., 2009). An extreme outcome such as the end of human civilization seems unlikely (Cumming & Peterson, 2017), but smaller, less obvious declines in human quality of life that result from ecological degradation occur frequently and can provide informative insights into social-ecological feedbacks and how they can be managed (Chapin et al., 2010; Maciejewski et al., 2015). My research addresses an existing gap in knowledge of social-ecological feedbacks by exploring the human side of the nexus between people and ecosystems using the concept of Cultural Ecosystem Services (CES) (Chan, Guerry, et al., 2012).

CES refer to the interactions between people and nature that deliver non-material benefits that directly contribute to changes in human wellbeing (Fish et al., 2016). CES are inherently subjective, and the ways in which people value and experience CES are influenced by individual perceptions, preferences, and socialization (Chan, Satterfield, et al., 2012; A. Fischer & Eastwood, 2016; Kenter et al., 2015; Zoeller et al., 2021). Depending on the magnitude of ecological change, ecosystem condition may be only a secondary driver of CES benefits; individual experiences of an ecosystem service may exert a stronger influence on CES benefits unless ecological degradation is extreme. Understanding the relationships between an ecosystem’s condition, the services it produces, and its perceived effects on human wellbeing is vital in understanding human responses to ecosystem change and setting conservation priorities for degrading systems (Plieninger et al., 2013).

Recreation is an important CES. It is often enabled through the socioeconomic services offered by tourism operators. For example, in ecosystems like the Florida Everglades and the Australian Great Barrier Reef (GBR), it can be difficult for people without local knowledge and experience to recreate safely, affordably, and comfortably without a third-party intermediary. By providing access to ecosystems in accordance with consumer preferences, tourism operators enable people to experience the ecosystem in different ways. The services delivered by tourism operators are in themselves not an ecosystem service (Pueyo-Ros, 2018), but the demand for tourism activities can be used as a tangible proxy for the intangible value of recreational ecosystem services and people's conservation priorities (i.e. "willingness to pay") (van Berkel & Verburg, 2014). Indeed, the tourism sector often adds substantial value to the economy (Spalding et al., 2017), of which direct expenditures by tourists (to participate in tours) make up a large proportion. Linking CES benefits derived from recreation to monetary value can thus provide a useful metric to better understand how people perceive and value ecosystems, and how CES benefits might change in response to changes in ecological condition.

In this paper I empirically tested the impact of climate-induced ecosystem change on the demand for and satisfaction with recreation on coral reefs in the Great Barrier Reef (GBR) region of Australia. The GBR is the world's largest coral reef ecosystem, covering 344,400 km^2 along the east coast of Queensland in Australia (GBRMPA, 2021). It contributed $6.4 billion annually in economic value and 64,000 jobs to the Australian economy in the years 2015–16 (Deloitte Access Economics, 2017). Due to increasing sea temperatures, marine heatwaves linked to El Niño conditions have exceeded the thermal limits of corals and their zooxanthellae (Hoegh-Guldberg, 1999). As a result, the GBR has been severely affected by coral bleaching. Bleaching events in 2016 and 2017 have had a severe impact on the integrity of the GBR ecosystem (Dietzel et al., 2020; Hughes, Kerry, et al., 2018), although there have been indications of reef recovery in recent years (AIMS, 2022).

2.1.1 Theoretical Foundations and Hypotheses

I tested two sets of hypotheses that could explain the relationship between ecosystem conditions and recreation, as shown in Table 2.1.

Table 2.1

Overview of Hypotheses and Methods

Effect	**Hypotheses**
Hypothesis Set 1: Explaining demand	H10 – no effect of coral bleaching on visitor numbers H1a – coral bleaching decreases visitor numbers (“reputation effect”) H1b – coral bleaching increases visitor numbers (“last-chance tourism”)
Hypothesis Set 2: Explaining satisfaction	H20 – no effect of coral bleaching on visitor satisfaction H2a – coral bleaching decreases visitor satisfaction due to reduction in service received

I evaluated the effect of climate-induced ecosystem impacts on the tangible value of recreation by analyzing the effects on the demand for tourism (H1). I posit two competing hypotheses here: first, that climate-induced impacts on the ecological quality of a nature-based tourism destination would negatively impact visitor numbers (H1a) (Pickering, 2011; Rosselló et al., 2020). Second, lower than expected quality of the ecosystem due to climate impacts may increase visitor numbers (“last-chance tourism,” H1b). There are a number of empirical studies which led us to posit the first hypothesis. For example, a survey of 194 Canadian and 109 Australian scuba divers revealed that the majority would change their behavior in response to marginal reef conditions (Verkoeyen & Nepal, 2019). The most likely response was change of location, followed by decreasing dive frequency. Similarly, Uyarra et al. (2005) found that 80% of the 654 surveyed tourists on Bonaire and Barbados would not return to the island for the same price if coral bleaching occurred. However, a recent study suggested the opposite effect, i.e. the impacts of climate change increased visitor numbers in a rush for taking advantage of the "last chance" for people to visit the ecosystem (Piggott-McKellar & McNamara, 2017). Finally, I introduced a null hypothesis through which no change in visitor numbers would occur as a result of climate change impacts. The null hypothesis could be the result of a limited elasticity of tourism demand to changes in ecosystem quality (Mourey et al., 2020).

I evaluated the effect of climate change impacts on the intangible value of recreation by analyzing satisfaction levels of tourists visiting the ecosystem (H2). Here, I hypothesized that climate change impacting the ecological quality of a nature-based tourism destination would negatively impact tourist satisfaction (H2b). Indeed, a number of studies have shown that visitors to coral reefs (and specifically divers) put a higher value on reefs with higher coral cover and biodiversity (Grafeld et al., 2016; Peng & Oleson, 2017; Pert et al., 2020; Schuhmann et al., 2013). However, tourist operators' ability to compensate for lower ecosystem quality by improving other parts of their offering could potentially offset any negative impacts on tourist satisfaction (Atzori et al., 2018). I thus included a null hypothesis (H20) that posited that tourist satisfaction would not be affected by coral bleaching. In the absence of compensation effects, the null hypothesis could also be explained by tourist satisfaction being insensitive to changes in ecosystem quality.

2.2 Methodology

I used TripAdvisor (TA) data to extract the number of customer reviews as a proxy for visitor numbers (Ma & Kirilenko, 2021; Teles da Mota & Pickering, 2020). Although TA data has been found to be a good predictor of tourist flows (Ma & Kirilenko, 2021), I cross-verified my results with actual visitor data on the GBR (GBRMPA, 2020). TA data was also used to extract customer satisfaction ratings, which have previously been used as a measure of recreation-based CES benefits (Cong et al., 2014). One obvious limitation of this approach is that TA reviews and ratings might be biased towards providing an evaluation of a visitor's experience directly with the tourism provider rather than an evaluation of a visitor's experience with the ecosystem.

I focused my research on tourism operators in the central and northern sections of the GBR because these areas were most severely affected by the coral bleaching events in 2016 and 2017 (AIMS, 2017; GBRMPA, 2017; Hughes, Kerry, et al., 2017). My sample thus addresses reef tourism operators between Townsville and Cape Tribulation. Although it is possible that not all operators in these areas were directly affected by the bleaching events, they do operate in the areas that had the highest chance of being affected. I sampled the full population of in-water reef tourism operators that offer recreation-based activities like diving and snorkeling that are directly linked to coral reefs. These operators were identified through an online search (i.e. Google search engine, Google Maps and TripAdvisor) with the search terms "coral tours" and "coral reefs tours," and "great barrier reef tours." I excluded dive resorts because TA reviews will likely be biased towards rating the sleeping arrangements rather than reef-based tourism activities. Scenic flight operators and fishing charters were excluded because I judged their visitors to be less closely interacting with coral reefs during their tours as compared to in-water activities. Private charter boats were excluded because of the limited availability of TA data. Finally, I limited my analysis to TA reviews written in the English language to facilitate review content analysis. My final dataset included a total of 41 coral reef tourism operators and some 48,000 customer reviews from the years 2008–2021.

The choice for the time period of 12 years helped us to extract longer term trends in visitor numbers and tourist satisfaction.

In my experimental design, I included a counterfactual from a different and less impacted Australian ecosystem. Specifically, I paired reef locations and dates with tourist locations in the rainforest areas of Northern Queensland where the tourism operators included in my sample are also based. I made this decision because many people who visit the GBR also visit the nearby rainforest (Reef & Rainforest Research Centre, 2007). Through this counterfactual I therefore expected to include many of the same people in both datasets. Because of the linkage between coral reef and rainforest visitors, I acknowledge that the counterfactual might not be fully valid for H1 which related to demand for coral reef activities. In H1, I therefore hypothesized that a reduction in visitors to the reef would also lead to a reduction in visitors to the rainforest. However, for H2, related to tourist satisfaction, the counterfactual helped us to control for any potential exogenous changes in the underlying sample of tourists. For example, a demographic shift (e.g. age or nationality) might have caused a change in the rating bias of tours. For the counterfactual, I included a full sample of rainforest operators in the North Queensland region based on an online search (i.e. Google search engine, Google Maps and TripAdvisor) with the search terms “rainforest tours” and “Daintree tours.” My dataset included a total of 18 rainforest tourism operators and some 17,000 customer reviews over the study period (2008–2021).

I extracted TA reviews using the web scraping package ‘rvest’ (Wickham, 2019) in R modeling software (R Core Team, 2013). After extracting the TA data, the number of reviews and customer satisfaction ratings were averaged on a monthly basis. I then filtered out the seasonality in the data using the ‘bfast’ package in R (Verbesselt et al., 2010). The ‘bfast’ package iteratively filters out the trend, seasonal effects, and noise components from time series data using methods to detect breakpoints. Breakpoints are points in the time series when the trend switches from one direction to another. I analyzed whether any breakpoints occurred in the number of TA reviews, and whether these breakpoints coincided in time with the occurrence of the coral bleaching events in 2016 and 2017. To better understand any existing trends in satisfaction ratings, I used an exploratory post-hoc analysis of the written reviews. To do so, I used R to assess how often specific words in TA reviews were used per year. I then extracted the words that had seen the largest relative increase and decrease over my sample period. I cleaned the data to remove any company names and/or words that could not be meaningfully interpreted. For the reef reviews I removed company names whereas they showed up as fastest growing or shrinking words (i.e. “Poseidon,” “Wavelength,” “ABC,” “Magic,” “Freedom”). I merged “knowledge” and “knowledgeable” as they reflect the same concept. I deleted non-informative words whereas they showed up as fastest growing or shrinking words (i.e. “highly,” “recommend,” “reviews,” “found,” “decided,” “stayed”). For the rainforest reviews I removed non-informative words whereas they showed up as fastest growing or shrinking words (i.e. “highly,” “lot,” “bit,” “tours,” “recommend”). I also merged “knowledge” and “knowledgeable” as they reflect the same concept.

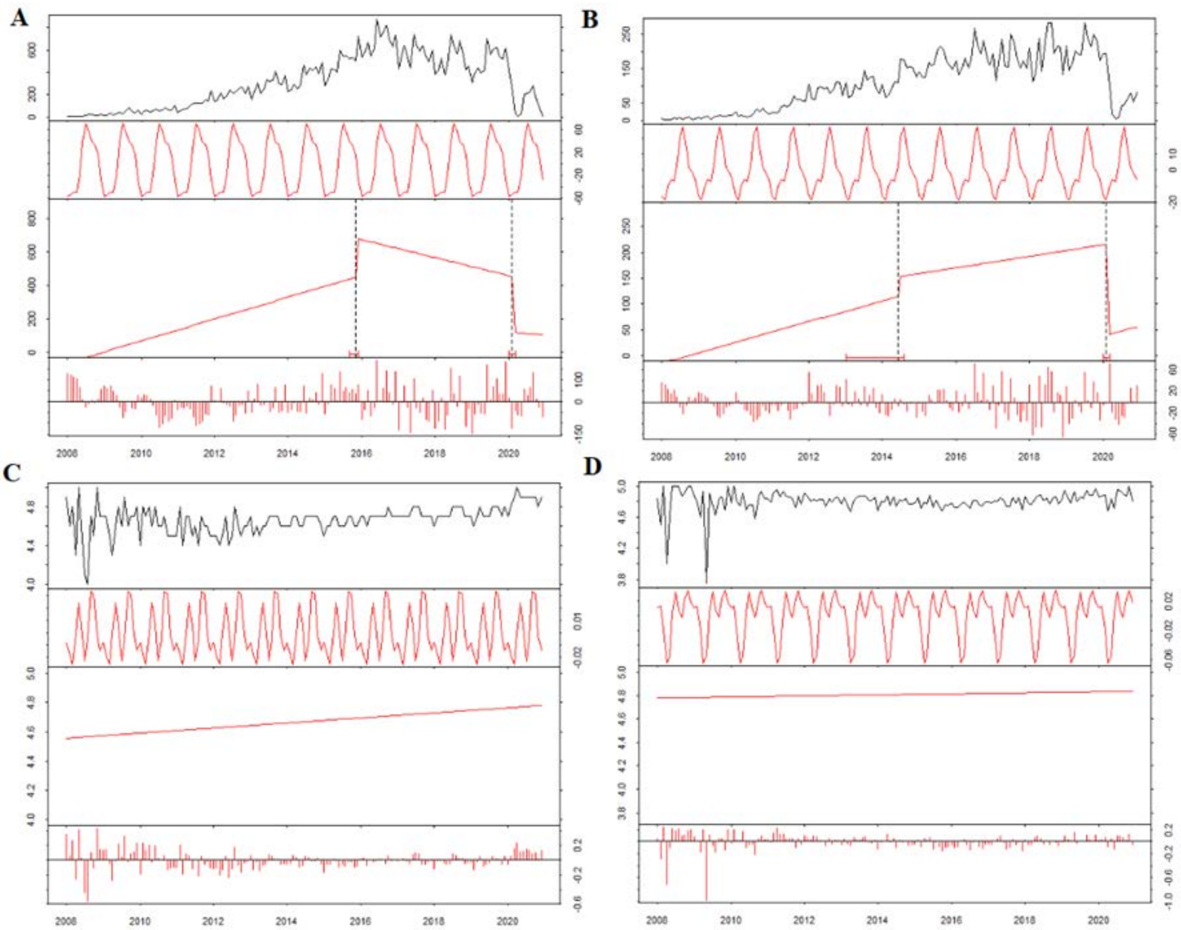
2.3 Results

I identified two breakpoints in the monthly number of TA reviews for GBR tourism (Figure 2.2A). Over the period 2008 to 2016, the number of monthly reviews increased from zero to 400. This increasing trend was likely the result of both increasing visitor numbers to the GBR, and increasing popularity of TA as a review medium. In the year 2016, a breakpoint was observed, with the number of monthly reviews decreasing from 600 back to 400 in 2020. The third breakpoint began in 2020, and was associated with the COVID-19 pandemic. Figure 2.2B shows the results for doing the same analysis on a nearby and less-impacted Australian ecosystem, the rainforest. I found two breakpoints in the monthly number of TA reviews, a proxy for rainforest trips in the Cairns region of Tropical North

Queensland. Over the period 2008 to mid-2014, the monthly number of reviews increased from about zero to about 100. From mid-2014, the number of reviews increased from some 150 to some 200 in 2020.

Figure 2.2

Trend Analysis of Reef and Rainforest Tourist Operators

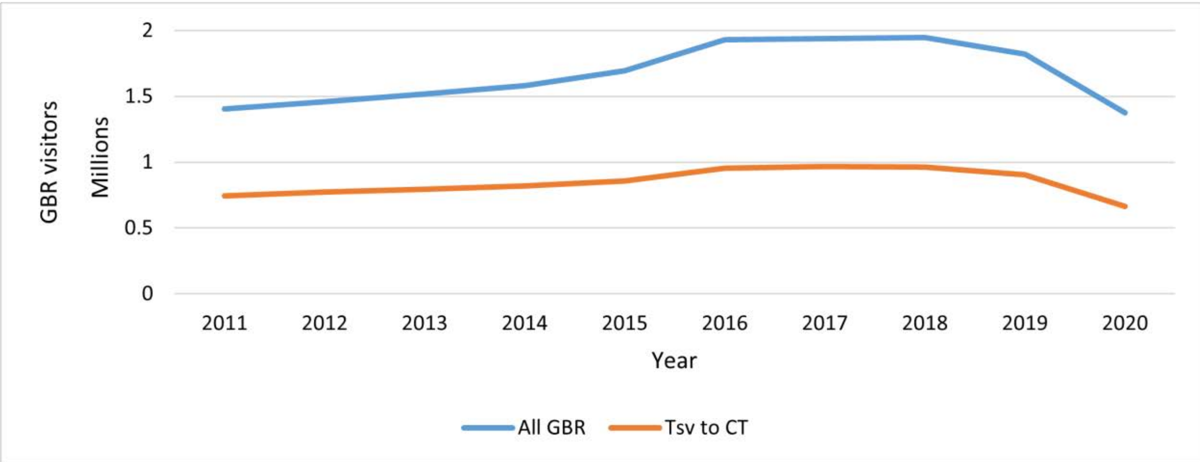


Note. Top figures show number of TripAdvisor reviews for reef (A) and rainforest (B) tourism operators in Tropical North Queensland. Bottom figures show TripAdvisor customer satisfaction ratings (i.e. between 1 and 5) for same reef (C) and rainforest (D) operators. Reef operators' data based on 47,735 reviews of 41 reef tourism operators on the Great Barrier Reef between 2008 and 2021, specifically those that operate in the areas most affected by the 2016 and 2017 coral bleaching events (i.e. located between Townsville and Cape Tribulation). Rainforest operators' data based on 16,930 reviews of 18 rainforest tourism operators nearby the Great Barrier Reef between 2008 and 2021, specifically those visiting the Daintree Rainforest (i.e. operators between Cairns and Cape Tribulation). Datasets were aggregated and averaged on monthly basis. Seasonality was filtered out using 'bfast' package in R. The top frame in each figure displays monthly data, while the second panel depicts seasonal variation detected in the number of reviews over time. This variation was then removed and the resulting trend is displayed in panel three. The fourth panel depicts residual variation which cannot be accounted for in the seasonal variation or trend.

The actual number of reef trips from my sample of operators, i.e. Townsville (Tsv) to Cape Tribulation (CT), as well as for the GBR as a whole, levelled off around 2016 and started a slow decline (Figure 2.3).

Figure 2.3

Great Barrier Reef (GBR) Tourist Numbers, Derived From Environmental Management Charge Receipts From Commercial Tourist Operation (GBRMPA, 2020)



Note. Townsville (Tsv) to Cape Tribulation (CT) includes Cairns/Cooktown Management Area, Townsville/Whitsunday Management Area (minus Whitsunday Plan of Mgmt). Includes only 'Full Day' and 'Part Day' visitations, but excludes 'Total Exempt.' The years reflect the financial year, thus the latest data point reflects mid-2020 and so the steep decline in the last year can be attributed to the impact of the COVID-19 pandemic.

Comparing TA review data to actual visitor data to the GBR, I found that the fraction of visitors that wrote a TA review ranged between 0.17% (2011) and 0.85% (2016). Assuming an average group size of four people, this meant that about 3% of groups visiting the GBR wrote a TA review. Although my TA sample thus includes only a small selection of visitors, I did find a similar breakpoint around the year 2016 in my cross-verification data set (Figure 2.3). I noted that the same trend applies to the GBR as a whole, not just to those areas that were most severely affected by coral bleaching in 2016 and 2017.

No breakpoints were found in the customer satisfaction ratings for my sample of reef operators (Figure 2.2C). The average monthly customer rating increased from about 4.6 in

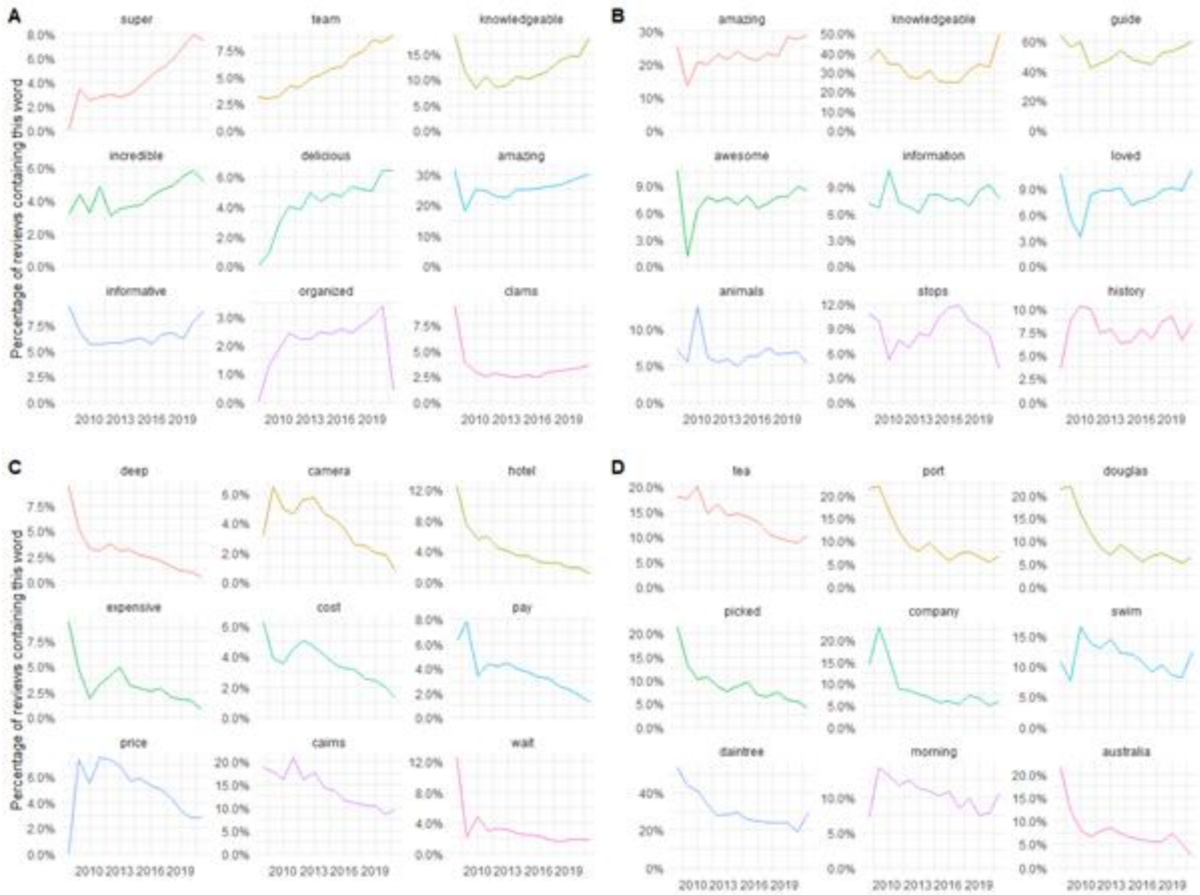
2008 to about 4.8 in 2020. This result showed no visible effect from the coral bleaching events in 2016 and 2017 on recreation-based CES benefits from the GBR in terms of tour-based satisfaction. My analysis showed that average monthly customer ratings for rainforest tourism operators remained approximately constant at about 4.9 between 2008 and 2020 (Figure 2.2D). Thus, my results suggest that recreation-based CES benefits for the GBR have been increasing relative to benefits from rainforests in terms of tour-based satisfaction.

I identified several causal factors that could have been responsible for the increase in customer satisfaction ratings for GBR operators, despite the impacts from coral bleaching (Figure 2.4). I noted that most of the trends in word usage in the written reviews preceded the coral bleaching events by a number of years. I found, as shown in Figure 2.4A, that several words linked to the organization of the tours and the quality of staff have seen an increase in the written TA reviews, e.g. 'team,' 'knowledgeable' and 'informative.' Food and beverages might also have improved as the word 'delicious' has grown. On the other hand, as shown in Figure 2.4C, words related to the costs of the tours have decreased, e.g. 'expensive,' 'price,' and 'pay.' Words related to the ecosystem featured prominently in the written reviews, e.g. the words 'reef,' 'coral,' and 'fish' are used in respectively 61%, 16%, and 23% of written reviews in the year 2019. However, I did not find strong trends in wording that are linked to the ecosystem, except for 'deep' that has decreased and 'clams' that has increased.

My analysis showed that for rainforest operators, the relative growth in words seemed less steep compared to the reef operators. I also noted that the word 'knowledgeable' that saw strong growth with reef operators (14% of reviews in 2019) was already more frequently used for rainforest operators (35% in 2019).

Figure 2.4

TripAdvisor Review Content



Note. Top figures show words in review text that have seen the largest relative increase between 2008 and 2021 for reef operators (A) and rainforest operators (B) respective. Bottom figures show words in review text that have seen the largest relative decrease between 2008 and 2021 for reef operators (C) and rainforest operators (D) respectively.

Through my analysis and findings I was not able to reject two of the hypotheses that I posited at the start of my research (Table 2.2).

Table 2.2

Summary of Hypotheses and Results

Effect	**Hypotheses**	**Result**
Hypotheses 1: Demand effect	H10 – no effect of coral bleaching on visitor numbers *H1a – coral bleaching decreases visitor numbers ("reputation effect")* H1b – coral bleaching increases visitor numbers ("last-chance tourism")	A breakpoint in the trend of visitors occurred in the year of the bleaching event in 2016. Thus, I could not reject H1a.
Hypotheses 2: Satisfaction effect	*H20 – no effect of coral bleaching on visitor satisfaction* H2a – coral bleaching decreases visitor satisfaction due to reduction in service received	Visitor satisfaction kept its increasing trend despite bleaching. Thus, I could not reject H20.

2.4 Discussion

I found support for my hypothesis (H1a) that climate change impacts on ecosystems led to a reduction in visitor numbers due to a societal response to ecological degradation. Specifically, my results show that the ecosystem impacts from coral bleaching could have contributed to a reduction in the demand for recreation on the GBR, as shown by the decreasing trend in visitor numbers around the time of the first bleaching event in 2016 (Figure 2.2A). Climate change impacts might have affected visitor numbers through marketing and reputational effects (Evans et al., 2016; Gössling et al., 2012). Previous research had shown that it was international visitor numbers to Tropical North Queensland, where the GBR is located, that peaked in 2016 and started a slow decline, while domestic visitations saw a strong increase post-2016 (Queensland Government, 2020). Thus, marketing and reputational effects might have mostly affected international visitors. There may also be other, non-climate related explanations for the trend changes in international and domestic visitor numbers however. For example, competition from other industries, like mining and construction, could have affected the opportunity cost for capital and the public and private priority of infrastructure expansion for the tourism industry (Jarvis et al., 2016). Thus, the reduction in visitor numbers could be explained by a supply (reduction in tourist capacity) rather than a demand effect. My findings reject the ‘last-chance’ tourism hypothesis (Piggott-McKellar & McNamara, 2017) and the null hypothesis of a limited elasticity of tourism demand to changes in ecosystem quality (Mourey et al., 2020). I found that visitor numbers to rainforests in the same region as the GBR did not see a similar breakpoint, but kept their increasing trend (Figure 2.2B). This is surprising because previous research found that people tend to visit both forest and coral ecosystems on their trip to Tropical North Queensland (Reef & Rainforest Research Centre, 2007).

The hypothesis (H2a) that climate change impacts on ecosystems would lead to a reduction in the delivery of recreation-based CES benefits, as measured by tourist satisfaction, was not supported. My results show that tourist satisfaction continued to increase throughout my sample period, despite severe coral bleaching events in the years 2016 and 2017 (Figure 2.2C). Thus, I found support for my hypothesis (H20) that coral bleaching would not affect visitor satisfaction levels. I found evidence for tourism operators’ ability to compensate for lower ecosystem quality by improving other parts of their offering (Atzori et al., 2018). However, these compensatory services mostly preceded the bleaching events, and have thus not been implemented solely because of the impacts from coral bleaching. Specifically, I found evidence of several aspects of tour offerings that could have contributed to the increasing trend in satisfaction levels: the organization of the tours, quality of staff, knowledge about the ecosystem, food and beverages, and the quality-price ratio. Despite ecosystem-related words featuring frequently in TA reviews, I found little evidence for trends in the written reviews that linked to either the quality of the ecosystem, or climate change impacts. I found that the delivery of recreation-based CES benefits in the GBR, measured via tourism satisfaction, increased relative to rainforest operators in the same region, who to my knowledge have not seen similar climate-related ecosystem impacts (Figure 2.2D). My findings could be interpreted as evidence for the (partial) substitutability of natural capital by man-made capital (Chiesura & de Groot, 2003). Specifically, a reduction in natural capital (e.g. quality of coral reefs) might have been compensated for by an increase in man-made capital (e.g. quality of staff). Further research is required to evaluate whether indications of such substitutability are also observed for CES in other contexts and places, in particular in locations that are considered more vulnerable because of lower levels of wealth (Brooks et al., 2005).

My findings regarding the demand and satisfaction effects (H1 and H2) lead to a counterintuitive implication. Namely, my results suggest that climate change impacts could have contributed to a reduction in tourist visitations. Yet my results also suggest that tourists who decided not to visit the GBR due to climate impacts would likely have received substantial recreation-based CES benefits if they had instead chosen to visit. Indeed, customer satisfaction ratings associated with GBR tourism have been continuously increasing (Figure 2.2C). Additionally, official GBR visitor data (Figure 2.3) shows that the demand effect also affected GBR visitor numbers to areas that were not, or were less directly affected by coral bleaching (i.e. areas south of Townsville). Both findings imply a potential mismatch between people's travel behavior, and the actual impacts from climate change. Similarly, during and after the severe bushfires in Australia in 2019–2020, tourist sites thousands of kilometers away from the fire-affected area had to deal with cancellations. This effect was likely related to significant (social) media coverage as well as governments, including the United States and United Kingdom, warning their visitors about traveling to Australia. Both in the bleaching and wildfire cases, further information is required about the demographics of tourism market segments that decided not to visit and their motivations. Individual-specific factors such as expectations (Cumming & Maciejewski, 2017), the perceived contribution of the service to wellbeing (Plieninger et al., 2013) and specific socio-demographic characteristics such as age and education level (Jarvis et al., 2016) have previously been found to be key contributors to tourist satisfaction, and they might also affect people's decision to visit a particular location or ecosystem (Gössling et al., 2012).

My finding that the CES benefits associated with recreation continued to increase despite the impacts from coral bleaching on the health of the GBR conflicts with conclusions from experimental studies showing that visitors put a higher value on reefs with higher ecological quality (Grafeld et al., 2016; Peng & Oleson, 2017; Pert et al., 2020; Schuhmann et al., 2013). I propose several mechanisms that may have contributed to this finding. First, it is possible that tourism operators were able to relocate their tours to areas that were not affected or were less affected by coral bleaching. Second, while coral reefs might have been affected by coral bleaching and mortality, the effect on the reef substrate takes a longer time to become visible. That is, the structural complexity of the reef would likely remain intact for quite some time even after the coral has died, allowing it to continue providing a suitable habitat for fish and other marine life, which may be what tourists are most interested in (Grafeld et al., 2016). The structural complexity of a reef tends to decrease about four to five years after severe coral loss (Pratchett et al., 2011). However I did not find evidence for a time lagged effect in at least the five years of data available on customer satisfaction after the first bleaching event in my sample area, which occurred in 2016. Furthermore, reefs in my study areas have seen rapid recovery in coral cover since 2019 (AIMS, 2022). Third, while tourists might have experienced coral reefs with reduced ecological quality, customer satisfaction might have been influenced by a myriad of factors of which ecosystem quality may not have been dominant (Cumming & Maciejewski, 2017; Roux et al., 2020). In other words, tourist satisfaction with the ecosystem might have decreased, but due to improvements in other parts of the tour service, I was not able to capture this effect. Finally, tourist satisfaction with the ecosystem might not have decreased due to “shifting baselines” (Pauly, 1995; Soga & Gaston, 2018), i.e. non-repeat visitors may lack a baseline of what a high-quality coral reef looks like. Indeed, existing research found that prior reef visitation on the GBR affected peoples’ aesthetic ratings of reefs, specifically producing more extreme ratings [although not significantly more positive or negative (Pert et al., 2020)]. Further research is required to understand how tourism operators responded to the coral bleaching events, the spatial variation in climate change impacts within individual reefs, and the underlying processes linked to customer satisfaction (e.g. through visitor surveys with a rating system separating ecosystem satisfaction from other tour specifics).

Currently, many CES studies suffer from non-standardized measurement approaches. Since TA scores are ubiquitous across tourism-based CES, my approach offers a way to standardise value comparisons. TA data, or other publicly available social media data (Martinez-Harms et al., 2018), give researchers access to big data sets that do not suffer from hypothetical bias (Hausman, 2012). However, a limitation of this approach is that TA comments are likely more focused on informing other tourists about their experience with particular tours, and thus details about tour operators are weighted more heavily compared to a random survey of reef visitors. Other limitations can be identified and addressed in the study design, as I have done here. For example, there is the potential for TA samples to be biased. I addressed this by adding a comparison with another ecosystem that was correlated with my sample in both time and space. Another limitation is that TA review data might not coincide with actual visitor data, and thus provide inaccurate results for demand-based hypotheses (such as H1 here). I managed this limitation by cross-validating my findings with official visitor statistics (Figure 2.3). Other types of data could be used to extend my methods and hypotheses to non-cultural ecosystem services (e.g. provisioning services). Coastal communities that are dependent on fisheries might find it more difficult to adapt to ecosystem change than recreation providers, e.g. because they have few other readily available sources of food or livelihood activities available. However, the adaptation mechanisms I identified for CES might also be applied to provisioning or other ecosystem services. First, there could be delayed ecosystem effects as well as shifting baselines. Second, fishermen might spatially diversify (Gonzalez-Mon et al., 2021) or substitute their dependence on natural capital by shifting towards human-made capital, e.g. aquaculture. Thus my findings create a potential opportunity to synthesize responses across different kinds of ecosystem services (Grantham et al., 2020).

My research has broader implications for recreation-focused CES research and for research on social-ecological feedbacks more generally. My findings shed new insights into the role that ecosystem management authorities play in facilitating the delivery of recreation-based CES (Roux et al., 2020). Management authorities can play a role in the development of expertise in tourism operators' staff to ensure visitors have a more informed nature experience. For example, on the GBR, the Marine Park Authority's 'Master Reef Guides' program trains tourism operators' staff to become leading reef guides and ambassadors (GBRMPA, 2019). Management authorities' role could thus also focus on certification, i.e. to make sure that tourists can identify the reef operators that are up to date on the latest scientific and cultural knowledge about the ecosystem. Management authorities could also play a more active role in providing reliable and scientific information about the spatial characteristics of ecosystem damage and travel safety. During the coral bleaching events in 2016–17 (and the bushfires in 2019–2020), visitor areas that did not experience any direct ecological impacts were affected by reductions in visitor numbers. In the age of social media, information (true of false) can spread more rapidly than even the most severe bushfire.

2.5 Conclusion

My findings provide valuable insights into social-ecological feedbacks, most notably showing that social-ecological feedbacks can be complicated by compensatory and adaptation effects in human societies and individuals. In theory, we would expect first-hand experience of ecological degradation to provide an 'honest' signal that reliably informs each individual visitor to the reef of its current state and underlines the need for urgent action to reduce carbon dioxide emissions. We would also expect that an experience of a degraded ecosystem would be less pleasant and provide fewer wellbeing benefits than an experience of a pristine ecosystem. My analysis raises the possibility that depending on their baselines and values, people may be vastly more accommodating of ecological degradation than conservation biologists and managers would expect; or conversely, that the threshold level of change (beyond which unease and a direct response to degradation are triggered) may be much higher than might be expected. This observation in turn suggests that where they are strongly modulated by social adaptation, feedbacks from ecosystems to the social system may be weaker than expected, and may be unreliable if they are expected to drive corrective action that seeks to conserve and restore ecosystems and ecosystem service provision. It thus seems essential for future research and management that models and scenarios that assume people will respond to ecological degradation start to take social adaptation into account, ideally based on a stronger understanding of its causes and context-dependence.

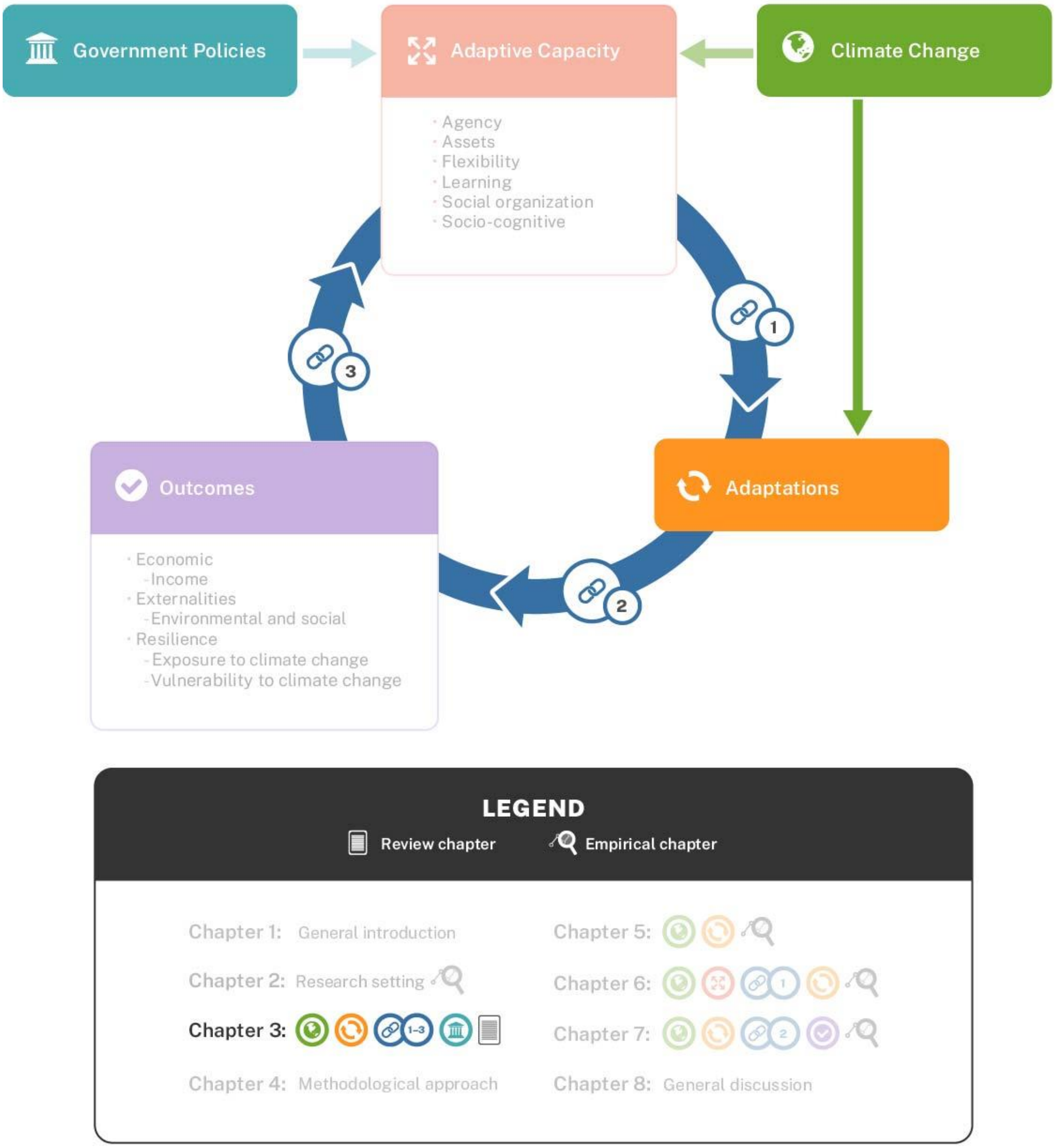
Chapter 3. Literature Review

Adapted from: Bartelet, H.A., Barnes, M.L., Cumming, G.S. (2022). Determinants, outcomes, and feedbacks associated with microeconomic adaptation to climate change. *Regional Environmental Change*, *22*, 59. https://doi.org/10.1007/s10113-022-01909-z

In my third chapter, I reviewed the empirical literature on microeconomic adaptation to climate change to develop a framework for the most common types of microeconomic adaptation and to synthesize the existing state of knowledge on the links between adaptive capacity, adaptation, and the outcomes associated with different adaptation strategies.

Figure 3.1

Research Gaps Addressed in Review Chapter 3



Note. The specific gaps that are addressed in this chapter include (1) common climate impacts; (2) common adaptation measures; (3) relationship between adaptive capacity and adaptation measures; (4) relationship between adaptation measures and their outcomes; (5) effect from adaptation outcomes on adaptive capacity; (6) common policies to facilitate adaptation.

Contributions

HB conceived the manuscript and developed the methodological approach with input from MB and GC. HB reviewed and synthesized the literature, ran the analyses and wrote the first draft. MB and GC helped write and revise the manuscript.

Abstract

Actors across all economic sectors of society will need to adapt to cope with the accelerating impacts of climate change. However, little information is currently available about how microeconomic actors are adapting to climate change and how best to support these adaptations. I reviewed the empirical literature to provide an overview of (1) the climate change adaptations that have been undertaken in practice by microeconomic actors (i.e. households and firms) and their determinants; and (2) the outcomes of these adaptations and the manner in which public policies have supported them. About a quarter of actors across the studies included in my review took no adaptation measures to climate change. Of those that did, the most commonly identified determinant of adaptation was assets, which were predominantly discussed as facilitating diversification within livelihoods. Few (14 out of 80) of the studies I reviewed which described empirical climate change adaptations evaluated the outcomes of these adaptations. Of those that did, evidence suggests that conflicts exist between the microeconomic outcomes of adaptations, social and environmental externalities, and long-term resilience. Different public policy interventions intended to support adaptation were discussed (53 in total); the provision of informational support was the most prevalent (33%). My analysis suggests that microeconomic adaptation occurs as a cycle in which social and ecological feedbacks positively or negatively influence the adaptation process. Thus, efforts to facilitate adaptation are more likely to be effective if they recognize the role of feedbacks and the potential diversity of outcomes triggered by public policy incentives.

3.1 Introduction

Here, I review empirical research over a 25 year period (from 1995–2020) to provide an overview of what is known about the *actual* adaptations made by microeconomic actors and their relationship to the private and public sectors, respectively. Specifically, I assess: (1) the kinds of climate adaptations that have been applied in practice by microeconomic actors (i.e., people and businesses) affected by climate change and the determinants of those adaptations, and (2) the outcomes of these implemented adaptations and the public policies that have supported them.

3.2 Methodology

Recent reviews have focused on how individuals and households respond to climate change risks, and most notably on identifying the psychological drivers of pre-emptive action to the expected effects of climate change (Bamberg et al., 2017; Hamilton et al., 2018; Koerth et al., 2017; van Valkengoed & Steg, 2019). Changes made in response to climate change impacts (whether experienced or predicted) can be considered an adaptive behaviour. I focused my review on the latter, i.e., the adaptive behaviour of microeconomic actors to experienced impacts of climate change. However, it should be acknowledged that adaptation to experienced impacts of climate change is often still anticipatory of the next expected climate impact. Even when individuals have been affected by a climate disturbance, their responses are often based on an acknowledgement that the disturbance was not an anomaly but rather a more permanent shift in conditions that will re-occur or continue to occur into the future. Therefore, responses could be argued to be anticipatory of that potential re-occurrence, rather than purely reactive, which can be classified as maladaptive in some circumstances given the nature of climate variability and change.

Ford and colleagues (Berrang-Ford et al., 2011, 2011; Ford et al., 2015) provided the last comprehensive reviews of adaptive behaviour to the experienced effects of climate change. They systematically reviewed peer-reviewed literature published in the period 2006–2009 dealing with adaptation efforts at a global scale (Berrang-Ford et al., 2011), in developed nations (Ford et al., 2011), and in Africa and Asia (Ford et al., 2015). These reviews focused on implemented adaptations by both private (i.e. microeconomic) and public actors. Here, I build on this important foundation by reviewing the literature focused on *implemented* adaptations to the experienced impacts of climate change *by microeconomic actors*, not those by governments or other institutions.

Recent reviews of microeconomic adaptation to the experienced effects of climate change have focused on particular sectors, e.g. small-scale fisheries (Green et al., 2021), and/or particular regions, e.g. Asian farmers (Shaffril et al., 2018). I aimed to review the academic and grey literature on microeconomic adaptation to climate change over a longer period of time than has previously been studied, enabling us to provide a snapshot of key studies and concepts within the field. The time frame I chose for my sample was 1995 to 2020. I began in the year 1995 because the following year saw one of the first key empirical studies published on microeconomic adaptation to climatic change (Smit et al., 1996). I scoped different review approaches to address my research aims. Due to my chosen time period, it was not feasible to do a systematic review using general search terms, which are typically focused on shorter periods of time. For example, a search process in Web of Science using the search terms: ‘‘climat* chang*’’ AND ‘‘adapt*’’ (Berrang-Ford et al., 2011) for the time period 1995–2020 identified some 52,000 papers. Instead, my research aim was more suited towards a systematic search and review, which combines the strength of a comprehensive search process with those of a critical review to address broad questions in order to produce the best evidence synthesis (Grant & Booth, 2009). I chose to use Google

Scholar (GS) because of its greater breadth of grey and interdisciplinary literature than other alternatives. This process helped us to identify a World Bank paper (Maddison, 2007) that was a key initiator of many subsequent academic studies on climate change adaptation. GS was also found to be a more comprehensive database for social science papers as compared to Web of Science (Kousha & Thelwall, 2007).

Table 3.1 gives an overview of the inclusion and exclusion criteria that were used for my systematic search and review.

Table 3.1

Inclusion and Exclusion Criteria for my Critical Review Process

Inclusion	Exclusion
Phase 1: Keyword search	
English	Non-English
Time period: 1995–2020	Pre-1995 or post-2020
Retrievable through Google Scholar database	Non-retrievable through Google Scholar database
Phase 2: Abstract and methodology review	
Human system adaptation	Natural system adaptation
Empirical evidence of actual implemented adaptations to the experienced effects of climate change	Papers focused on attitudes and intentions towards adaptation, and/or the discussion of potential adaptation options
Adaptation by microeconomic actors (i.e. households and firms)	Adaptation by public actors (i.e. governments)

My review process was performed through the different stages outlined in Table 3.2 and was as exhaustive as possible.

Table 3.2

Overview of Literature Review Process

	Method	Results
Step 1	Search GS database using "climate change" in conjunction with the additional terms: "actual adaptation" (1050 results), "implemented adaptation" (832 results), "adaptive response" (17600 results), "adaptive behaviour" (3550 results), "adaptive action" (2710 results), and "adaptation outcome" (1350 results) for the time period 1995–2020.	54 papers
Step 2	Search GS database using a more general search with the terms "adaptation" AND "climate change," which came up with over 2 million hits. I filtered these results by year to identify relevant papers that had not yet been picked up in step 1.	13 papers
Step 3	Search within identified papers through steps 1 and 2 for relevant cited papers that had not yet been picked up in my review (i.e. cross-referencing).	10 papers
Step 4	Search in the databases of recent reviews on adaptation to climate change (van Valkengoed & Steg, 2019), flooding (Bamberg et al., 2017), wildfires (Hamilton et al., 2018), and sea level rise (Koerth et al., 2017) to identify relevant papers that had not yet been picked up in my review based on my inclusion criteria.	3 papers

Note. 'Results' indicate the number of papers reviewed following the inclusion and exclusion criteria described in Table 3.1.

For each search term I reviewed the first 100 results because the GS retrieval algorithm ranks the papers according to the importance of their citations. Though citations are not a perfect measure of importance, the beginning of GS search results are argued to largely pick up the most relevant studies for a critical review (Chen et al., 2007). Overall, I reviewed some 3000 papers. Most of the papers returned through this search process focused on attitudes and intentions towards adaptation, and/or the discussion of potential adaptation options, but did not contain empirical evidence of actual, observed or stated adaptations. I did not include these papers as I was looking only for empirical evidence of actual implemented adaptations by microeconomic actors. The 80 papers that were identified were widely dispersed amongst different journal outlets. Specifically, I identified publications in more than 50 different scientific journals, reducing the probability of bias due to publication outlet in the results.

The selected papers were critically evaluated based on theoretical gaps that have been identified with regards to microeconomic adaptation to climate change, as referred to in the introduction. These theoretical gaps include:

1. A lack of knowledge on adaptation to experienced effects of climate change rather than potential or preventive adaptations (Barnes et al., 2020; Berrang-Ford et al., 2011).
2. Adaptive capacity as proxy for adaptation is poorly understood (Barnes et al., 2020; Green et al., 2021; Mortreux et al., 2020; Mortreux & Barnett, 2017), in particular the multidimensional character of adaptive capacity (Cinner & Barnes, 2019; Mortreux & Barnett, 2017).
3. Discussion of the broader outcomes of adaptation should be considered in evaluating the success of adaptation, rather than taking a binary approach (Adger et al., 2005; Doria et al., 2009).
4. Government policies to facilitate adaptation by microeconomic actors are understudied (Fankhauser, 2017).

I first recorded the type of climatic impacts to which the microeconomic actors adapted. I did not find an applicable microeconomic adaptation categorization framework in literature, and thus I developed my own categorization of adaptive behaviour based on the empirical evidence found in this review. To understand the determinants of adaptation, I classified factors that were identified as facilitating adaptation using the different domains of adaptive capacity described by Cinner and Barnes (2019).

I evaluated whether the reviewed papers discussed any outcomes of the adaptations by microeconomic actors and classified them according Doria et al's (2009) definition in terms of economic outcomes, externalities, and resilience. For economic outcomes, I looked for any evidence of the impact of adaptive behaviour on indicators like productivity, income and yields. For externalities, I looked for social and environmental consequences as a result of the implemented adaptations. This could, for example, include impacts on natural capital or public health. For resilience, I looked for evidence of the adaptations on the actors' exposure and vulnerability to future climate change. Focusing on the outcome categories proposed by Doria et al. (2009), I did not evaluate normatively positive outcomes of adaptation such as social identity and attributes of cultural importance.

Finally, I identified whether the reviewed papers included the effects of government policies to facilitate microeconomic adaptation and whether these policies had a positive or negative effect on adaptation. I classified adaptation policies in a number of broader policy categories. I did not find an applicable microeconomic adaptation policy categorization framework in literature, and thus I developed my own categorization of policies based on the empirical evidence found in this review.

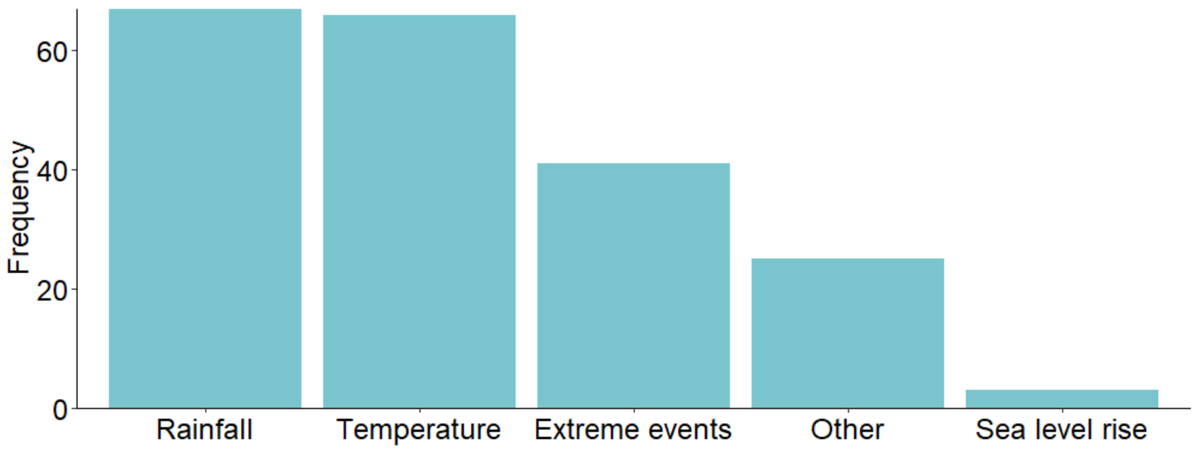
3.3 Results

3.3.1 Microeconomic Adaptations to Climate Change

A majority of the papers identified in my review were written post-2007, following two major publications on climate change adaptation. First, the release of a large-scale study by the World Bank (Maddison, 2007) on adaptation to climate change in Africa. This report remains the most cited publication about empirical adaptation to climate change, and many of its methods and recommendations have been used in later studies. Second, in the year 2007 the IPCC's Fourth Assessment Report was published that formally evaluated the status of climate change adaptation research and practice (Orlove, 2022; Schipper, 2006). Almost half of all studies included in my review took place on the African continent. 29% were in Asia, 12% in South America, 7% in Europe, 6% in North America, and 1% in Australasia. Case studies were most frequently from Bangladesh (12), South Africa (8), and Ethiopia (7). The majority (72 out of 80) of the empirical studies I identified were focused on farmers. Other microeconomic actors featured in this body of literature included fishers, tourist operators, urban dwellers, hunters, and pastoralists. Gradual changes in precipitation and temperature were the most frequently experienced climate impacts by the microeconomic actors in the papers I reviewed (Figure 3.2).

Figure 3.2

Categorization of Climatic Impacts to Which Microeconomic Actors Adapted, Based on a Total of 202 Climate Impacts Featured in the 80 Reviewed Papers



Note. Extreme events include droughts (14), floods (13), (undefined) extreme weather (6), storms (3), coral bleaching (1), and cold spells (1). Other includes wind, radiation, soil salinity, biomass productivity, access to coastal resources, weed/insect pressure, disease from water shortage, crop disease, heat stress, loss of nutrients in waterways, sickness of fish, water temperatures, glacial shrinkage, rock fall, and delayed monsoon onset. Rainfall and temperature include gradual trends in land-based climate. Sea level rise includes coastal erosion.

3.3.1.1 Empirical Evidence for Microeconomic Adaptations, Determinants, and Outcomes. About two-thirds (50 out of 80) of the papers in my dataset explicitly assess the ability of microeconomic actors to perceive historical climate change that affected them, although different time horizons are used in the studies. In those 50 papers, the majority of respondents perceived climate trends that corresponded with climatic data records. In all papers in my review, I have attempted to explicitly identify adaptive behaviours linked to the impacts of climate change, although it must be acknowledged that microeconomic decisions are made on the basis of a myriad of interwoven pressures (e.g. including changes in markets and demographics). For the microeconomic actors identified to have been affected by climate change, diversification (within livelihoods) was the most common measure of adaptation, followed by changes in the mode of operating and the management of natural resources (Table 3.3). Measures to protect livelihoods were the least common, and this category includes both ecological measures (e.g. planting trees) and financial measures (e.g. taking up insurance).

Table 3.3

Categorization of Microeconomic Adaptation Measures

Adaptation category	Definition	Frequency	Example
Div. WL	Diversification within livelihoods	96	Crop type
MO	Changes in mode of operating	83	Harvesting dates
NRM	Natural resource management	80	Water conservation
Div. BL	Diversification between livelihoods	40	Off-farm activities
Relief	Reduction of immediate impact	37	Selling livestock
Protection	Protection of livelihoods	34	Planting trees

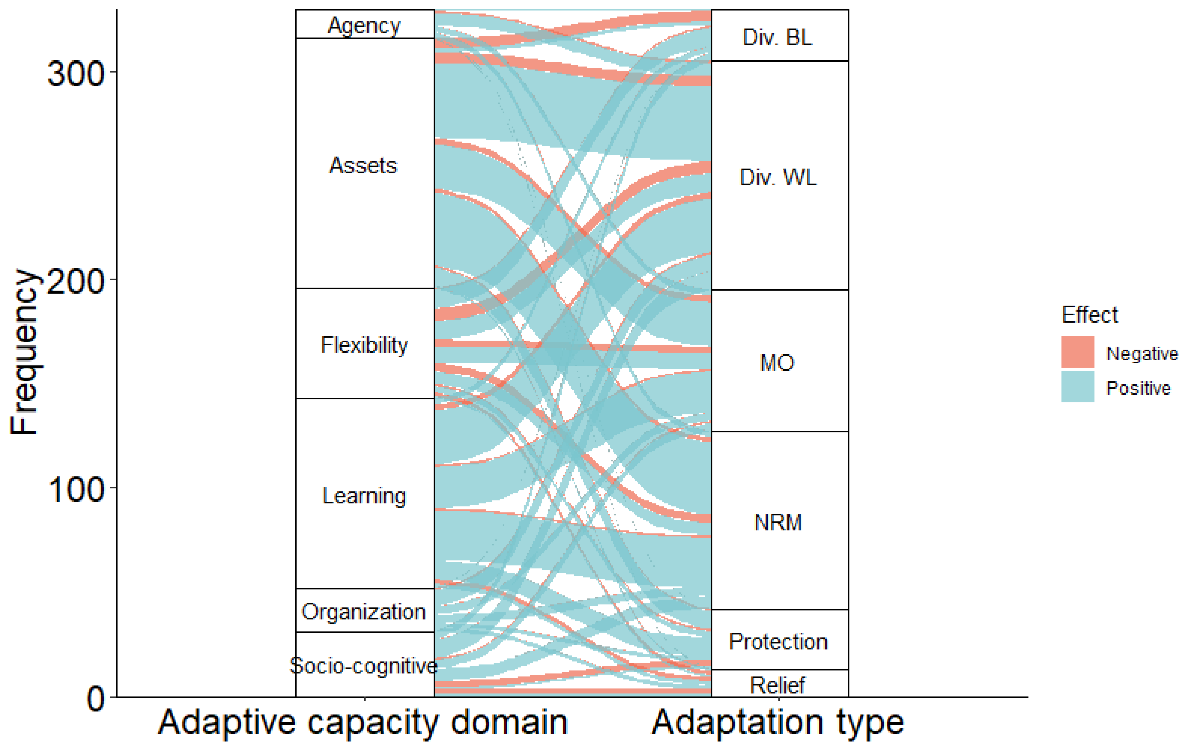
Note. Based on a total of 370 adaptation measures featured in the 80 reviewed papers. Div. BL includes off-farm activities, migration, and switching to wage labouring. Div. WL includes changing crop types and varieties, livestock (and feed) types, and firm location. MO includes changing harvesting dates and seasonality, land use (e.g. switching to dual land use, mixed cropping etc.), crop rotations, changing crop inputs, and other farm and crop management. NRM includes water conservation, soil conservation, irrigation, fertilizer use, reforestation and land improvements. Protection includes planting trees for shading and sheltering, building sea walls, land elevation, using pesticides, artificial drains, ventilation against heat and the use of risk management (e.g. risk sharing, crop insurance, etc,). Relief includes selling livestock, seeking social and financial support, relying on savings, reducing consumption, crop storage, prayer, changing diet, and intercommunity trade.

About a third (26 out of 80) of the papers in my dataset provided a quantitative estimate of the percentage of microeconomic actors that did not implement *any* kind of adaptation. The average non-adaptation rate was 26% (σ=22%). Based on the 11 papers that provided a quantitative estimate for both the percentage of actors that do not perceive climate change and the non-adaptation rate, it appears that most actors that do perceive climate change are implementing at least some kind of adaptation. In these papers the average percentage of actors that did not perceive climate change was 20% (σ=10%), and the average percentage of actors that did not undertake any adaptation was 22% (σ=15%). In the following section I will focus on the determinants of adaptations, under the assumption that most actors that *do* perceive climate change (and thus are likely to be affected by it) *will* at least implement some kind of adaptation.

The determinants of the different adaptation categories, as identified and discussed by the authors of the papers included in my review, were clustered within the adaptive capacity domains proposed by Cinner and Barnes (2019). Here I have included those factors that were identified and/or discussed as having a statistically significant effect on the implementation (e.g. positive) or non-implementation (e.g. negative) of specific adaptation measures (Figure 3.3).

Figure 3.3

Categorization of Determinants for Individual Microeconomic Adaptation Categories, Based on a Total of 330 Determinants Featured in the 80 Reviewed Papers



Note. This figure shows which indicators within one of the adaptive capacity domains have been found to have a significant effect on the likelihood of implementing a particular kind of adaptation measure. It includes evidence only from studies that have analysed the relationship between adaptive capacity and individual adaptation measures. In this case, agency includes land ownership and joint decision-making power. Assets include land availability (e.g. farm size), labour availability (e.g. household size), income, savings, access to credit, and water availability. Flexibility includes access to markets, soil fertility, alternative livelihood options (e.g. low dependency on particular livelihood), younger age, diversity of skills, elasticity of market demand, and access to electricity and digital technologies. Learning includes education, access to extension services, local knowledge (e.g. farming experience), access to weather/climate information, and knowledge about advanced adaptation measures. (Social) organization includes social networks, association membership, and government support. Socio-cognitive constructs include prior experience with climate change, (high) attitude to risk, (low) place attachment, (high) trust in government/NGOs/traders, attitude towards innovation, perceived easiness of adaptation, and perception of future climate change.

Assets and learning were the most common determinants of adaptation measures identified in my review, followed by flexibility. Assets and learning were both identified as being strongly, positively related to the implementation of adaptations to diversify within livelihoods as well as adaptations related to natural resource management. Flexibility appeared to be the most frequently identified determinant of adaptation to diversify between livelihoods. Having assets was described as decreasing the likelihood of making livelihood changes. Overall, the domains of agency, (social) organization, and socio-cognitive constructs were less commonly identified as determinants of adaptation measures in the studies I reviewed. This may partly be explained by there being fewer papers that considered factors that fit within these domains.

Few of the reviewed papers (14 out of 80) evaluated the outcomes of implemented adaptations as a measure of the success of the adaptation process. Only three studies (Abid et al., 2016; Gorst et al., 2018; Khanal et al., 2018) were explicit and quantitative about adaptation outcomes on a micro level. They found a positive impact from adaptation on crop yields. However, taking a wider definition of outcomes, based on Doria et al.'s (2009) definition of successful adaptation, I found some evidence for potential negative adaptation externalities on social and environmental sustainability and resilience (Table 3.4).

Table 3.4

Multidimensional Outcomes of Microeconomic Adaptations

Category	Adaptation	Microeconomic	Externalities	Resilience	Source
Div. WL	Crop type	Higher returns per unit area of land		Susceptible to future CC	(Kabir et al., 2017); (Manandhar et al., 2011)
	Crop variety		Conserves water resources	Increases resilience	(Antwi-Agyei et al., 2018; E. M. Biggs et al., 2013b)
Div. BL	Migration	Decreases farm productivity		Reduces vulnerability	(Antwi-Agyei et al., 2018; E. M. Biggs et al., 2013a)
	Off-farm employment	Decreases farm productivity; lower gross income per workday			(Gorst et al., 2018); (Kabir et al., 2017)
MO	Integrated farming			More resilient to severe CC	(Seo, 2010)
NRM	Irrigation	Increases farm productivity	Resource depletion (water)		(Antwi-Agyei et al., 2018; Gorst et al., 2018; Laube et al., 2012; Udmale et al., 2014)
	Organic farming	Lower crop production	Soil conservation; deforestation		(Antwi-Agyei et al., 2018)
	Mulching	Higher crop yields		Increases resilience	(Antwi-Agyei et al., 2018)
Protection	Pesticides		Pest resistance		(Manandhar et al., 2011)

Relief	Reducing consumption /utilizing savings			Increases vulnerability	(Hisali et al., 2011)
	Selling livestock	Increases short-term income		Increases vulnerability	(Antwi-Agyei et al., 2018)
	Reducing food consumption	Increases income from selling food	Health consequences	Increases vulnerability	(Antwi-Agyei et al., 2018)

Note. Based on a total of 25 outcomes featured in the 80 reviewed papers. Papers that mentioned outcomes of particular adaptation measures in terms of physical or financial outputs are classified under microeconomic. Non-economic outcomes that might extend beyond the microeconomic actor are classified under externalities. Outcomes in terms of exposure or vulnerability to future climate change (CC) are classified under resilience.

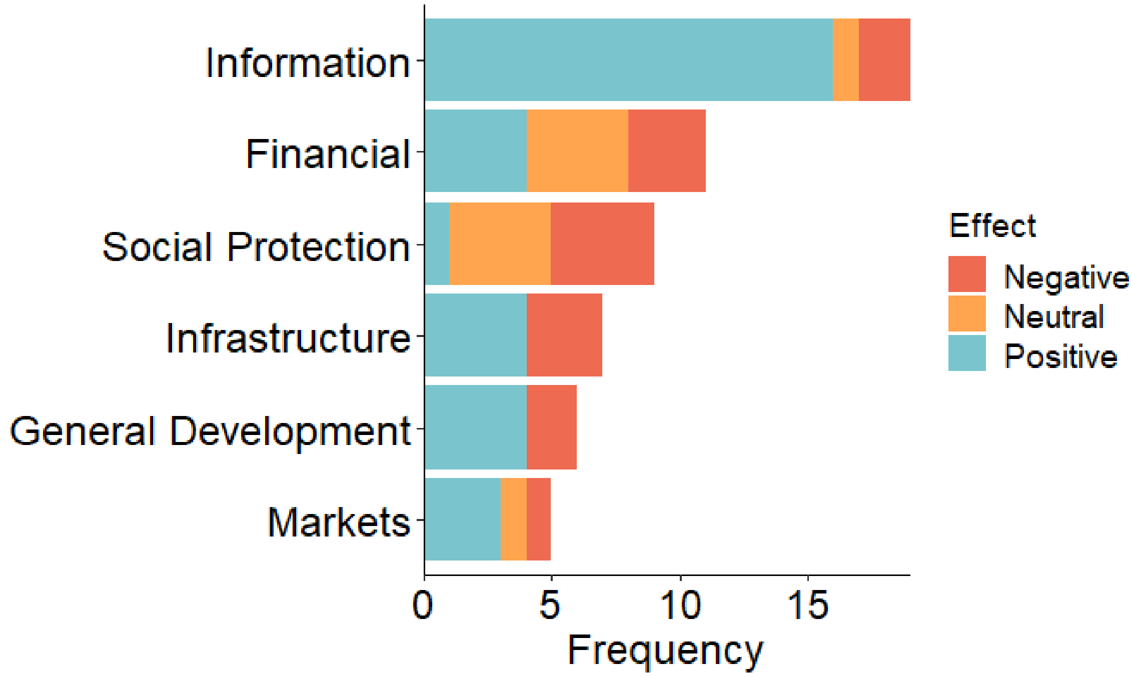
For example, there was evidence that adaptions involving the use of irrigation and organic farming lead to groundwater depletion and deforestation, respectively. Adaptations such as crop switching and selling livestock were also linked to potential increases in vulnerability to future climate change impacts. On the other hand, switching to stress-resilient crop varieties, mulching, and integrated farming were found to increase a microeconomic actor's resilience.

3.3.2 Private and Public Responsibilities

3.3.2.1 Empirical Evidence for Public Interventions and Their Impact on Adaptation. About 40% of the reviewed papers (29 out of 80) discussed how interventions and policies by government and/or NGOs have influenced the adaptation process. Support in the form of information was the most frequently discussed intervention, followed by financial support and social protection (Figure 3.4).

Figure 3.4

Most Frequently Mentioned Public Interventions Affecting Microeconomic Adaptation to Climate Change, Based on a Total of 53 Interventions Featured in the 80 Reviewed Papers



Note. Financial includes farm support, (micro) credit, and subsidies (water, fuel and fertilizer). General development includes general economic development, job programs, land-use policies, and access to electricity. Information includes extension advice, technology-linked support, agro-forestry, seasonal forecasts, and communication networks. Infrastructure includes infrastructure support, for example drainage systems. Markets includes market access and deregulation. Social protection includes social protection schemes, crop insurance, and food aid.

Importantly, a majority of reviewed papers looked at whether the policies had a positive effect on the likelihood of implementing *any* adaptation. Therefore, there was often no discussion on the qualitative nature of the adaptations, e.g. whether government intervention led to adaptations which could be deemed more successful in achieving specific outcomes.

Among the studies included in this review that did evaluate the outcomes of adaptation, providing information and technical advice had the most positive effect on the likelihood that the actors would implement any kind of adaptation. This seems intuitive as many such interventions directly recommend particular adaptation measures. Policies aimed at general economic development and market liberalization also had a positive effect in the majority of cases where these strategies were implemented. My review suggests that general economic development may come with a trade-off, as it was found to give farmers more flexibility and choice on how to adapt given local circumstances (Mertz et al., 2009), but might not be sufficient in regions where the affected industries, such as farming, are already considered as weak and might require more direct support (Deressa et al., 2011).

I found conflicting evidence for the efficacy of a number of other government interventions. Infrastructure support had a positive effect in half of the cases I reviewed that examined adaptation outcomes. Negative effects of infrastructure support related to inequity (e.g. the infrastructure did not benefit all actors equally) (Barbier et al., 2009; Udmale et al., 2014), unreliability (Udmale et al., 2014), and increased vulnerability as compared to informal infrastructure (Laube et al., 2012). Financial support in the form of access to credit and direct financial support had a mostly positive effect on adaptation. Subsidies had a mostly neutral or negative effect, because of unreliability (Gandure et al., 2013) and overdependence on the support (Fosu-Mensah et al., 2012). However, fuel subsidies had a favourable impact on the use of irrigation pumps in one case (Sarker et al., 2013).

For social protection measures, when implemented, there was little evidence of a positive effect on adaptation. In the case of food aid, there were, as with other interventions, concerns about inequity (Barbier et al., 2009) and overdependence (Belay et al., 2017). Crop insurance was deemed to subsidize inaction on the part of the microeconomic actor (Mase et al., 2017).

3.4 Discussion

Based on my review of key empirical studies on microeconomic adaptation to the experienced effects of climate change from 1995–2020, I found some important gaps as compared to theoretical discussions on adaptation. First, I found that most adaptation studies remain focused on potential adaptation to future climate change rather than actual adaptations to the experience impacts of climate change. I did not review related research on ‘preparedness’ for climate change, ‘intentions to adapt,’ and ‘stated adaptive choices’ when faced with climate scenarios. As a recent review on preparedness for climate change (van Valkengoed & Steg, 2019) showed, most studies focusing on responses to forecasted ‘climate risks’ take place in OECD countries. My contrasting results which show that the majority of studies on actual adaptive behaviour by microeconomic actors focus on actors in Africa and Asia could mean that while OECD countries are largely in the preparing phase for climate change, microeconomic actors in non-OECD countries are already affected by actual climate change effects and thus have already begun to adapt (in contrast to ‘intending’). Non-OECD countries also generally have a higher share of households working in primary industries, such as farming, that may be more directly impacted by climate change (Nordhaus, 2013). This may help to explain why most (72 out of 80) of the empirical studies I identified that focused on microeconomic adaptation to the experienced effects of climate change were focused on farmers.

A recent review on responses to forecasted climate risks by the general (urban) public found that adaptive action consisted mainly of protective measures, such as taking up insurance and relocation/evacuation (van Valkengoed & Steg, 2019). While urban households may be mostly affected by the impacts of extreme climate events, rural households are affected by a wider range of climate impacts (see Figure 3.2), as their livelihoods tend to be directly dependent on natural resources (and the effects of climate on the output of these resources). Therefore, given that the vast majority of published papers discussing implemented microeconomic adaptations focus on African and Asian farmers to changes in temperature and precipitation, I find a wider range of adaptive behaviours to climate change impacts as compared to studies focused on urban households. I thus classified adaptations with a slightly different scheme, using six categories that reflect the actual implemented adaptations made by microeconomic actors at both short and long-term scales (Table 3.3).

Innovation can play a key role in adaptation (Westley et al., 2011), and I find it dispersed over different adaptation categories. For example, it occurred in natural resource management (irrigation, mulching, agrochemical use), diversification within livelihoods (climate-resistant crop varieties), mode of operating (mixed cropping, mechanization), and protection (pesticides, artificial drains, sea walls). Migration was part of my "Diversification between livelihoods" adaptation category, which was the fourth most frequent in my review. It is interesting to note that within this category, migration related to one or multiple people within the households migrating to diversify income streams. Notably, given that I study adaptation to the experienced effects of climate change (rather than potential or planned adaptation), if a full household had decided to migrate, the empirical papers would likely not have been able to capture this as an adaptation as the household would not be a part of the sample population anymore. Thus, this adaptation category might be underestimated.

My findings shed some further insights into the complex relationship between adaptive capacity and adaptation (Barnes et al., 2020; Green et al., 2021; Mortreux & Barnett, 2017). Most notably I found that factors related to the adaptive capacity domains of 'assets' and 'learning' were significant predictors of adaptations to diversify within livelihoods and natural resource management. However, the limited number of studies that included factors related to the (social) organization and socio-cognitive domains is a limitation of the current empirical evidence. A recent study found that social organization was an important determinant of transformative adaptation for coastal households (Barnes et al., 2020).

Most of the empirical papers identified in my review did not include an evaluation of the adaptation outcomes. In the papers that did assess outcomes, I found some evidence for trade-offs between different outcome categories (e.g. economic vs. environmental), which point towards an avenue for further study. A discussion of the broader outcomes of adaptation should be considered in evaluating the success of adaptation, rather than taking a binary approach (Adger et al., 2005; Doria et al., 2009).

Finally, my results provide some initial evidence on the effectiveness of different government policies to facilitate adaptation by microeconomic actors (Fankhauser, 2017). Currently, providing information and technical advice is the most common intervention discussed in existing empirical studies (Figure 3.4). While most papers conclude that this policy has a positive effect on adaptation, I identified three reasons why it may not. First, it will be necessary to understand the outcomes of the kinds of adaptations that are advised by external actors, and whether they incorporate enough knowledge about local environmental conditions. Second, the effect of extension activities on microeconomic actors' adaptive capacity should be evaluated to see whether interventions help to build the capacity to respond to future impacts, rather than creating dependence on external advice. Third, decades of psychological research have shown that information provision is not sufficient to promote behavioral change (Arnott et al., 2014; Sims & Baumann, 1983; Varotto & Spagnolli, 2017). Although informational strategies might not be effective to overcome socio-cognitive barriers to adaptation, they might be effective in terms of educational barriers. We therefore require further knowledge about the effect of specific government policies on the different domains of adaptive capacity, rather than assessing only the binary effect on adaptation (i.e., adaptation or not). Other common policies are focused on increasing assets, for example through farm support, (micro) credit, and subsidies. Although access to assets was identified as the most common determinant of different adaptation measures, there is little evidence for a positive impact from asset-focused policies on adaptation. Conflicting evidence was found for other interventions such as infrastructure, and some (e.g. crop insurance) were found to promote adaptations that might reduce microeconomic actors' resilience in the long-term.

3.4.1 Adaptation Feedbacks

I found evidence for some adaptation feedbacks in the papers considered in this review. For example, in one paper, migration of labour (adaptation) was found to cause a reduction in social cohesion (outcome), which in turn reduced the strength of social networks (adaptive capacity) which are beneficial for sharing best practices and organizing collective action (Berman et al., 2015). Another study found that an ineffective response to climate change led to high damage costs (outcomes) which reduced financial assets (adaptive capacity), thereby leaving microeconomic actors less able to invest in adaptation to future impacts (Brouwer et al., 2007).

Feedbacks might also be helpful in explaining differences between adaptation to experienced climate change, the focus of this review, and adaptation to expected climate change (e.g. climate risks) (Bamberg et al., 2017; Hamilton et al., 2018; van Valkengoed & Steg, 2019). Cognitive factors, such as trust in governments, beliefs and attitudes towards climate change, and adaptation confidence might be a significant barrier for preparatory responses. It is possible however that cognitive factors may be less prone to impede adaptation by people that are already experiencing climate change impacts (Barnes et al., 2020). Actors that do not take preventive action might be more heavily impacted by actual climate change (i.e. high damage cost), which reduces their financial assets, as discussed earlier. The impacts from climate change as experienced by microeconomic actors are also likely to have an impact on their socio-cognitive constructs, at least in terms of the perceptions about the reality and severity of climate change (Truelove et al., 2015). On the other hand, investing in preventive action comes at a cost and impacts microeconomic outcomes now, while also creating sunk costs and potential lock-ins, which might give the actors less flexibility to respond in the future.

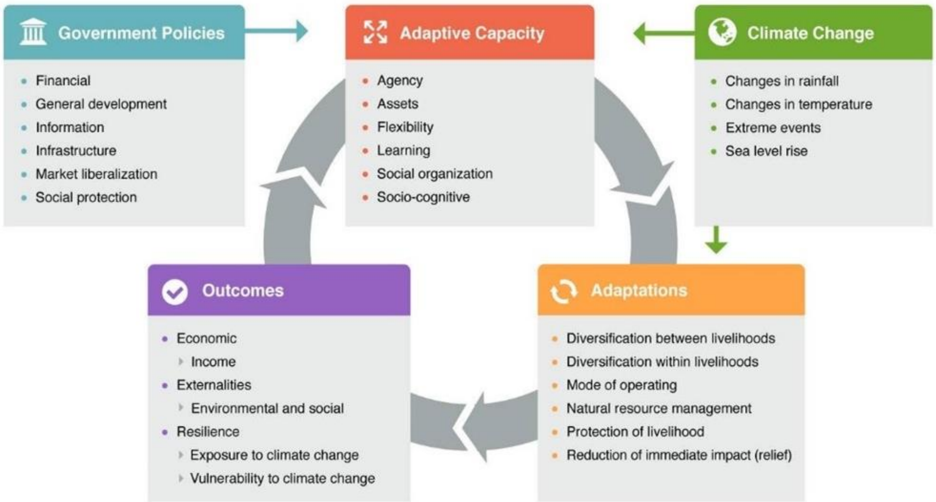
Environmental feedbacks can also affect the adaptation cycle. For example, farmers might respond to reduced rainfall by increased use of irrigation, which could improve overall farm productivity (Gorst et al., 2018). However, in this example, a negative externality occurred in terms of depletion of water resources (Gorst et al., 2018), which can decrease the available water (assets) for future use and adaptation to further reductions in rainfall (Antwi-Agyei et al., 2018; Laube et al., 2012; Udmale et al., 2014). Adaptations to switch to drought-resistant crop varieties, on the other hand, can reduce water use, thereby having the opposite effect (Antwi-Agyei et al., 2018). This raises the question as to what extent positive environmental externalities linked to some adaptation measures can compensate for potential lower benefits in microeconomic terms.

I previously discussed how flexibility on a micro response level provides microeconomic actors with options to adapt to climate change in ways that can improve their resilience, e.g. through switching between livelihood options. On a larger scale, such as the industry or community level, diversity in responses of individual actors has been argued to increase resilience (S. R. Carpenter et al., 2012; De Vos & Cumming, 2019; Ember et al., 2020; Grêt-Regamey et al., 2019). This macro response diversity could be measured by looking at the diversity in adaptations that are implemented. A counter argument could be made that some of the “best” adaptation measures might require cooperation between microeconomic actors, and thus a lower response diversity. Examples would include the building of protective infrastructures, reforestation, and/or land elevation. Such adaptation would be strongly linked to the adaptive capacity domain of social organization. Social organization can enable the collective (lobbying for) funding required for high-cost adaptation solutions (Nunn & Kumar, 2019). For such collective adaptations, it might become more efficient to switch from private to public responsibility.

A better understanding of the dynamic complexities and feedbacks within the adaptation process will provide key insights for policy making (Eisenack et al., 2014). Interventions to foster successful adaptation to climate change should take account of adaptation cycle dynamics and conflicting interests between microeconomic outcomes, social and environmental externalities, and resilience. Microeconomic outcomes, through their effect on savings, have proven to be a key enabler of adaptation. They are likely the first concern for microeconomic actors. However, the market might not automatically promote adaptations that have positive outcomes for social and environmental externalities and resilience. Economic incentives could promote adaptations with negative environmental outcomes, particularly in the case of common-pool resources and ecosystems. Government intervention might be required to give sufficient value to vital ecosystem services. To foster resilience, government-provided crop insurance or other social protection measures might reduce the incentive for microeconomic actors to take actions to protect against extreme climate events. Overall, I thus identify a strong need to recognize the temporal and spatial complexities involved within the microeconomic adaptation process, and the potential problems of interventions for which the effects on adaptation feedbacks are poorly understood (Figure 3.5).

Figure 3.5

Conceptual Framework: Microeconomic Adaptation to Climate Change



Note. This figure describes the inter-dependent relationships and consequential linkages between adaptive capacity, adaptations, outcomes, and government policies. Adaptive capacity domains adapted from Cinner and Barnes (2019), outcome indicators derived from Doria et al. (2009). Adaptation categories from my synthesis of empirical literature. Government policies here are only those that facilitate microeconomic adaptations. Policies that are directly implemented by governments are not a part of the microeconomic adaptation process. The type of climate change and its severity are seen here as a mediating factor on the kind of adaptations that are implemented.

3.4.2 Limitations

Here I provided a snapshot of key empirical studies, published between 1995 and 2020, on microeconomic adaptation to the experienced effects of climate change. Given the sheer volume of potential studies over this period (i.e. 52,000 papers), I focused my search strategy on picking up the most relevant studies for a critical review. For feasibility reasons, I therefore chose to conduct a systematic search and review of key empirical papers on microeconomic adaptation to climate change, rather than a systematic review of all 52,000 papers. This strategy is not without its limitations. While this methodological decision would have inevitably resulted in potentially relevant papers being missed, my search process within the constraints I operated within was comprehensive (Table 3.1 and Table 3.2), and I minimized any potential bias towards older publications (which would likely be more highly cited) by doing a separate search for each of the years in my sample period. I also checked for any additional relevant papers that had been missed using cross-referencing (Table 3.2, Step 3), and reviewed every paper referenced in all recent reviews on adaptation to climate change and were sure to include them (Table 3.2, Step 4). Though these steps surely helped to ensure I covered as much ground as was feasible, it is still possible that I missed key information regarding novel adaptation strategies discussed in less well known (and less cited) papers. My findings should thus not be considered as exhaustive.

3.4.3 Implications for Practice

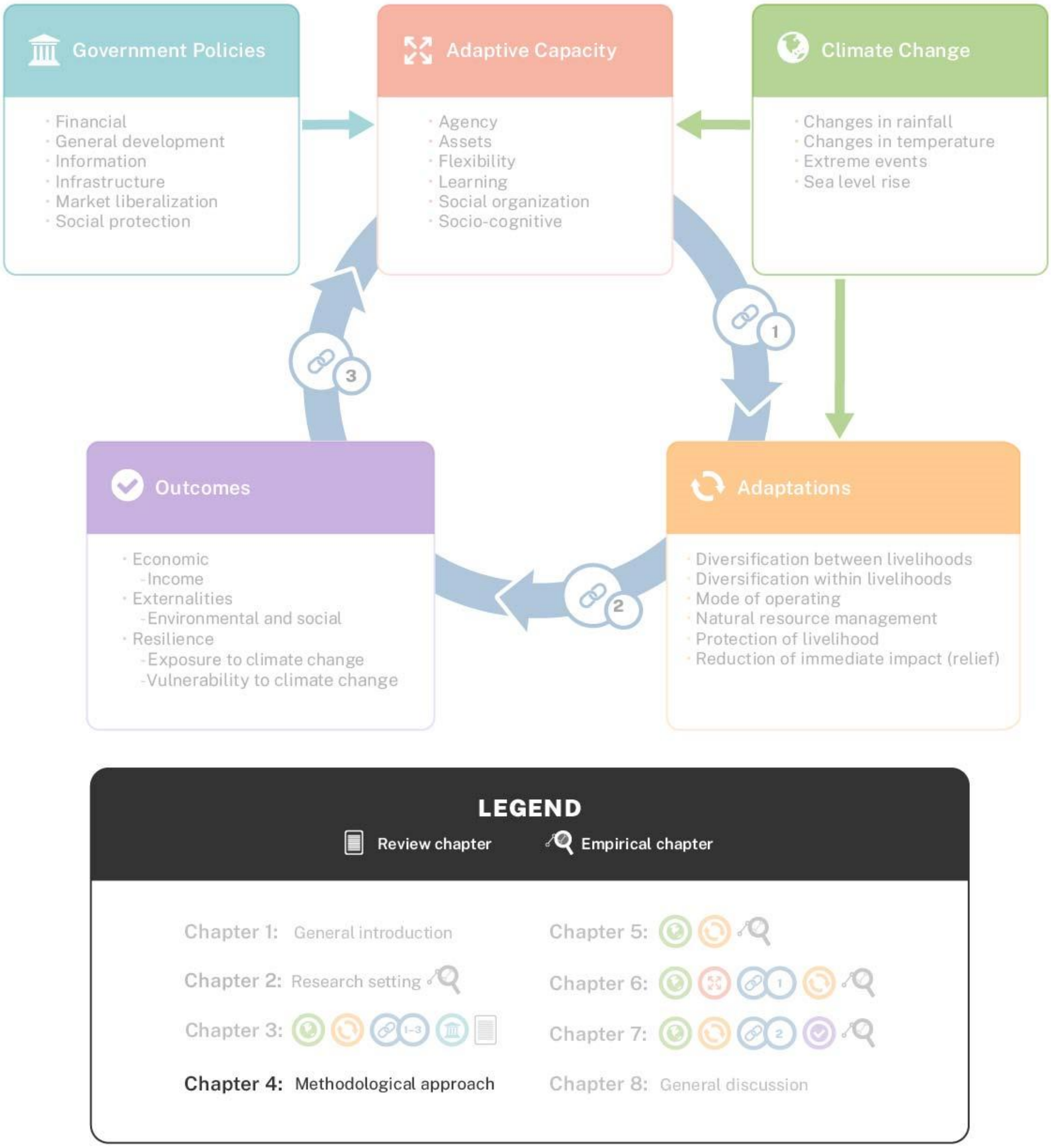
My analysis of key empirical papers on microeconomic adaptation to climate change provides some important implications for practice. First, I find that the large majority of papers that I reviewed studied potential and/or intended adaptation rather than actual adaptation. With climate change already impacting human communities, more empirical evidence is needed to understand adaptation to the experienced effects of climate change. Second, based on my clustering of the initial evidence of relationships between adaptive capacity and adaptation (Figure 3.3), there seems to be a bias in empirical literature towards the adaptive capacity domains of 'assets' and 'learning.' Recent evidence has found that '(social) organization' and 'socio-cognitive' constructs might be critically important domains of adaptive capacity (Barnes et al., 2020; Mortreux & Barnett, 2017). Most adaptation support programs are focused on increasing assets and flexibility (Cinner et al., 2018; Lemos, 2007), and without considering the other domains integrally, this might limit their effectiveness. Third, my findings reveal the need to better track the outcomes of adaptations. Most empirical studies on adaptations currently evaluate adaptation in a binary way (i.e., adaptation or not), rather than evaluating the diversity of adaptive responses and what outcomes are produced by particular adaptation strategies. Similar to adaptive capacity, adaptation outcomes should be evaluated in a multidimensional way. Fourth, most empirical papers evaluate policies to facilitate microeconomic adaptation in a binary way, whether they increase the likelihood of adaptation. However, for policy makers, it will be necessary to understand whether their policies lastingly increase the adaptive capacity of their communities and economies to respond to future changes in climate (and other impacts). More studies are required to evaluate the impact of government policy on adaptive capacity and whether it influences these domains of adaptive capacity that are most likely to lead to successful adaptation strategies by microeconomic actors. Empirical studies that take into account the feedbacks between adaptive capacity, adaptation, outcomes and policies could help untangle some of the complex interdependencies involved in the (microeconomic) adaptation process (Eisenack et al., 2014).

Chapter 4. Methodological Approach, Study Sites, and Data Collection

In my fourth chapter, I present the methodological approach, study sites and data collection protocol that I used for my consequent data chapters on adaptation to climate change by reef tourism operators in the APAC Region.

Figure 4.1

Methodological Approach for Empirical Data Chapters on Reef Tourism Adaptation to Severe Climate Disturbances



4.1 Research Approach

My research approach is deductive, aiming to test the conceptual model I developed about the dynamics of microeconomic adaptation (Figure 1.2 and Figure 3.5). My research adopts a positivist perspective and is primarily quantitative, with data being obtained through research surveys with reef tourism operators. A quantitative approach was chosen because I had a strong *a priori* indication of the variables of interest, for example the types of adaptive responses, the adaptive capacity domains, and the outcome indicators. Using a survey approach helped me to gather a relatively larger sample size that was needed for the statistical analyses. In particular in terms of adaptive capacity, I wanted to include multiple indicators for each of the six domains of adaptive capacity, as well as using some contextual factors, and therefore I required a sample size of at least around 180 reef tourism operators. My data collection efforts were affected by the COVID-19 pandemic, which started in April 2020. As a result, I switched from in-person to online surveys with reef tourism operators.

In **Chapter 5**, I first focused only on Australian reef tourism operators, as a case study focused on understanding whether the adaptive response categorization based on other microeconomic actors (Table 3.3), was applicable to the reef tourism industry. **Chapter 5** is also a direct answer to some of the hypotheses posited in **Chapter 2**, for example whether GBR tourism operators changed their reef sites in response to coral bleaching. In **Chapter 6** and **Chapter 7**, I focused less on discussing the adaptive responses themselves and more on how these responses are related to adaptive capacity and adaptation outcomes.

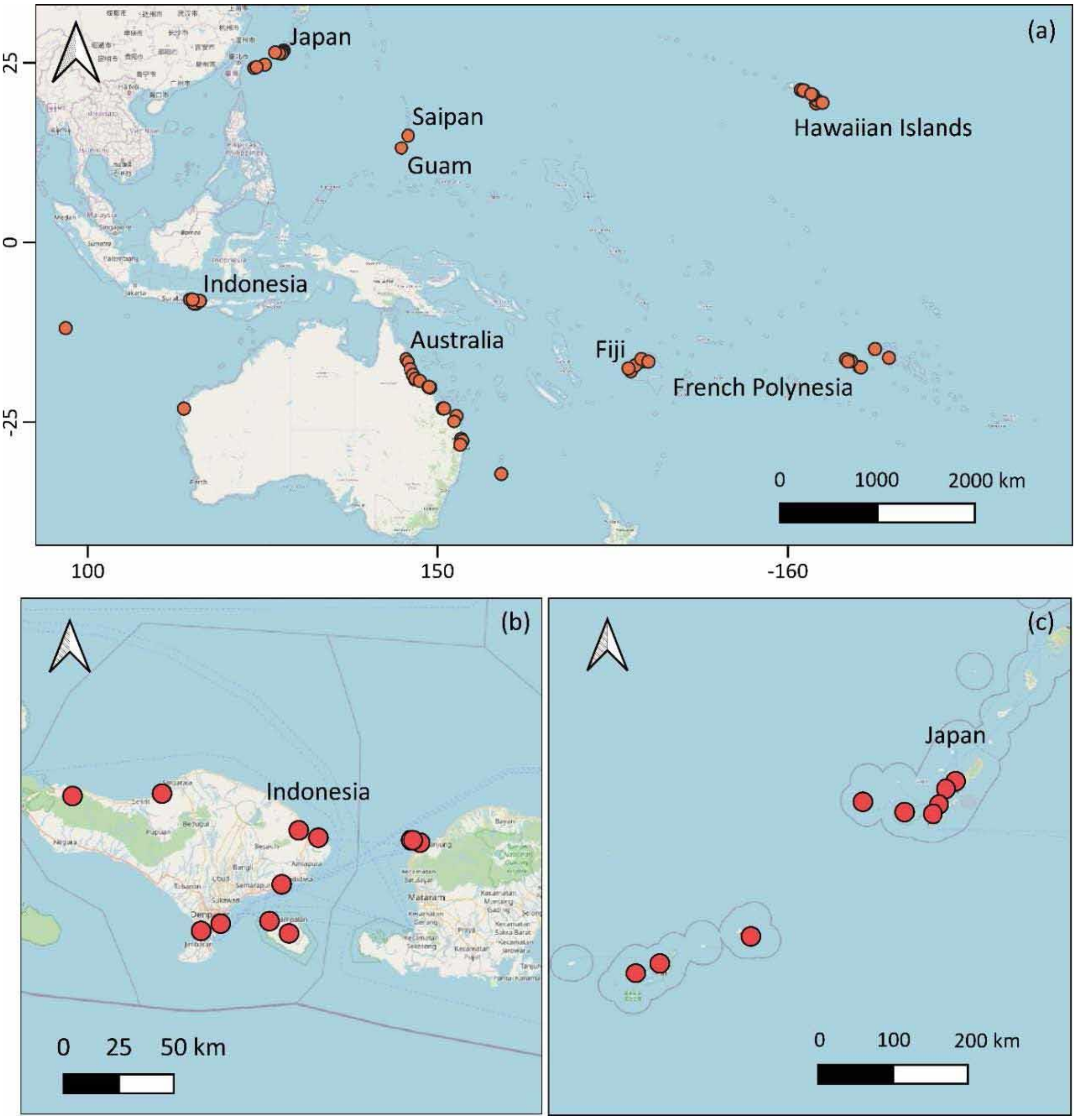
4.2 Study Sites

I focused sampling on the APAC Region, in which 80% of coral reefs are located globally (Spalding et al., 2001). I deliberately selected locations where high reef tourism density (Spalding et al., 2017) coincided with high bleaching severity (Hughes, Anderson, et al., 2018). I limited my focus to bleaching events that occurred in the last five years (2014–2019) due to the need for accurate recall data from respondents. I also selected study locations spanning a wide range of human and institutional development because it has frequently been assumed that people in countries with lower living standards have lower adaptive capacity than their counterparts in more affluent countries (Brooks et al., 2005; Fankhauser & McDermott, 2014; Hughes et al., 2012). By including this diversity in my study locations, I sought to include a wide range of values of different indicators of adaptive capacity and adaptation outcomes. With the exception of the Maldives and Taiwan (both 2016 bleaching event) that I was not able to sample due to time constraints, my sample included representative operators from all reef tourism locations in the APAC Region that were known to be severely affected by coral bleaching between 2014 and 2019 (Figure 4.2).

I implemented a separate survey for reef tourism operators from Fiji and Australia that had been subject to cyclone impacts (Cyclone Winston in 2016, Cyclones Yasi in 2011 and Debbie in 2017, respectively) to test for a mediating effect of the type of climate disturbance on the relationship between adaptive capacity and adaptive responses.

Figure 4.2

Overview of my 28 Study Locations (Red Dots) Across Eight Countries in the Asia-Pacific (APAC) Region and the Respective Number of Reef Operators I Sampled out of the Total Number of Operators That Were Active at the Time of a Specific Climate Disturbance



Note. Indonesia (Bali and Lombok, *n* = 86/212); Australia (East and West coast, *n* = 56/109); Japan (Ryukyu Islands, *n* = 24/116); Guam & Saipan (Mariana Islands, *n* = 17/33); United States (Hawaiian Islands, *n* = 15/81); France (French Polynesia, *n* = 14/36); and Fiji (*n* = 16/79). Purple lines indicate national marine boundaries; dotted blue lines are ferry routes.

My study locations with the most reef tourism operators were the islands of Bali and Lombok in Indonesia (Figure 4.2); these islands were severely affected by the mass coral bleaching event in 2016 (Wouthuyzen et al., 2018). Other countries in the APAC Region that were considered to have relatively lower living standards, e.g. Malaysia, the Philippines, and Thailand, were affected by severe bleaching in 2010, but this was outside my selected temporal range. For countries with higher living standards, I included some of the most severely-affected reef tourism locations: Australia, 2016 and 2017 (AIMS, 2022; Eakin et al., 2017; GBRMPA, 2017); the Ryukyu Islands, Japan, 2016 (Eakin et al., 2017; Kayanne et al., 2017); the Mariana Islands (Guam and Saipan), 2016 and 2017 (Eakin et al., 2017; Raymundo et al., 2019); the Hawaiian Islands, 2014 and 2015 (Eakin et al., 2017; Rodgers et al., 2017; University of Hawaiʻi, 2017); and French Polynesia, 2016 and 2019 (Hédouin et al., 2020; Pérez-Rosales et al., 2021). During data collection in Indonesia and French Polynesia, I learned that another severe bleaching event had occurred in 2019, and I included this event in a separate survey that I used for companies that started operations after 2016, in particular on the islands of Nusa Penida and Nusa Lembongan (Bali) that have seen recent growth in reef tourism.

My analytical design included *a priori* treatment and control groups of tourism operators based on whether their reef sites had been directly affected by a specific climate disturbance. My main focus was on reef operators affected by coral bleaching (treatment), and I included operators that were not affected by bleaching as a control group. For example, in Australia I included tourism operators from the southern Great Barrier Reef (GBR) that were less directly affected by coral bleaching in 2016 and 2017 (Chapter 2. The effect of coral bleaching on the recreational value derived from the GBR). I included a question about disturbance severity in my surveys to check whether my treatment/control divide was consistent with operators' personal experiences. Operators that did not experience direct ecological impacts might still have been affected by reputational effects, or may have undertaken other kinds of potentially adaptive responses; thus my control group surveys provided insights into responses to the indirect or non-ecological impacts of climate-related disturbances.

4.3 Sampling

I sought to represent the full population of in-water reef tourism operators that offered recreation-based activities (e.g. diving and snorkeling) that are directly linked to coral reefs. Operators were identified through an online search (using Google search engine, Google Maps and TripAdvisor) with the search terms "coral tours," "coral reef tours," "reef diving," "reef snorkeling," and a term for the location. I identified a total of 665 reef tourism companies within my study locations that were in operation during the specific climate disturbances I studied, the majority (212) in Bali and Lombok, Indonesia. All operators were initially invited through e-mail and were later followed up with through either in-person visits or phone calls. For my sampling in Guam, Indonesia, Japan, Saipan, and the Hawaiian Islands I used local research assistants to follow up with potential participants. I followed up with operators in Australia, where I am based. I used online surveys with company representatives, undertaken with Kobotoolbox survey software, to collect data. Because I was interested in adaptive responses to climate disturbances that occurred before my study, the data I collected were based on recall. I used separate surveys for each specific climate disturbance that I studied depending on the location and the specific period over which the climate disturbance occurred. I also used appropriate languages in the surveys (e.g. Indonesian and Japanese) to reduce any chance of bias towards English-speaking operators. Most surveys were undertaken between October 2020 and December 2021, while some of the surveys in Fiji were undertaken in the first half of 2022. My sampling strategy resulted in a total of 231 operator surveys, representing about a third of the total population (Table 4.1).

Table 4.1

Overview of Study Locations and Participation Fractions

Study location	Sampling location	Sample size (fraction of companies in sampling location)
Bali and Lombok, Indonesia	South Bali (e.g. Sanur, Kuta, Nusa Dua)	12 out of 27 (44%)
	Southeast Bali (e.g. Padang Bai, Nusa Lembongan, Nusa Penida)	19 out of 47 (40%)
	Northeast Bali (e.g. Amed, Tulamben)	26 out of 66 (39%)
	North Bali (e.g. Pemuteran, Lovina)	12 out of 34 (35%)
	Gili Islands, Lombok	17 out of 38 (45%)
	Total	**86 out of 212 (41%)**
Australia	Cairns/Cooktown Management Area, GBR	22 out of 39 (56%)
	Townsville/Whitsunday Management Area, GBR	17 out of 29 (59%)
	Mackay/Capricorn Management Area, GBR	4 out of 11 (36%)
	Western Australia (Ningaloo & Cocos Islands)	6 out of 16 (38%)
	Moreton Bay Marine Park	5 out of 9 (56%)
	Lord Howe Island Marine Park	2 out of 5 (40%)
	Total	**56 out of 109 (51%)**
Ryukyu Islands, Japan	Okinawa Islands (e.g. Naha, Zamami, Kume)	12 out of 52 (23%)
	Yaeyama Islands (e.g. Ishigaki, Iriomote)	8 out of 45 (18%)
	Miyako Islands (e.g. Miyakojima, Irabu Island)	4 out of 19 (21%)
	Total	**24 out of 116 (21%)**
The Hawaiian Islands, United States	Maui Island	3 out of 27 (11%)
	Hawaii Island (Big Island)	6 out of 25 (24%)
	Oahu Island	6 out of 20 (30%)
	Kauai Island	0 out of 9 (0%)
	Total	**15 out of 81 (19%)**
The Mariana Islands, United States	Guam	9 out of 22 (41%)
	Saipan	8 out of 11 (73%)
	Total	**17 out of 33 (52%)**
French Polynesia, France	Leeward Islands	4 out of 13 (31%)
	Palliser Islands	4 out of 10 (40%)
	Moorea Island	4 out of 9 (44%)
	Tahiti Island	2 out of 4 (50%)
	Total	**14 out of 36 (39%)**

Fiji	Viti Levu	6 out of 23 (26%)
	Mamanuca & Yasawa Islands	3 out of 27 (11%)
	Vanua Levu & Taveuni Island	6 out of 24 (25%)
	Kadavu Island	1 out of 5 (20%)
	Total	**16 out of 79 (20%)**

Note. Anonymized list with all identified operational reef tourism operators by location is available at (Bartelet, 2023b).

The lower sampling fraction in the Hawaiian Islands (19%) was partly the result of this being the oldest climate disturbance in my sample (2014–2015), with many tourism companies not having retained staff from that time and/or changed ownership. There was also a relatively larger share of the sample of operators in the Hawaiian Islands for whom coral reefs were not the major focus of tours (e.g. operators focused on dolphins, whales, or sailing) and thus they did not have the knowledge or interest to participate in the survey. The lower sampling fraction in Fiji (20%) was caused by the COVID-19 pandemic; most of the reef tourism operators in Fiji are affiliated with a resort, most of which were completely closed during my sampling period.

4.4 Adaptive Responses to Climate Disturbances

Because of the lack of empirical knowledge on adaptation to climate change by coral reef tourism operators, in designing my survey I used an exploratory approach to identify and classify response types that were likely to have been adopted. My classification drew on existing empirical evidence of adaptive responses to climate change by microeconomic actors (Table 3.3), expert consultation with reef tourism industry experts in Australia (e.g. tourism research institutes, local reef tourism industry associations, and reef management agencies), and pilot interviews with tourism operators. Through this process I identified nine potential adaptive responses to climate disturbances on coral reefs that were explicitly included in my surveys with reef tourism operators (Table 4.2). I also added a novel adaptive response linked to ‘climate action,’ i.e. reef tourism operators becoming involved in measures to reduce carbon emissions. The ten potential adaptive responses were not specifically characterized as “adaptations” (e.g. actions with the intention to reduce vulnerability or respond to opportunities offered by the climate impact) but include any kind of response undertaken in response to climate impacts. This is important, because some of the responses are not necessarily obviously intentional adaptations but could be logical responses to shock (whether they are intended to reduce risk/vulnerability or not).

Table 4.2

Microeconomic Adaptive Responses to Climate Disturbances on Coral Reefs, Based on my Microeconomic Adaptation Framework (Table 3.3), Which Identified the Most Common Responses by Other Microeconomic Actors in Response to Climate Change

Type of adaptation	Adaptive responses	Description
Diversification within livelihoods	(1) Spatial diversification (2) Product diversification	Changing reef sites company was visiting on tours. Changing the type of tours or activities company was offering to tourists.
Operational change	(3) Making changes to the way the company is running its day-to-day operations	Changing logistics (e.g. tour season), personnel, sales (e.g. price change), and/or marketing.
Natural resource management	(4) Reef restoration	Enacting or participating in measures to improve the health of the coral reef.
Diversification between livelihoods	(5) Switching livelihood activities entirely or partly	Diversifying to products/services outside of tourism.
Reduction of immediate impact (relief)	(6) Relief measures (7) Support-seeking	Selling of property (e.g. boats, equipment and/or office space), reduction of workforce, and/or relying on savings.

		Seeking support from government, local community, and/or relatives.
Protection of livelihood	(8) Risk protection	Seeking or purchasing protection from risks (e.g. insurance).
	(9) Monitoring	Beginning monitoring climate and/or reef conditions.
Climate action	(10) Carbon dioxide (CO_2) reductions	Enacting or participating in measures to reduce CO_2 emissions of company, customers, and/or community.

Note. Adaptive responses sorted by the frequency of observance in other microeconomic settings. I added 'climate action' as an additional response specifically for the (reef) tourism sector.

Respondents were asked: (1) whether they had used each of the ten particular adaptive responses identified in Table 4.2; (2) whether they had implemented any response that was not included in my list; and (3) to select their most important (primary) response to the climate disturbance out of all responses taken. For tourism operators that were affected by two consecutive bleaching events, I asked respondents for responses that were implemented over a two year period since the first bleaching event. For operators that were affected by a single climate disturbance, I asked for responses over a one-year period since the event happened. I decided to use an adaptation period of one year after a disturbance because using a longer time period would make it harder to attribute responses to specific climate events rather than other causes.

After collecting data on which of the ten adaptive responses were used by each operator, I used partial correlation analysis to identify which responses most often clustered together using Spearman's Rank correlation in the 'ppcor' package (Kim, 2015) in R software (R Core Team, 2013). Based on the data, the categorization of different types of adaptation found in other microeconomic settings (Table 3.3), and my contextual understanding of the reef tourism system, I merged some of the responses into combined response categories. As presented in my results, I found several significant correlations between my responses. This indicated that a large fraction of reef tourism operators implemented multiple adaptive responses to a climate disturbance, and that some of these responses were combined more frequently than others.

4.5 Contextual Conditions

Throughout my analyses, I included several contextual variables to control for external influences (Table 4.3): the country's '*governmental effectiveness,*' a company's '*distance to market,*' and the '*disturbance type*' and '*disturbance severity.*'

Table 4.3

Contextual Variables Used Throughout my Different Data Chapters

Variable	Description	Data type	Unit of measurement	Used in Chapters:
Business type	Fraction of customers that engaged in scuba diving versus snorkelling activities.	Binary	(0) Mostly snorkelling (1) Mostly scuba	**Chapter 5**
Business size	Total number of passenger seats on company's boats as proxy for business size	Categorical	(1) Small (0–20 seats) (2) Medium (20–200 seats) (3) Large (>200 seats)	**Chapter 5**
Age	Age group of the company representative (i.e. respondent in my survey)	Binary	(0) Above 45 years (1) Below 45 years	**Chapter 5**
Gender	Gender of the company representative (i.e. respondent in my survey)	Binary	(0) Male (1) Female	**Chapter 5**

Disturbance type	Type of climate disturbance to which the reef tourism operators had to adapt	Binary	(0) Bleaching (1) Cyclone	**Chapter 5**, **Chapter 6**, **Chapter 7**
Disturbance severity	Fraction of reef sites used on tours before disturbance that had more than a third of their area affected by climatic impact (i.e. either bleached or damaged by cyclone)	Continuous	(0) None of reef sites (1) 25% of reef sites (2) 50% of reef sites (3) 75% of reef sites (4) All of reef sites	**Chapter 5**, **Chapter 6**, **Chapter 7**
Distance to market	Distance to nearest commercial airport	Continuous	# kilometres	**Chapter 6**
Government effectiveness	Level of institutional development in the country where reef operator is based (Kaufmann et al., 2011; The World Bank, 2021)	Binary	(0) Lower (<0.5) (1) Higher (>0.5)	**Chapter 6**, **Chapter 7**

Through my *government effectiveness* indicator, I tested whether operators located in countries with higher levels of institutional development adopted significantly different adaptive responses, and/or experienced significantly different outcomes compared to operators located in countries with lower levels of institutional development, while accounting for my other predictor variables. Low institutional development reduces trust and willingness to follow government advice on adaptation, while on the other hand high institutional development might lead to people's perception that public authorities are responsible for adaptation (Mortreux et al., 2020; Mortreux & Barnett, 2017). I used the *government effectiveness* indicator from the Worldwide Governance Indicators initiative (Kaufmann et al., 2011; The World Bank, 2021) to control for differences in institutional development. This indicator reflects perceptions of the quality of public services, the quality of civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. The government effectiveness indicator was based on data for the year 2014 for all countries because the first climate disturbance I included started in 2014. My sample consisted of countries in two clusters, and I classified countries with a rating below 0.5 as having lower institutional development (48% of sample, including Indonesia, Fiji, and the Mariana Islands) and countries with a rating above 0.5 as having higher institutional development (52% of sample, including Australia, French Polynesia, Japan, and the Hawaiian Islands).

*Distance to marke*t (a proxy for access to markets, which has been associated with adaptation responses (Chapter 3. Literature review; Daw et al., 2012)) captured the distance by road of the reef tourism operator's shop to the nearest airport. In most of my study locations, airports are located near main urban and tourism centres, thereby providing the nearest access to both incoming tourists and alternative livelihood markets. In case of travel by ferry, I used the closest line between two ferry points as a proxy.

I controlled for *disturbance type* as a binary predictor that measured whether operators affected by cyclone impacts responded different taking operators affected by coral bleaching as the reference group. I distinguished between bleaching and cyclones because I expected a different qualitative and quantitative nature of these impacts (Cheal et al., 2017; Dietzel et al., 2021). Bleaching can destroy reefs, but there is a potential time lag of years between when a reef is bleached and declines in fish biomass (if the reef does not recover); whereas cyclones can turn reefs to rubble in a few hours, although the effects are patchy (Cheal et al., 2017; Dietzel et al., 2021). Additionally, for economic sustainability, cyclones affect not only the coral reef but can also damage boats, buildings, and communal tourism infrastructure.

Disturbance severity measures the spatial severity of the climate disturbance for a particular operator in terms of what fraction of the reef sites they were using were severely affected. Prior studies have argued that the severity of impacts on coral reefs might affect the availability of adaptation alternatives for tourism operators, for example their ability to relocate to healthy reef areas (Hoegh-Guldberg et al., 2019; Stoeckl et al., 2021). I followed previous research that identified severe bleaching as more than a third of a reef being affected (Hughes, Anderson, et al., 2018). For locations where I studied adaptive responses to two consecutive bleaching events, e.g. GBR 2016 and 2017, I asked for disturbance severity for each year separately and used the highest severity value as a predictor in my models.

I accounted for the business and business representative characteristics (Running et al., 2019) by including the business type (scuba diving versus snorkelling) and size as well as the age and gender of the company representative. I used the business type variable as a proxy for the company's customers' sensitivity to coral conditions. Here I hypothesized that reef tourism operators catering more towards snorkelling than diving would have visitors that are, on average, less knowledgeable about reef conditions and thus less sensitive to impacts from climate disturbances (Leujak & Ormond, 2007; Uyarra et al., 2009). On the other hand, snorkelling sites are usually shallower and these sites might have been more severely affected by the climate impacts, as measured through my control factor of disturbance severity. The business size was found to be an important determinant of adaptation in farming settings (Figure 3.3). For example, households with larger farms were more likely to diversify within their livelihood, to manage natural resources, and to change their mode of operating. They were less likely to diversify between livelihoods. I measured the number of passenger seats using nine multiple-choice options that ranged from '0-10 seats' to '>500 seats.' Through visual inspection of the data, I identified three clusters that I consequently categorized as small, medium, and large. I included company size as a categorical rather than an ordinal predictor because the effects were not ordered linearly for all response models.

Inclusion of the age group of the company representative was based on prior findings in a farming setting, where the age of the head of the household was a significant predictor for several adaptive responses (Figure 3.3). Specifically, younger age increased the likelihood of diversification between livelihoods, changes in the mode of operating and the management of natural resources, while reducing the likelihood of diversification within livelihood and protective measures. The effect of gender on adaptation has been acknowledged as a research gap, although so far there have been few specific hypotheses regarding its linkage to particular adaptation behaviors (Bunce & Ford, 2015; Mortreux & Barnett, 2017). One study found that within rural households in Australia, women are less likely to be involved in adaptation to wildfire due to low empowerment (C. Eriksen et al., 2010). Given that my dataset included formal tourism businesses, I hypothesized that the gender of the representative might be less of a barrier as compared to rural households, but acknowledge that any existing power differentials along the lines of gender could potentially have affected adaptive responses.

4.6 Sample Description

The majority of reef tourism operator representatives in my sample (Table 4.4) were European and Australian, followed by North Americans, Japanese, and Indonesians. About three-quarters of the sample were male and about 70% were aged between 35 and 54 years. On average, reef operators had 37% (σ=34%) of their reef sites severely affected by the climate disturbance with the highest averages on the Hawaiian Islands (48%) and the lowest in Indonesia (28%). Climate/reef monitoring, restoration measures, and climate action were the most commonly adapted responses to climate change impacts on coral reefs.

Table 4.4

Sample Description for Asia-Pacific Reef Tourism Operators by Location

Indicator	Units	Indonesia	Australia	Japan	Mariana islands	Hawaiian islands	French Polynesia	Fiji	Total
Respondents	#	87 (38%)	57 (25%)	24 (10%)	17 (7%)	15 (6%)	15 (6%)	16 (7%)	231 (100%)
Respondent nationality	Australian	2 (2%)	53 (93%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	10 (63%)	65 (28%)
	European	46 (53%)	3 (5%)	1 (4%)	0 (0%)	0 (0%)	14 (93%)	0 (0%)	64 (28%)
	Indonesian	25 (29%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	25 (11%)
	Japanese	2 (2%)	0 (0%)	19 (79%)	7 (41%)	0 (0%)	1 (7%)	0 (0%)	29 (13%)
	N-American	6 (7%)	1 (2%)	2 (8%)	8 (47%)	15 (100%)	0 (0%)	1 (6%)	33 (14%)
	Other	6 (7%)	0 (0%)	2 (8%)	2 (12%)	0 (0%)	0 (0%)	5 (31%)	15 (6%)
Respondent gender	Female	21 (24%)	24 (42%)	3 (12%)	3 (18%)	5 (33%)	4 (27%)	3 (19%)	63 (27%)
	Male	66 (76%)	33 (58%)	21 (88%)	14 (82%)	10 (67%)	11 (73%)	13 (81%)	168 (73%)
Respondent age	18–24	0 (0%)	2 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	2 (1%)
	25–34	12 (14%)	5 (9%)	2 (8%)	1 (6%)	3 (20%)	1 (7%)	2 (13%)	26 (11%)
	35–44	41 (47%)	19 (33%)	15 (62%)	5 (29%)	6 (40%)	4 (27%)	2 (13%)	92 (40%)
	45–54	27 (31%)	14 (25%)	6 (25%)	4 (24%)	0 (0%)	9 (60%)	2 (13%)	62 (27%)
	55–64	6 (7%)	14 (25%)	1 (4%)	6 (35%)	6 (40%)	1 (7%)	7 (44%)	41 (18%)
	65+	1 (1%)	3 (5%)	0 (0%)	1 (6%)	0 (0%)	0 (0%)	3 (19%)	8 (3%)
Distance to market	μ =	71	45	34	10	33	15	60	49
	σ =	37	49	28	4	29	20	45	42
Disturbance type	Bleaching	87 (100%)	44 (77%)	24 (100%)	17 (100%)	15 (100%)	15 (100%)	0 (0%)	202 (87%)
	Cyclone	0 (0%)	13 (23%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	16 (100%)	29 (13%)

Disturbance severity	μ = σ =	28% 27%	40% 39%	43% 35%	37% 32%	48% 44%	45% 42%	42% 31%	37% 34%
Adaptive responses	(1) Chgsites	26 (30%)	22 (39%)	9 (38%)	6 (35%)	2 (13%)	5 (33%)	7 (44%)	77 (33%)
	(2) Chgact	15 (17%)	11 (19%)	5 (21%)	4 (24%)	2 (13%)	4 (27%)	3 (19%)	44 (19%)
	(3) Chgop	10 (11%)	14 (25%)	4 (17%)	2 (12%)	2 (13%)	0 (0%)	3 (19%)	35 (15%)
	(4) Nrm	61 (70%)	24 (42%)	11 (46%)	12 (71%)	7 (47%)	6 (40%)	8 (50%)	129 (56%)
	(5) Divbl	6 (7%)	5 (9%)	0 (0%)	1 (6%)	1 (7%)	0 (0%)	0 (0%)	13 (6%)
	(6) Relief	6 (7%)	7 (12%)	1 (4%)	1 (6%)	0 (0%)	0 (0%)	5 (31%)	20 (9%)
	(7) Support	27 (31%)	6 (11%)	2 (8%)	5 (29%)	1 (7%)	1 (7%)	2 (13%)	44 (19%)
	(8) Risk	0 (0%)	1 (2%)	1 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	2 (1%)
	(9) Monitor	64 (74%)	31 (54%)	18 (75%)	12 (71%)	9 (60%)	10 (67%)	9 (56%)	153 (66%)
	(10) Co2	49 (56%)	22 (39%)	5 (21%)	8 (47%)	4 (27%)	5 (33%)	7 (44%)	100 (43%)

Note. Numbers indicate the number (and fraction of total) of operators in a particular location to which a particular category applied. Adaptive responses follow order from Table 4.2 and are presented in abbreviated form: spatial diversification (Chgsites); product diversification (Chgact); changes in mode of operating (Chgop); natural resource management (Nrm); diversification between livelihoods (Divbl); relief measures (Relief); support-seeking (support); risk protection (Risk); monitoring (Monitor); and Co2 emissions (Co2).

Chapter 5. Microeconomic Adaptation to Severe Climate Disturbances on Australian Coral Reefs

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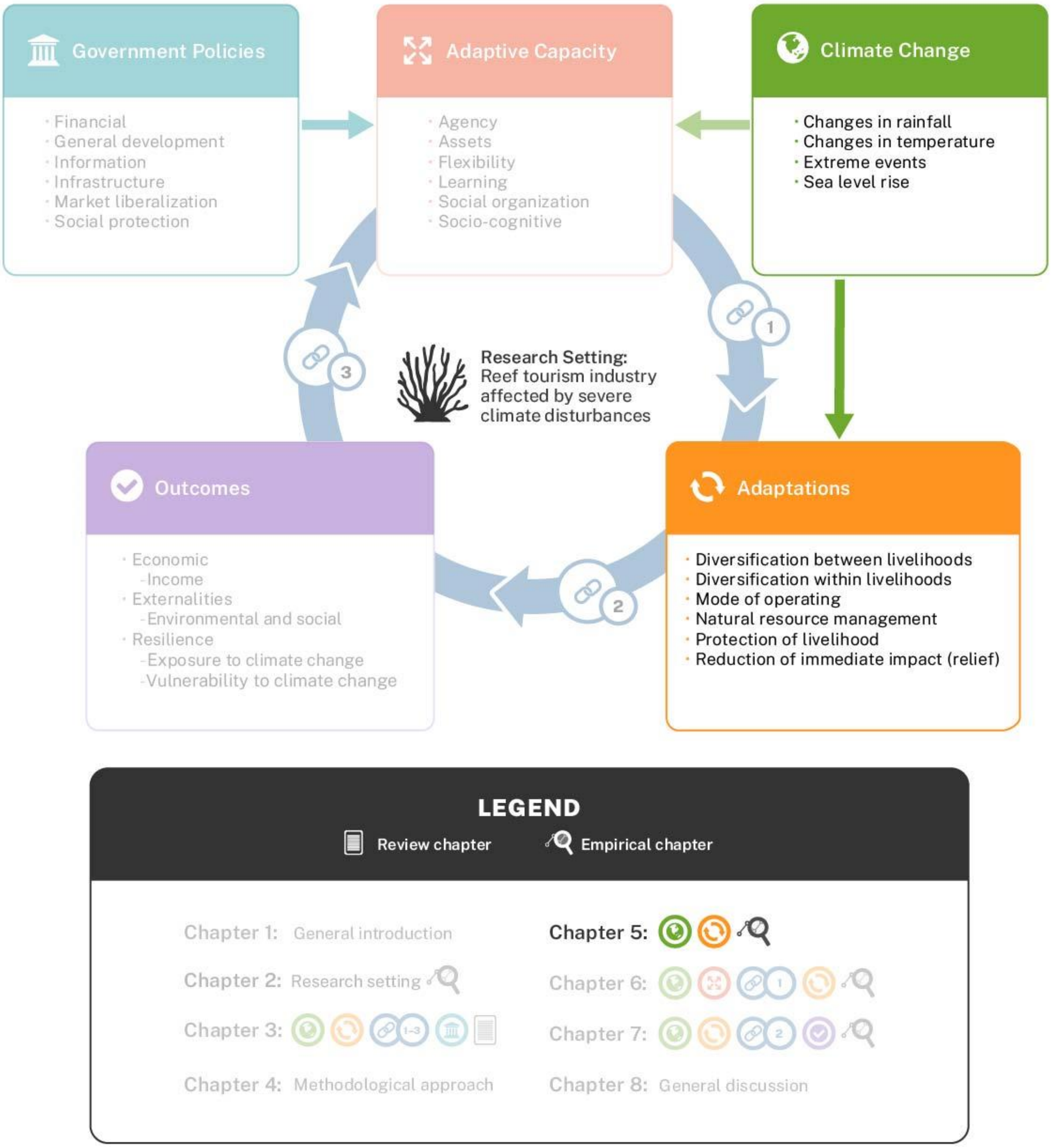
In my fifth chapter, I test the applicability of the microeconomic adaptive response typology (Table 3.3) to adaptation to climate disturbances by Australian reef tourism operators. I also explore which adaptive responses are most commonly used in response to climate disturbances on reefs and how these responses are associated with contextual and disturbance characteristics.

Figure 5.1

Research Gaps Addressed in Empirical Data Chapter 5: Reef Tourism Adaptation to Severe Climate Disturbances



Contributions

HB conceived the manuscript and developed the methodological approach with input from MB and GC. HB collected data, ran the analyses and wrote first draft. MB and GC helped write and revise the manuscript.

Abstract

Coral reefs are increasingly affected by climate-induced disturbances that are magnified by increasing ocean temperatures. Loss of coral reefs strongly affects people whose livelihoods and wellbeing depend on the ecosystem services reefs provide. Yet the effects of coral loss and the capacity of people and businesses to adapt to it are poorly understood, particularly in the private sector. To address this gap, I surveyed about half (57 of 109) of Australian reef tourism operators to understand how they were affected by and responded to severe impacts from bleaching and cyclones. Reef restoration and spatial diversification were the primary responses to severe bleaching impacts, while for cyclone-impacts coping measures and product diversification were more important. Restoration responses were strongly linked to the severity of impacts. My findings provide empirical support for the importance of response diversity, spatial heterogeneity, and learning for social-ecological resilience.

5.1 Introduction

Scholarly research on human adaptation to climate change has been steadily increasing, although most studies remain focused on intended adaptation to future climate change rather than actual adaptation to experienced climate impacts (**Chapter 3**; Berrang-Ford et al., 2021). Research on adaptation to actual climate impacts by microeconomic actors, specifically in the private sector, also remains limited (Berrang-Ford et al., 2021; Fankhauser, 2017; Linnenluecke et al., 2013). A recent framework was developed, based on a review of empirical evidence, stating the hypothesized primary responses microeconomic actors (i.e.

households and firms) might take in response to impacts from climate change (Figure 3.5). Within the microeconomic adaptation literature, empirical research on adaptation to experienced climate effects remains skewed towards farming (**Chapter 3**; Fankhauser, 2017). Coral reef social-ecological systems provide an excellent case study in which to address two specific research gaps: (1) a lack of information outside agriculture on adaptation to experienced climate change; (2) the responses to climate change by actors in the private sector.

To address the gap in existing knowledge about adaptation strategies in coral reef social-ecological systems, I undertook an exploratory study to empirically assess adaptation to severe climate disturbances on Australian coral reefs by tourism operators. I focused on four primary research questions: (1) how did tourism operators in Australia respond to severe climate-related disturbances, specifically the coral bleaching events in 2016 and 2017 and severe cyclones in 2011 and 2017? (2) How applicable is the microeconomic adaptation framework developed by Bartelet et al. (Figure 3.5) towards adaptation to climate change by coral reef tourism operators? (3) Did increasingly severe impacts reduce the adaptation alternatives that were available (Hoegh-Guldberg et al., 2019)? And (4) how did the contextual characteristics of the business affect the adaptation process?

5.1.1 Background and Study Sites

I focus my inquiry on coral reef tourism sites in Australia. My most notable sites are located in the Great Barrier Reef (GBR), the world’s largest coral reef ecosystem covering 344,400 km² along the east coast of Queensland in Australia (Great Barrier Reef Marine Park Authority, 2012). The GBR directly contributed an estimated $6.4 billion in economic value and 64,000 jobs to the Australian economy in the year 2016, of which $5.7 billion (90%) was provided either directly or indirectly by tourism (Deloitte Access Economics, 2017). Bleaching events in 2016 and 2017 were followed by coral mortality and significant losses in coral cover along the Central and Northern two-thirds of the Great Barrier Reef, also affecting some of the primary reef tourism locations (AIMS, 2018; GBRMPA, 2017), although there have been indications of reef recovery in recent years (AIMS, 2022). More localized reef areas have also been severely affected by severe tropical cyclones, most notably Cyclone Yasi in 2011 (affecting the area around Mission Beach) and Cyclone Debbie in 2017 (affecting the Whitsunday Islands). I complemented my GBR sites with data from reef tourism operators from other smaller coral reef ecosystems in Australia, specifically the Moreton Bay Marine Park (southern Queensland), the Lord Howe Island Marine Park (New South Wales), Ningaloo Marine Park (Western Australia), and the Cocos Islands Marine Park (Western Australia). My study thus included reef tourism operators from all around Australia (Table 4.1).

5.2 Methodology

5.2.1 Sampling

For my bleaching treatment group, I used data from tourism operators in the ‘Cairns/Cooktown’ and the ‘Townsville/Whitsunday’ Management Areas (Table 5.1) because these areas were most severely affected by the coral bleaching events in 2016 and 2017 (AIMS, 2018; GBRMPA, 2017; Hughes, Kerry, et al., 2017). I did not include reef tourism operators in the Whitsundays region in the bleaching sample, as they were affected by another severe climatic disturbance (i.e. Cyclone Debbie) in 2017, the same period when the bleaching events occurred. For my cyclone treatment group, I focused on tourism operators in the Whitsundays for Cyclone Debbie (2017) and in Mission Beach for Cyclone Yasi (2011).

Table 5.1

Overview of Study Locations and Participation Fractions

Marine Park Management Area (MPMA)	**State**	**Reef tourism locations**	**Sample size (fraction of companies in MPMA)**
Cairns/Cooktown Management Area (*a priori* treatment sample)	Queensland (Great Barrier Reef)	Cape Tribulation; Port Douglas; Cairns; Mission Beach	22 out of 39 (56%)
Townsville/ Whitsunday Management Area (*a priori* treatment sample)	Queensland (Great Barrier Reef)	Orpheus Island; Townsville; Magnetic Island; Alva; Airlie Beach; Hamilton Island; Daydream Island	17 out of 29 (59%)
Mackay/Capricorn Management Area (*a priori* control sample)	Queensland (Great Barrier Reef)	Yeppoon; Great Keppel Island; Pumpkin Island; Lady Elliot Island; Bundaberg	4 out of 11 (36%)
Moreton Bay Marine Park (*a priori* control sample)	Queensland	Sunshine Coast; Moreton Island; North Stradbroke Island; Brisbane; Gold Coast	5 out of 9 (56%)
Lord Howe Island Marine Park (*a priori* control sample)	New South Wales	Lord Howe Island	2 out of 5 (40%)
Ningaloo Marine Park & Cocos (Keeling) Islands Marine Park (*a priori* control sample)	Western Australia	Coral Bay; Exmouth; West Island (Cocos)	7 out of 16 (44%)

For my bleaching control group, I focused on tourism operators in the southern sections of the GBR (‘Mackay/Capricorn Management Area’) because these areas were least severely affected by the coral bleaching events in 2016 and 2017. I also approached reef tourism operators from all other coral reef ecosystems in Australia (Table 5.1) as part of my control group.

About half (57 out of 109) participated in my survey (Table 5.1) and one operator participated in both the bleaching and cyclone (2011) survey giving me a total sample size of 58. In my treatment samples I reached participation rates nearby 60%. Frequent reasons for not-participating in my survey were (1) no staff around from that time; (2) changed ownership; (3) no time available; and (4) some companies were (temporarily) out of operation due to the COVID-19 pandemic.

The posterior treatment/control divide differed slightly from my *a priori* assumption. One of the 18 reef tourism operators, which was located in the Ningaloo Marine Park MA, that I included in my *a priori* control sample had to be included in the posterior treatment group because their reef sites had been directly affected by severe bleaching in 2017. Five of the 39 reef tourism operators, four of which located in the Cairns/Cooktown MA and one in the Townsville/Whitsunday MA, had to be included in the posterior control group because none of their reef sites had been severely affected by bleaching in either 2016 or 2017.

5.2.2 Analysis

My response variables were classified as binary (i.e. whether a particular adaptive response was used or not used, Table 4.2). I therefore used logistic regression models to analyse the effect of the predictors on the likelihood of implementing a particular adaptive response. Modelling was done in R software using the generalized linear models (glm) function. I standardized my non-binary predictor (disturbance severity) using z-scores, by subtracting the mean and dividing by twice the standard deviation (Gelman, 2008). Dividing by twice the standard deviation standardizes a variable to have a mean of ‘0’ and a standard deviation of ‘0.5;’ this technically standardizes the variable on a binary scale. The coefficient for my disturbance severity predictor is now directly comparable and should be interpreted as the effect of a one-standard deviation change in the predictor variable on the response variable. All predictors had a variance inflation factor (VIF) below 4, indicating low collinearity in my models. The models were validated via DHARMa residuals (Hartig, 2018). Inferences were based on a 95% significance level.

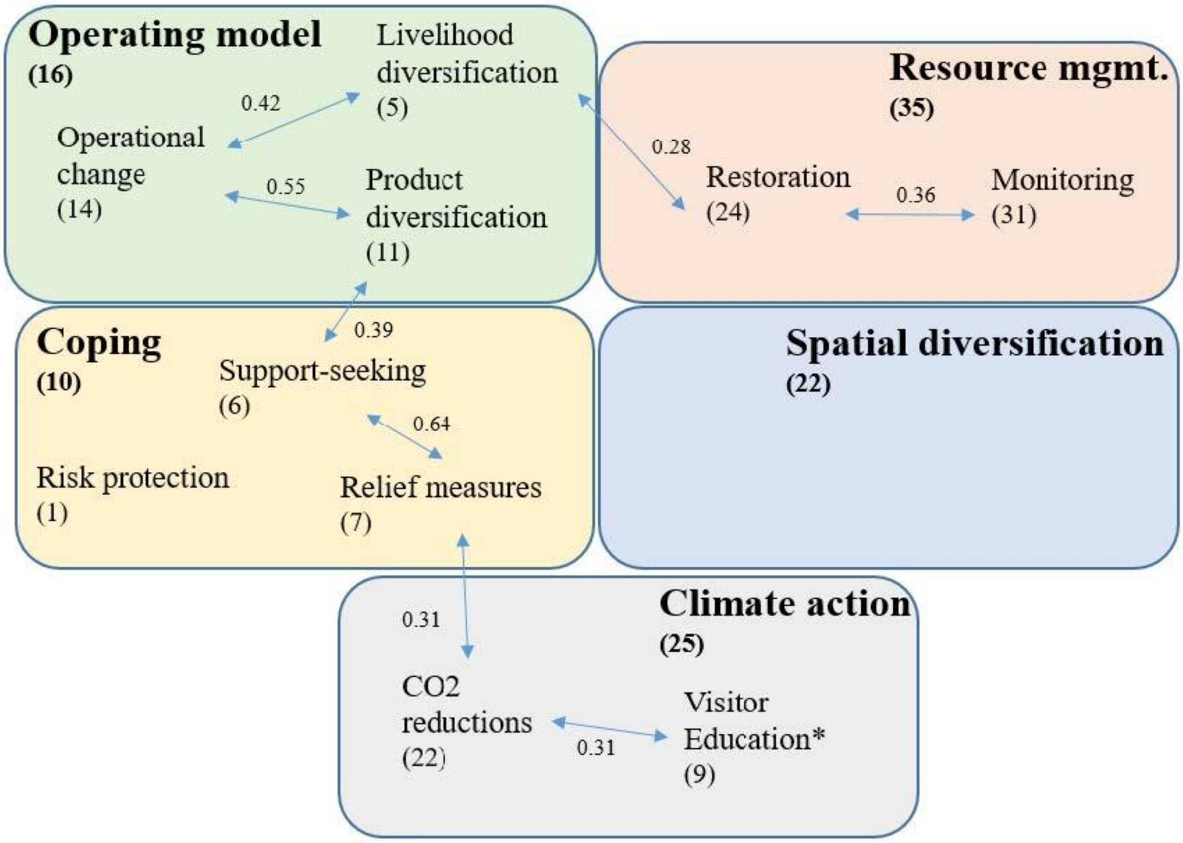
5.3 Results

5.3.1 Adaptive Responses to Climate Disturbances (Posterior Classification)

I found eight positive partial correlations between my individual adaptive responses that were significant at a p-level of 5% (Figure 5.2). Based on these significant associations, I decided to make some changes to the *a priori* classification of adaptive response as proposed in Table 4.2. Most notably I decided to merge the adaptive responses of operational change, product diversification, and livelihood diversification into a combined adaptive response cluster linked to changes in 'operating model' because they were all linked to responses on the business and operational side. Compared to my *a priori* categorization, I classified 'spatial diversification' as a separate adaptation cluster because it was frequently implemented and not significantly associated with any of the other adaptive responses.

Figure 5.2

Clustering of Adaptive Responses to Climate Disturbances by Australian Reef Tourism Operators (n=58)



Note. Graph includes only significant partial correlation effects (Spearman's rank correlation coefficient) between responses that are significant at a p-level of 5%. Numbers in brackets indicates prevalence of adaptive response (i.e., how many operators adopted a particular response). I decided to include risk protection within the 'Coping' cluster because it was only used by one operator in the sample and I conceptually judged it to be most applicable to this cluster. Visitor education was mentioned as 'other' response by nine operators in my sample (16%) and I merged this response within the climate action cluster because it was significantly correlated with actions to reduce carbon dioxide (CO_2) emissions.

I found that the adaptive responses of 'monitoring (reefs and/or climate)' and 'restoration' were significantly correlated, although my *a priori* classification had defined monitoring as a protective measure (Table 4.2). I used the monitoring and restoration responses as separate responses in my consequent analysis because these were each implemented by a relatively large fraction of operators. In accordance with my *a priori* classification, the adaptive responses of ‘relief measures’ and ‘support-seeking’ were significantly correlated.

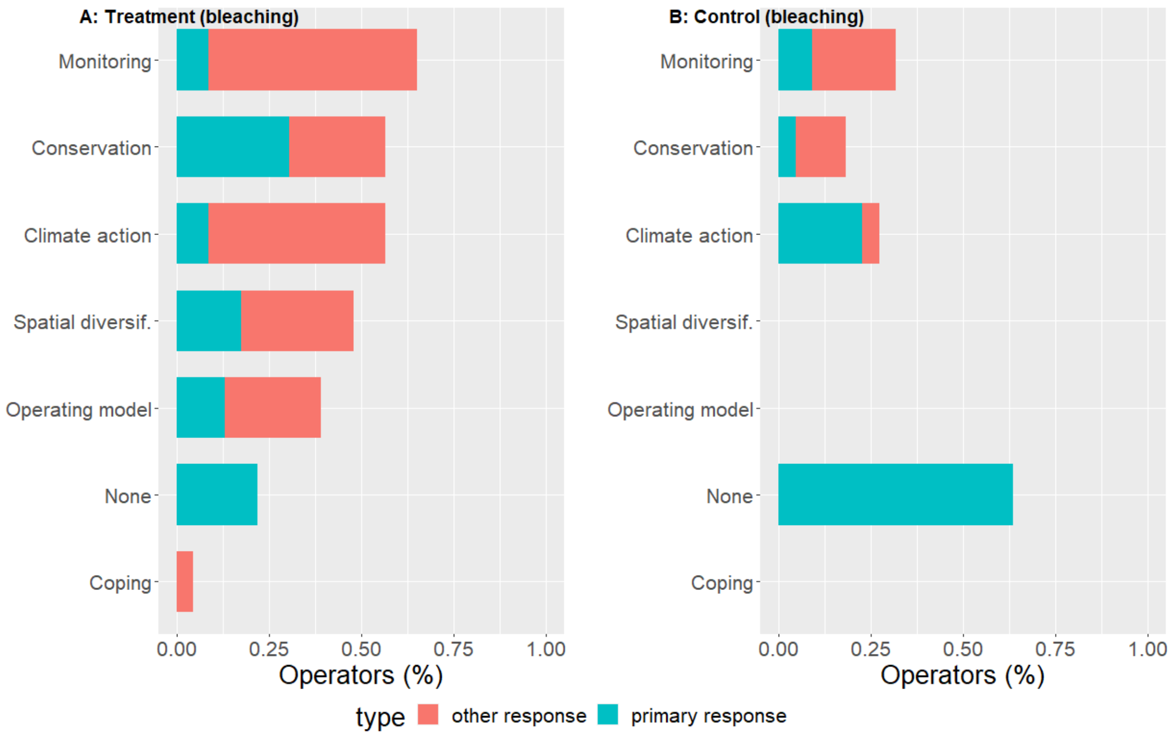
Finally, one of the adaptive responses that was mentioned as other response by 16% of the participants was ‘visitor education,’ i.e. informing and educating visitors about the causes and consequences of the climate disturbances. I merged the visitor education response with ‘climate action’ because they were significantly associated and because visitor education could potentially have an effect on future carbon emissions similar to a company taking climate action itself.

5.3.2 Adaptive Responses to Coral Bleaching

GBR tourism operators in my treatment sample implemented a wide variety of adaptive responses to impacts from coral bleaching (Figure 5.3A), while responses by operators in my control group were less diverse and common (Figure 5.3B).

Figure 5.3

Adaptive Responses to Coral Bleaching Impacts in Australia



Note. Graph (A) shows responses by reef tourism operators that had at least 25% of their reef sites severely affected by the climatic disturbance (n=23). Graph (B) shows the proportion of reef operators who took similar action in response to bleaching but were not directly affected by it (i.e., the control group, where none of their reefs were severely affected) (n=22). Climate action includes visitor education; operating model includes changes in the mode of operating, product diversification, and livelihood diversification. Coping measures includes relief measures, support-seeking, and seeking protection from risks.

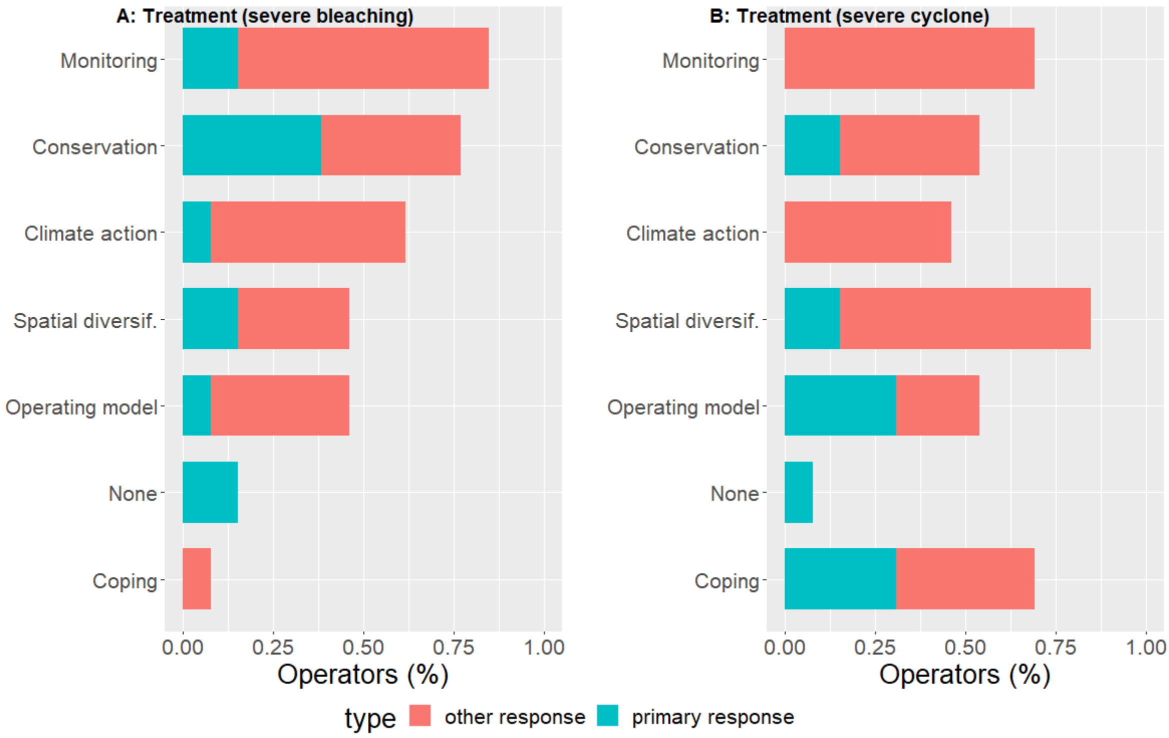
In my treatment sample, 22% of the reef tourism operators did not implement any adaptive response to the impacts from coral bleaching. The most common response to bleaching impacts was to begin with monitoring climate and/or reef conditions, while enacting or participating in measures intended to improve the health of the coral reef was most often mentioned as the primary response. Climate action and spatial diversification were implemented in response to bleaching impacts by about half of the sampled operators in the treatment sample. The majority (64%) of operators in my control group did nothing as primary response to the disturbance that did not directly affect their reef sites, while 23% took climate action as primary response. None of the operators in the control sample spatially diversified their reef sites and/or changed their operating model in response to bleaching. Operators in my treatment group were twice as likely to take climate action in response to coral bleaching as compared to operators in the control group (57% versus 28%).

5.3.3 Adaptive Responses to Tropical Cyclones

Adaptive response to impacts from coral bleaching differed from responses to cyclones (Figure 5.4). For cyclone impacts, spatial diversification became the most common adaptive response, while coping measures and changes in the company's operating model were most often implemented as a primary response. Three out of four of the primary responses within the 'operating model' responses for cyclones were linked to product diversification and one to livelihood diversification. Within the coping measures cluster, three out of four of the primary response were linked to relief measures and one to seeking protection from risks.

Figure 5.4

Adaptive Responses to Coral Bleaching and Cyclone Impacts in Australia



Note. Graph (A) shows responses by reef tourism operators that had at least 50% of their reef sites severely affected by coral bleaching (n=13). Graph (B) shows responses by reef operators that were affected by cyclone impacts, all of which had at least 75% of their reef sites severely affected (n=13).

5.3.4 Disturbance and Company Characteristics Associated With Adaptive Responses

About half of the operators in my sample had at least 50% of their reef sites affected by a climate disturbance (Table 5.2). The majority of respondents were mainly focused on snorkeling activities, had less than 20 passenger seats on their company's boats, and had a male company representative that was older than 45 years.

Table 5.2

Combined Sample Description for Reef Tourism Operators Affected by Bleaching and Cyclones

Indicator	Indicator levels	Frequency (sample fraction)
Disturbance type	Bleaching Cyclones	45 (78%) 13 (22%)
Disturbance severity (% of reef sites severely affected)	0% of reef sites 25% of reef sites 50% of reef sites 75% of reef sites 100% of reef sites	22 (38%) 10 (17%) 7 (12%) 8 (14%) 11 (19%)
Business type	Mostly snorkeling Mostly scuba	35 (60%) 23 (40%)
Business size (# of passenger seats on company's boats)	Small (0–20 seats) Medium (20–200 seats) Large (>200 seats)	28 (48%) 21 (36%) 9 (16%)
Company representative: age	Above 45 years Below 45 years	31 (53%) 27 (47%)
Company representative: age	Male Female	33 (57%) 25 (43%)

I found six relationships between my predictor variables and the adaptive responses that were significant at a p-level of 5%, four of which were linked to disturbance characteristics and two to the company representative (Table 5.3). I could not model the response of coping measures as the model did not converge because this response was highly skewed towards the cyclone sample. The models for the adaptive responses of spatial diversification and reef conservation had the highest predictability with respective R-squared values of 0.34 and 0.32.

Table 5.3

Logistic Regression Statistics for Adaptive Responses to Climate Disturbances on Australian Coral Reefs

	Operational	**Spatial**	**Monitoring**	**Restoration**	**Climate action**
Adoption rate	26%	38%	53%	41%	43%
R-squared	0.23	0.34	0.13	0.32	0.16
Disturbance: Cyclone	-0.27 (0.792)	1.11 (0.334)	-0.71 (0.508)	**-2.79 (0.038)***	-1.26 (0.221)
Disturbance severity	**2.82 (0.010)***	1.94 (0.067)	**1.92 (0.044)***	**4.11 (0.003)****	1.26 (0.156)
Business type: Scuba	-0.32 (0.680)	-0.52 (0.499)	0.44 (0.502)	-0.75 (0.336)	0.99 (0.147)
Business size: Medium	-1.25 (0.151)	0.97 (0.226)	0.91 (0.174)	0.62 (0.436)	0.67 (0.340)
Business size: Large	-0.74 (0.484)	-0.03 (0.977)	0.91 (0.317)	1.47 (0.165)	1.06 (0.265)
Representative: Below 45 years	0.17 (0.830)	-0.96 (0.244)	0.06 (0.929)	1.32 (0.141)	**-1.47 (0.036)***
Representative: Female	-0.28 (0.714)	1.02 (0.224)	0.11 (0.864)	**-2.12 (0.013)***	0.08 (0.906)

Note. Adoption rate reflects fraction of the total sample (n=58) that adopted particular response. R-squared reflects the proportion of the variance in the response variable that could be explained by the predictor variables. Coefficients are on log-odds (logit) scale. Coefficient for disturbance severity is based on z-scored variable to make its effect size comparable to the other binary predictors, and should be interpreted as the effect of a one-standard deviation change in the predictor variable on the response variable. Evidence against the null hypothesis of 'no effect' for each predictor is estimated using *p*-values with a 5% significance level (*p*-valued provided between brackets). Bold values are the correlation coefficients that were found to be significant at a *p*-value of 5%.

I found significant evidence against the null hypothesis that the severity of disturbance effects on individual operators would have no effect on the likelihood of three out of five responses being adopted to a climate disturbance: changes in operating model, monitoring, and restoration. Disturbance severity had the strongest effect size on the likelihood of implementing restoration measures. As compared to responses to coral bleaching, operators that were affected by tropical cyclones were more likely to spatially diversify their reef sites and less likely to adopt all other responses. The evidence against the null hypothesis (of no difference between bleaching and cyclone impacts) was significant for restoration measures: this response was significantly less likely for cyclone impacts. I found significant evidence against the null hypothesis that age of the company representative would not affect the likelihood of climate action: Companies with younger representatives were significantly less likely to undertake climate action. Finally, I found evidence against the null hypothesis that the gender of the company representative would not affect the likelihood of restoration responses: Companies with female representatives were significantly less likely to undertake restorative action.

5.4 Discussion

I explored adaptive responses by reef tourism operators to severe climate disturbances on coral reefs in Australia. I found that climate impacts from coral bleaching and tropical cyclones led to a diverse range of adaptive responses (research question 1). The most common responses included the monitoring of climate and/or reef conditions, reef restoration, spatial diversification, and climate action (Figure 5.3 and Figure 5.4). Overall, a previous classification of adaptive response categories based mostly on farmers affected by climate change (Table 3.3) applied well to adaptation by GBR tourism operators (research question 2). Increasingly severe impacts had an overall positive effect on the diversity of responses that were implemented. However, the impacts from tropical cyclones reduced the likelihood of restoration responses (research question 3). Finally, contextual characteristics of the company representative (age and gender) mediated some of the observed diversity in responses (research question 4).

My study identified only one common adaptive response that was not included in my survey: the education of visitors about climate impacts. Given that tourism operators are directly interacting with consumers (unlike most farmers), this additional response is likely to be industry-specific. My results indicate that in the specific case of reef tourism operators the adaptation categories of ‘diversification between livelihoods,’ ‘changes in the mode of operating,’ and ‘product diversification’ were associated and could be clustered together as one common response focused on making changes to a company’s operating model. While product diversification was conceptually clustered together with ‘spatial diversification’ within the ‘diversification within livelihood’ adaptation category (Table 4.2), my results (Figure 5.2) indicate that spatial diversification might be a qualitatively different adaptation response from other kinds of within-company diversification, and therefore may need to be treated separately. Further empirical research within other settings, such as agriculture, are needed to explore the accurateness of the adaptive response classification used here (Table 4.2). Within an agricultural setting, empirical studies could test whether the changing of crop types and/or varieties is associated with the spatial diversification of farm sites or whether these should be considered as separate types of adaptation.

Reef restoration measures (to improve the health of the coral reef) were most often implemented as the primary, i.e. the most important, response to coral bleaching (this was the primary response for 30% of the treatment sample). This could be interpreted as evidence for resource users seeking to restore service provision as triggered by changes in ecosystems (Chapin et al., 2010, 2022). The likelihood of responding by engaging in reef restoration was strongly affected by disturbance severity; i.e., the effect was larger than that for other adaptive responses (Table 5.3). This could indicate that if most touristic reef sites are severely affected by a climate-related disturbance, it may trigger some kind of restoration response (e.g. trying to prevent disturbance to damaged areas and/or facilitating its restoration) by commercial users of the reef. However, the effectiveness of specific restoration responses requires further research as persistent, reoccurring bleaching reduces the reef's ability to recover because of dead coral skeletons that reduce coral regrowth (Hughes, Kerry, Connolly, et al., 2019) and lower levels of stock replenishment (Hughes, Kerry, Baird, et al., 2019). Increased mortality of corals, and the direct destruction of reefs, might explain why reef tourism operators who were affected by cyclone impacts were less likely than operators affected by bleaching to adapt by enacting or participating in measures to improve the health of the coral reef. Cyclone-related damage on coral reefs is likely more severe in the short-term than bleaching-related coral mortality because it often affects not only the coral polyps but also the reef substrate. Tourism operators might consider restoration activities less suitable for impacts from cyclone-damaged reefs. My findings thus provide some support for the hypothesis that increasingly severe impacts might reduce the adaptation alternatives that are available to resource users (Hoegh-Guldberg et al., 2019). There may also be other mechanisms that contributed to my finding that reef restoration was a less frequent response for operators affected by cyclones. For example, it is highly likely that tourism operators that were affected by cyclone impacts had to deal with additional above-the ground damage (to boats, buildings, and communal tourism infrastructure), which may have provided them with less financial and human resources to participate in measures to improve the health of the coral reef as well.

Spatial diversification was an important adaptive response to climate disturbance on coral reefs as hypothesized by other authors (Hoegh-Guldberg et al., 2019; Stoeckl et al., 2021). About half of the operators relocated to different reef sites on their tours in response to bleaching impacts. This finding could explain why visitor satisfaction on the GBR did not decrease during and after the bleaching events in 2016 and 2017, which was reported in my earlier study (Figure 2.2). Operators might have temporarily or permanently relocated their tours to other reef sites that were of similar quality to the sites they were using before the disturbance, and thus visitor experiences might have been comparable before and after. My findings align with other recent empirical studies that identified spatial diversification as key adaptation strategy to environmental change (Gonzalez-Mon et al., 2021; Pecl et al., 2019; Powell et al., 2022; Silas et al., 2020) and as an important response by alpine tourism operators affected by climate change (Hoffmann et al., 2009; Mourey et al., 2020; Welling & Abegg, 2021). In my cyclone-impacts sample, about 80% of operators responded by changing their reef sites. This fraction was higher than the 50% of reef tourism operators in my treatment sample that responded spatially in response to bleaching. This difference was mostly explained by impacts from cyclones in my sample being overall more severe than those from coral bleaching. When I accounted for disturbance severity in my models, I did not find cyclone-affected operators to be significantly more likely to spatially diversify their reef sites.

Adaptive responses that were not, or were sparsely used by my bleaching treatment sample were more frequently used by my cyclone-impacts sample. That is, relief measures (e.g. selling assets, reducing staff, etc.), seeking support, and diversification between livelihoods were implemented by respectively 50%, 40%, and 30% of the reef tourism operators in my cyclone treatment sample. Notably, relief measures and the changing of tour activities were most often implemented as the primary response to impacts from cyclones. Thus I found that impacts from cyclones led a significant fraction of resource users to diversify their livelihoods away from their preferred ecosystem (Hoegh-Guldberg et al., 2019; Stoeckl et al., 2021). My findings complement other empirical research that suggests microeconomic actors are likely to diversify their livelihoods in response to environmental change (Barnes et al., 2020; Hossain et al., 2018). The support-seeking response might be more common for cyclone impacts because of the larger terrestrial impacts, while habituation might also play a role. The Queensland Government (where many of my sites were affected by both bleaching and cyclones) has well-established disaster relief packages for cyclones, but not for bleaching, which could have impacted this result.

Characteristics related to the company representative had a strong effect on the implemented adaptive responses, in particular on reef restoration and climate action. Reef tourism operators that were represented by female respondents were less likely to become involved in reef restoration. Speculatively, this could indicate that companies represented by females might have less confidence or opportunities in restoration-related activities. Further research is required, for example to evaluate whether any gender-related differences exist in perceptions towards restoration and to access to restoration funding and opportunities. Younger company representatives were significantly less likely to take climate action. The lower likelihood of companies represented by younger representatives to take climate action was surprising, as existing research indicates that older people are often more sceptical about climate change (Weber, 2016). Speculatively, my findings could indicate a legacy effect (Frumkin et al., 2012) where the companies led by an older generation of leaders want to leave an intact ecosystem for younger generations. Alternatively, younger leaders (and/or companies) might not have the required financial resources to invest in carbon reduction technologies.

More generally, my results provide a clear example of several proposed principles of resilience theory in action (R. Biggs et al., 2015). Diversity (in the form of spatial heterogeneity in the impacts of disturbance regimes), coupled with the availability of large areas of coral reef, appeared to enhance resilience by allowing operators to choose less-impacted reefs for tourism activities. However it remains unsure whether current adaptive responses enhance longer-term social-ecological resilience. The options for relocating to unaffected sites will become more limited as threats from elevated water temperatures and changes in disturbance regimes will increase. It could thus be argued that current adaptive responses are mainly ‘buying time’ until more robust adaptation and mitigation strategies are being developed and undertaken (Hallegatte, 2009; Howden et al., 2007). A substantial number of operators deliberately encouraged learning and participation in reef management, presumably in an effort to enhance reef social-ecological resilience. Whether local restoration efforts will be successful in increasing reef resilience and sustaining the attractiveness of the coral reef ecosystem as a major tourist attraction remains an empirical question for the future. In the case of local reefs that were severely affected by cyclone impacts, my results suggest that reef tourism operators already consider product diversification as a viable adaptation strategy.

The main limitation of my study was the exploratory approach I used to identify the most common and important adaptive responses within a coral-reef tourism setting. While I aimed to identify the most common types of adaptation, further research focusing on studying the most common responses in more detail as well as their social-ecological outcomes would enhance our understanding of adaptation and reef decline. For example, I did not account for the different types of involvement in restoration measures that could range from observation and reporting to active engagement (e.g. in crown-of-thorns starfish (*Acanthaster planci*) control or coral nurseries). Second, my sample might have been biased towards operators that would be more likely to engage in restoration measures as compared to the total population. I found that two common reasons for not participating in my study were that operators had either changed ownership or did not have staff around from the time of the first bleaching event I studied in 2016. Previous research with GBR tourism operators had identified lifestyle values as a key predictor of conservation responses (D. Biggs, Ban, et al., 2012). Companies that have their lifestyles attached to the reef will likely be those that have owners, managers, and/or staff that remain with the companies for longer periods of time. Third, given the relatively small population of reef tourism operators in Australia, I did not have the statistical power to include other relevant company and representative characteristics as predictors in my models, such as: quality of coral reefs used by operator; education and experience level of representative; and membership in environmental society or non-governmental organization.

My study provides empirical evidence for responses to climate change from actors in the private sector, which was identified as a key research gap in the adaptation literature (Berrang-Ford et al., 2021). My results indicate that adaptation is widespread within the tourism industry and driven in particular by the experienced severity of effects on individual operators. Adaptation is also commonly implemented in tandem with mitigation measures. My findings provide insights on the views and actions of tourism operators in response to climate-related disturbances, and thereby help in understanding the role of different actors in curbing and adapting to climate-related threats to coral reefs (Barnes et al., 2022). The importance of restoration and spatial responses has implications for reef-related policy makers, in particular in Australia, because environmental regulations and access permit systems might interfere with these preferred adaptive responses by microeconomic actors. On the other hand, government-led reef monitoring and restoration activities that involve tourism operators might have had a positive effect on the observed frequency of restoration and monitoring responses in my sample. For example, the Great Barrier Reef Marine Park Authority involves reef tourism operators in reef monitoring through the ‘Eye on the Reef’ program and in reef restoration through the ‘Crown-of-Thorns Starfish (COTS) control program.’

Further research could focus on doing comparative research on adaptation by reef operators in other locations (e.g. Caribbean, Coral Triangle, and the Red Sea) and in other industries (e.g. agriculture). Comparative research involving multiple regions with larger underlying populations of tourism operators would enable larger samples to be collected, which would permit testing how different levels of adaptive capacity might influence the adaptation process. Such comparative research could also test whether differences in the likelihood of implementing restoration as an adaptive response are indeed linked to the severity of ecological damage. For example, there might be some level of damage from which restorative adaptation becomes unfeasible, whereby microeconomic actors focus dominantly on spatial adaptation and partial or full livelihood change. Understanding such behavioural thresholds and nonlinear effects in complex systems (Janssen, 2002; Sterman, 2012), e.g. in coral reef social-ecological systems (Bartelet, 2017; Leenhardt et al., 2017), will be increasingly important due to the increasing severity of ecological change that is expected in the coming decades.

5.5 Conclusion

Here I showed that reef tourism operators in Australia are already severely affected by and actively adapting to the impacts from climate change. Prominent responses to climate disturbances such as reef monitoring, restoration, and spatial diversification point towards an intensified relationship between commercial users and the natural resource on which they depend. Australian reef tourism operators are also becoming involved in climate action. For cyclone impacts, as compared to bleaching, product and livelihood diversification become more relevant, and they point towards decoupling from the ecosystem. All adaptive responses became more common as operators were more severely affected, although climate action was already frequently undertaken even by operators that were not directly affected by a particular climate disturbance. The ecological impacts from cyclones that could generally be considered as more severe reduced the likelihood of restoration responses. My results thus point to potential limitations regarding the ability of microeconomic actors to adapt to more severe impacts on ecosystems. Finally, I found that company representative characteristics mediated some of the observed variety in how different actors adapted to climate disturbances. My findings provide real-world evidence for how resource users are impacted by, and are adapting to, the loss of coral reefs. Such empirical evidence can contribute to knowledge that can be useful for both on-the-ground actors in the private sector as well as policy makers aiming to design effective policies to facilitate microeconomic adaptation to ecological change. Comparative research within and outside of coral reef ecosystems is needed to facilitate generalization of theories on microeconomic adaptation.

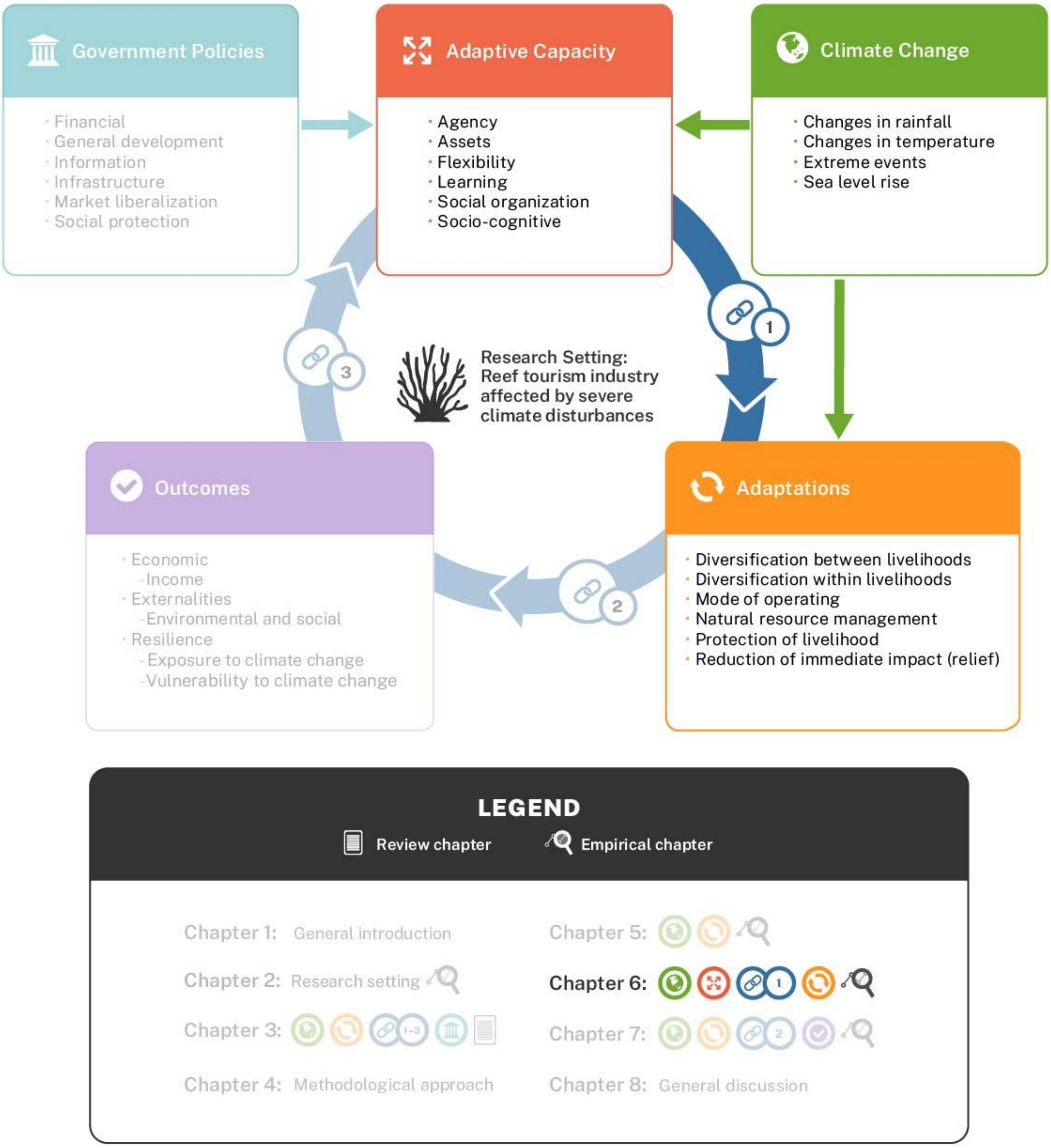
Chapter 6. Testing the Reliability of Adaptive Capacity as a Proxy for Adaptive and Transformative Responses to Climate Change

Adapted from: Bartelet, H.A., Barnes, M.L., Bakti, L.A.A., Cumming, G.S. (2023). Testing the reliability of adaptive capacity as a proxy for adaptive and transformative responses to climate change. *Global Environmental Change, 81, 102700.*
https://doi.org/10.1016/j.gloenvcha.2023.102700

In my sixth chapter, I test whether a multidimensional (using tangible and intangible determinants) measure of adaptive capacity is a reliable proxy for adaptation to climate disturbance by reef tourism operators in the APAC Region. This chapter builds on the previous chapter by testing for the effect of multidimensional adaptive capacity indicators on the likelihood that reef operators adopt particular responses to climate disturbances.

Figure 6.1

Research Gaps Addressed in Empirical Data Chapter 6: Reef Tourism Adaptation to Severe Climate Disturbances



Contributions

HB conceived the manuscript and developed the methodological approach with input from MB and GC. HB collected data in Australia, the Hawaiian Islands, the Mariana Islands, Japan, Fiji, and French Polynesia; HB and LB collected data in Indonesia; HB ran the analyses and wrote the first draft. MB, LB, and GC helped write and revise the manuscript.

Abstract

The concept of adaptive capacity is increasingly being applied to understand and predict people's ability to adapt to the emerging impacts of climate change. Despite its potential utility, the degree to which adaptive capacity is a reliable predictor of adaptation remains unclear; evidence for a causal relationship is insufficient and conflicting. To address this gap, I surveyed 231 reef tourism companies across eight countries in the Asia-Pacific that have been affected by severe climate disturbances between 2014 and 2019. I used a combination of descriptive and multivariate statistical approaches to explore the relationships between adaptive capacity, adaptive responses, and contextual conditions. My findings indicate that a comprehensive operationalization of actor-specific adaptive capacity is not necessarily a reliable proxy for measuring potential adaptation to future climate change. The severity of impacts on individual operators was the major determinant of adaptive action. Adaptive action might therefore be adopted autonomously by the majority of microeconomic actors (when they are severely affected), irrespective of their *a priori* adaptive capacity. Adaptive capacity was, however, a reliable proxy for the likelihood that an operator would take transformative action as their primary response to a climate disturbance; several of my indicators of adaptive capacity had a meaningful effect size, in particular those within the adaptive capacity domain of social organization. Policies focused on improving coordination and collaboration between industry, research, and government actors might therefore be more effective than alternatives in promoting long-term transformation of social-ecological

systems. Adaptation confidence and government effectiveness were barriers to transformative action, and I provide some potential explanations. Further empirical research is needed to evaluate the generality of my findings in different contexts over space and time.

6.1 Introduction

The intensity and scale of climate change impacts on people's lives are increasing rapidly (Pörtner et al., 2022; Watts et al., 2018). In addition to its longer-term influence on ecosystems and people, global heating has increased the frequency and severity of extreme weather events, with direct impacts on human life, property, and wellbeing (Canadell et al., 2021; Diffenbaugh et al., 2017; Hasegawa et al., 2021). It is assumed that the severity of direct climate change impacts on people can be reduced by careful planning and preparation, but the degree to which different responses are effective at reducing vulnerability can vary substantially; building houses out of flood zones when possible and otherwise building flood resilient homes, for example, is a much more proactive response to flooding than making additional resources available to flood victims (Andersson et al., 2022). Managing the impacts of climate change on people requires not just disaster preparedness, but also the adoption of proactive, forward-looking measures to reduce vulnerability. Adaptation to climate change ranges from coping measures to more transformative actions that can have long-term benefits for the sustainability and resilience of people and ecosystems (Fedele et al., 2019; Pelling et al., 2015; Wilson et al., 2020).

Human adaptation is considered key in buffering some of the most severe socio-economic consequences of the forecasted impacts of 21st century climate change on ecosystems and people (Nordhaus, 2013; Pörtner et al., 2022), but human ability to adapt to rapid climate change impacts is poorly understood. To predict adaptability, scientists have increasingly focused on measuring people's *adaptive capacity*; i.e., their latent potential to adapt to change and disruption (Cinner et al., 2018; Lemos et al., 2013; Siders, 2019; Smit &

Wandel, 2006; Yohe & Tol, 2002). However, the contribution of adaptive capacity within the adaptation discourse depends on the (assumed) axiom that adaptive capacity is indeed a reliable predictor of adaptation. Most research that assesses adaptive capacity aims to assess the (latent) state of a system prior to or independent of a significant change in climate exposure as a means of understanding the potential for adaptation (e.g. Engle, 2011).

In this paper, I contribute to recent empirical efforts to understand whether adaptive capacity is a reliable predictor for adaptation to climate change impacts (Barnes et al., 2020; Mortreux et al., 2020). Specifically, I explore how coral reef tourism operators in the Asia-Pacific (APAC) Region have been affected by severe climate disturbances (coral bleaching and tropical cyclones), and how their responses to these disturbance events related to both tangible and less-tangible determinants of adaptive capacity. I asked whether a comprehensive operationalization of actor-specific adaptive capacity could usefully explain variations in observed responses among tourism operators, while controlling for contextual conditions related to the disturbance characteristics and governance settings where the tourism operators were based. I first summarize the broader theoretical foundations of my research and then detail my methods and results.

6.2 Theoretical Framework

Although research on adaptive capacity and adaptation is rapidly increasing (Berrang-Ford et al., 2021; Siders, 2019; Vincent & Cundill, 2021), the extent to which adaptive capacity is a good proxy for people's ability to adapt to climate change remains unclear (Chapter 3; Barnes et al., 2020; Daw et al., 2012; Green et al., 2021; Mortreux et al., 2020). For example, some existing empirical evidence has shown that higher adaptive capacity does not necessarily lead to higher levels of adaptation (Coulthard, 2008; Linnekamp et al., 2011; Mortreux et al., 2020; Nielsen & Reenberg, 2010). This may be explained by adaptive capacity being too narrowly defined, e.g. where the focus is only on one of the many identified domains of adaptive capacity, such as ‘flexibility’ (Coulthard, 2008). Moreover, while adaptive capacity has been measured as a proxy for adaptation potential at varying levels, from households (Goldman & Riosmena, 2013) to regions (Vanschoenwinkel et al., 2016), there is a growing need to gain a better understanding of actor-specific adaptive capacity (Eisenack et al., 2014). This is because the existing literature on adaptation by microeconomic (i.e. firms and households) actors is heavily biased towards indicators of adaptive capacity in the domains of assets and learning; while other domains like agency, social organization, and socio-cognitive constructs are under-represented (Figure 3.3). Indeed, there have only been few quantitative empirical studies that have operationalised actor-specific adaptive capacity along multiple axes (Barnes et al., 2020; D’agata et al., 2020; Datta & Behera, 2022; Mortreux et al., 2020; Nyboer et al., 2022; Salgueiro-Otero et al., 2022), and thus our understanding of how tangible and less-tangible determinants of adaptive capacity influence adaptive behavior is in its infancy. The question thus remains whether a more comprehensive operationalization of adaptive capacity including tangible and less tangible determinants (captured by the six domains described above: assets, flexibility, learning, social organization, agency, and socio-cognitive constructs) can better predict adaptive behavior and ultimately lead to replicable findings in different contexts over space and time.

6.3 Methodology

I used a combination of descriptive and multivariate statistical approaches to explore the relationships between adaptive capacity, adaptive responses, and contextual variables that were relevant to the relationship between adaptive capacity and adaptive responses.

6.3.1 Adaptive Capacity and Contextual Conditions

I developed 15 key actor-specific indicators (Table 6.1) to capture the six broad domains of adaptive capacity as identified by Cinner and Barnes (2019). A recent review synthesized empirical evidence of microeconomic adaptation to climate change, mostly from Asian and African smallholder farms, and the adaptive capacity indicators that were most often found to be significant determinants of adaptation (Chapter 3. Literature review). Nine (out of 15) of my adaptive capacity indicators were based on this review, including '*exclusivity of reef access*' (agency, proxy for land ownership status in an agricultural context), '*participation in management*' (agency), '*savings*' (assets), '*boats*' (assets, proxy for farm size in an agricultural context), '*other services,*' e.g. rental and/or servicing of dive equipment, first-aid training, scientific activities, or transport (flexibility, as proxy for alternative livelihood options in an agricultural context), '*education*' (learning), '*experience*' (learning), '*government ties*' (organization), and '*industry memberships*' (organization, I focused on associations between local operators and stakeholders and excluded memberships in international dive associations such as PADI and SSI). My savings indicator was operationalized as a relative rather than an absolute measure of financial assets. I chose for a relative measure because (1) we deemed it a better proxy for company viability; (2) it facilitated comparison between smaller and larger companies; and (3) it contained less privacy-sensitive information which reduced the risk of non-response.

I developed three indicators capturing the adaptive capacity domain of socio-cognitive constructs, which is mostly absent within the current microeconomic adaptation literature (Figure 3.3). These indicators were based on a recent review that emphasized the role of socio-cognitive constructs in shaping adaptive capacity within the disaster risk reduction and behavioural science literature (Mortreux & Barnett, 2017). I included '*adaptation confidence*' as a proxy for self-efficacy to measure the respondent's assessment of the company's ability to perform adaptive action. I included '*competing concerns*' as a measure of the number of other issues of concern the business had with higher priority than the potential effect of climate disturbances (e.g. exchange rates, international politics, competition with other destinations, local issues, and/or within-company issues). '*Reef attachment*' was included as a proxy for place attachment, representing people's emotional ties to specific places. I measured this indicator as the importance of the coral reef sites the operator was using in the company's identity, a measure of place identity (Gurney et al., 2017). I hypothesized that operators with identities strongly linked to their local reefs might, for example, be less willing to adapt spatially by moving location and more likely to adapt by implementing stewardship measures.

Finally, three of my indicators were included based on deliberations with an Australian reef tourism industry expert (M. Curnock, personal communication, 2019). These indicators, based on local knowledge about a reef tourism social-ecological system (the Great Barrier Reef in Australia), included '*accessible dive/snorkel sites*' (flexibility), '*employee involvement*' (learning), and '*research ties,*' i.e., reliance on research institutes in decision-making (organization). The justification was that (1) a higher number of accessible sites could provide operators with more flexibility, e.g. to spatially diversify their reef sites; (2) the inclusion of employees in decision-making could enable operators to capture on-the-ground knowledge relevant for adaptation; and (3) a higher reliance on research institutes in decision-making could provide operators with the latest scientific insights relevant for adaptation.

I collected data on the indicators in my surveys using multiple-choice categories to provide a consistent and directly comparable level of detail in the answers. Based on the distribution of the collected data, I transformed each indicator into a binary variable (distribution of data before transformation is provided in R Markdown in datafile (Bartelet, 2023b)). While transforming some of my indicators into continuous or ordinal variables would likely have provided slightly more nuance, the nature of my research warranted the comparison of indicators at similar levels of complexity. I asked respondents about each indicator of adaptive capacity as they judged it to be before they were affected by the particular climate disturbance.

Table 6.1

Adaptive Capacity (AC) Indicators and Contextual Conditions Used as Predictor Variables to Understand Adaptive Responses to Climate Disturbances on Coral Reefs in the Asia-Pacific (APAC) Region

AC domain	AC indicator	Variable type	Variable units	Description
Contextual conditions	Government effectiveness	Binary	(0) Lower	Operators in Fiji, Indonesia, and the Mariana Islands.
			(1) Higher	Operators in Australia, French Polynesia, Japan, and the Hawaiian Islands.
	Distance to market	Continuous	# kilometres	Distance to nearest commercial airport.
	Disturbance type	Binary	(0) Bleaching	Company was affected by impacts from coral bleaching.
			(1) Cyclone	Company was affected by impacts from cyclone.
	Disturbance severity	Continuous	(0) None (1) 25% (2) 50% (3) 75% (4) All	Fraction of reef sites that company was using on tours that had more than a third of their area affected by climate disturbance.
Agency	Exclusivity of reef access	Binary	(0) Open	Accessed same sites as everyone else.
			(1) Limited	Accessed sites that were shared with few other operators or where no one else was able to go.
	Participation in management (coral and/or tourism)[a]	Binary	(0) Passive	No participation or attended meetings but didn't usually speak up.
			(1) Active	Attended and spoke up at meetings or had a formal position/ power over decision-making.

Assets	Savings	Binary	(0) <6 months (1) >6 months	Months the company would have been able to cover overhead costs (including costs for servicing debt) without revenue.
	Boats	Binary	(0) <20 seats (1) >20 seats	Total passengers-capacity on company's boats.
Flexibility	Other services	Binary	(0) Absent (1) Present	Company did not sell services other than tourism activities. Company sold services other than tourism activities.
	Accessible dive/snorkel sites	Binary	(0) <10 sites (1) >10 sites	Dive/snorkel sites that were accessible to the company.
Learning	Education	Binary	(0) Secondary (1) Graduate	General manager had secondary schooling and/or trade certificate. General manager had graduate degree (bachelor) or higher.
	Experience	Binary	(0) <10 years (1) >10 years	Years of reef tourism industry experience of general manager.
	Employee involvement	Binary	(0) Passive (1) Active	Employees not involved or informed prior to change. Employee opinions taken into account and/or employees participated in decision-making.
Organization	Government ties	Binary	(0) Absent (1) Present	Did not interact much with reef-related government agencies. Had at least some interaction with reef-related government agencies, mainly through formal events.
	Research ties	Binary	(0) Absent (1) Present	No reliance on research institutes in decision-making. At least some reliance on research institutes in decision-making.
	Industry memberships	Binary	(0) Absent (1) Present	Did not have membership in any tourism industry association. Had a membership in at least one tourism industry association.
Socio-cognitive	Reef attachment	Binary	(0) Weak (1) Strong	Coral reef sites not or somewhat important in company identity. Coral reef sites are major part of company identity.
	Competing concerns	Binary	(0) Absent (1) Present	Did not have competing concerns with higher priority. Had at least one competing concern with higher priority.

	Adaptation confidence	Binary	(0) Absent	None or low level of confidence in company's ability to adapt.
			(1) Present	At least moderate level of confidence in company's ability to adapt.

[a] For my *management participation* variable (agency), I separately measured participation in coral reef management and in reef tourism management. Because these predictors were highly correlated (Spearman's rank correlation coefficient of 0.74, *p*-value = 0.000), I merged them into a combined predictor. Specifically, I used the maximum value on any of these predictors for each operator.

I used the 'mice' package (Buuren & Groothuis-Oudshoorn, 2011; Zhang, 2016) in R modeling software to impute missing values in my dataset. For the 231 reef tourism operator surveys in my dataset, I had missing data for savings (15), competing concerns (7), adaptation confidence (5), education (1), accessible dive/snorkel sites (1), and reef attachment (1). Without imputing missing data, I would have had to exclude 20 operators from my sample and this would have led to the exclusion of other relevant data for these operators.

6.3.2 Analysis

I focused my efforts on exploring the effect of actor-specific adaptive capacity on the likelihood that reef tourism operators would primarily focus their adaptive responses to climate disturbances on coping, adaptive, or transformative measures (explained below). As such I did not, for example, analyze the frequency of which each respective adaptive response was implemented by respondents, but rather used the response that each operator took as their stated primary response to the studied climate shocks as my response variable. Because an operator could only have one primary response, the clusters were mutually exclusive and therefore I was able to use a multinomial logistic regression model to integrate and explore all of my data in one coherent statistical model. Multinomial logistic regression mimics some of the trade-offs and opportunity costs in the real world when prioritizing one behavioral response over another (Koster & McElreath, 2017).

The relationship between adaptive capacity and the primary responses to climate disturbances were explored using multinomial logistic regression in a Bayesian framework (Gelman et al., 2013). The Bayesian approach for binary regression extends to multinomial models. I used a baseline-category logit model in which the primary response of 'coping measures (short-term reactive measures enacted quickly to ward off immediate impacts)' was used as the baseline category. The likelihood of other response clusters ('adaptive' and 'transformative' measures) were then estimated against the baseline category. As such with sample size ni and αi representing the probability of an operator either adopting a coping (αi1), adaptive (αi2), or transformative (αi3) primary response to a climate disturbance:

$yi \sim \text{Multin}(ni; \alpha i1, \alpha i2, \alpha i3)$, with $\alpha i1 + \alpha i2 + \alpha i3 = 1$

The multinomial generalized linear model is parameterized in terms of the logarithm of the ratio of the probability of each category relative to that of my baseline category (coping: αi1), where β(j) is a vector of parameters for each category (Gelman et al., 2013, p. 426):

$\log(\alpha i2/ \alpha i1) = Xi\beta(j)$

$\log(\alpha i3/ \alpha i1) = Xi\beta(j)$

I used weakly-informative normal priors on the intercept and slope coefficients:

$\beta 0 \sim N(0,3)$

$\beta 1\text{-}19 \sim N(0,3)$

Although I had some indications of the effect of my predictor variables on adaptive responses (Figure 3.3), I decided to not use informative priors because most of the prior knowledge providing the foundation for my study is based on a different context, i.e., mostly smallholder farming in Asia and Africa.

Model was fit in the R modeling software, using Stan probabilistic programming language (B. Carpenter et al., 2017) and the 'brms' package (Bürkner, 2017), with the 'categorical' distribution family. Code is available in R Markdown (Supplementary Information). All predictors had a variance inflation factor (VIF) below 2, indicating no collinearity in my model. A total of 5000 'No-U-Turn (NUTS)' iterations with a warmup of 1000 and thinning rate of 5 were performed on each of the three chains. The chains were all well-mixed and converged upon a stable posterior (all rhat values < 1.05). The model was validated via DHARMa residuals (Hartig, 2018). Inferences were based on 80% (weak evidence) and 95% (strong evidence) credible intervals, using median highest posterior density intervals (HPDI).

Because all of my socio-economic indicators of adaptive capacity were included on a binary scale, I standardized all non-binary contextual variables (i.e., distance to market and disturbance severity) using z-scores, by subtracting the mean and dividing by twice the standard deviation (Gelman, 2008). Dividing by twice the standard deviation standardizes each variable to have a mean of '0' and a standard deviation of '0.5;' this technically standardizes all predictors on a binary scale. Coefficients for continuous predictors from the Bayesian models are now directly comparable and should be interpreted as the effect of a one-standard deviation change in the predictor variable on the response variable.

6.4 Results

6.4.1 Sample Description (Adaptive Capacity)

The pre-disturbance adaptive capacity of operators in my different study locations is summarized in Table 6.2. Other sample description details were presented in Table 4.4.

Table 6.2

Sample Description for Asia-Pacific Reef Tourism Operators by Location

Indicator	Units	Indonesia	Australia	Japan	Mariana islands	Hawaiian islands	French Polynesia	Fiji	Total
Respondents	#	87 (38%)	57 (25%)	24 (10%)	17 (7%)	15 (6%)	15 (6%)	16 (7%)	231 (100%)
Exclusivity of reef access	Open Limited	82 (94%) 5 (6%)	23 (40%) 34 (60%)	18 (75%) 6 (25%)	14 (82%) 3 (18%)	12 (80%) 3 (20%)	12 (80%) 3 (20%)	9 (56%) 7 (44%)	170 (74%) 61 (26%)
Participation in mgmt.	Passive Active	45 (52%) 42 (48%)	36 (63%) 21 (37%)	19 (79%) 5 (21%)	7 (41%) 10 (59%)	11 (73%) 4 (27%)	9 (60%) 6 (40%)	6 (38%) 10 (63%)	133 (58%) 98 (42%)
Savings	<6 months >6 months	52 (60%) 35 (40%)	39 (68%) 18 (32%)	14 (58%) 10 (42%)	11 (65%) 6 (35%)	9 (60%) 6 (40%)	10 (67%) 5 (33%)	6 (38%) 10 (63%)	140 (61%) 91 (39%)
Boats (seats)	<20 seats >20 seats	66 (76%) 21 (24%)	27 (47%) 30 (53%)	16 (67%) 8 (33%)	11 (65%) 6 (35%)	12 (80%) 3 (20%)	13 (87%) 2 (13%)	11 (69%) 5 (31%)	156 (68%) 75 (32%)
Other services	Absent Present	39 (45%) 48 (55%)	32 (56%) 25 (44%)	17 (71%) 7 (29%)	10 (59%) 7 (41%)	7 (47%) 8 (53%)	13 (87%) 2 (13%)	13 (81%) 3 (19%)	131 (57%) 100 (43%)
Accessible sites	<10 sites >10 sites	26 (30%) 61 (70%)	32 (56%) 25 (44%)	9 (38%) 15 (62%)	6 (35%) 11 (65%)	8 (53%) 7 (47%)	10 (67%) 5 (33%)	7 (44%) 9 (56%)	98 (42%) 133 (58%)
Education	Secondary Graduate	26 (30%) 61 (70%)	27 (47%) 30 (53%)	10 (42%) 14 (58%)	8 (47%) 9 (53%)	1 (7%) 14 (93%)	1 (7%) 14 (93%)	5 (31%) 11 (69%)	78 (34%) 153 (66%)
Experience	<10 years >10 years	66 (76%) 21 (24%)	23 (40%) 34 (60%)	7 (29%) 17 (71%)	5 (29%) 12 (71%)	5 (33%) 10 (67%)	6 (40%) 9 (60%)	7 (44%) 9 (56%)	119 (52%) 112 (48%)

Employee involvement	Passive	30 (34%)	23 (40%)	15 (63%)	12 (71%)	3 (20%)	6 (40%)	7 (44%)	96 (42%)
	Active	57 (66%)	34 (60%)	9 (38%)	5 (29%)	12 (80%)	9 (60%)	9 (56%)	135 (58%)
Government ties	Absent	62 (71%)	21 (37%)	20 (83%)	8 (47%)	8 (53%)	9 (60%)	11 (69%)	139 (60%)
	Present	25 (29%	36 (63%)	4 (17%)	9 (53%)	7 (47%)	6 (40%)	5 (31%)	92 (40%)
Research ties	Absent	41 (47%)	30 (53%)	21 (88%)	7 (41%)	5 (33%)	11 (73%)	9 (56%)	124 (54%)
	Present	46 (53%)	27 (47%)	3 (13%)	10 (59%)	10 (67%)	4 (27%)	7 (44%)	107 (46%)
Industry memberships	Absent	33 (38%)	30 (53%)	8 (33%)	6 (35%)	7 (47%)	5 (33%)	3 (19%)	92 (40%)
	Present	54 (62%)	27 (47%)	16 (67%)	11 (65%)	8 (53%)	10 (67%)	13 (81%)	139 (60%)
Reef attachment	Weak	33 (38%)	14 (25%)	9 (38%)	5 (29%)	6 (40%)	12 (80%)	4 (25%)	83 (36%)
	Strong	54 (62%)	43 (75%)	15 (63%)	12 (71%)	9 (60%)	3 (20%)	12 (75%)	148 (64%)
Competing concerns	Absent	34 (39%)	25 (44%)	12 (50%)	9 (53%)	7 (47%)	9 (60%)	6 (38%)	104 (45%)
	Present	53 (61%)	32 (56%)	12 (50%)	8 (47%)	8 (53%)	6 (40%)	10 (63%)	127 (55%)
Adaptation confidence	Absent	22 (25%)	7 (12%)	4 (17%)	10 (59%)	6 (40%)	8 (53%)	4 (25%)	62 (27%)
	Present	65 (75%)	50 (88%)	20 (83%)	7 (41%)	9 (60%)	7 (47%)	12 (75%)	169 (73%)

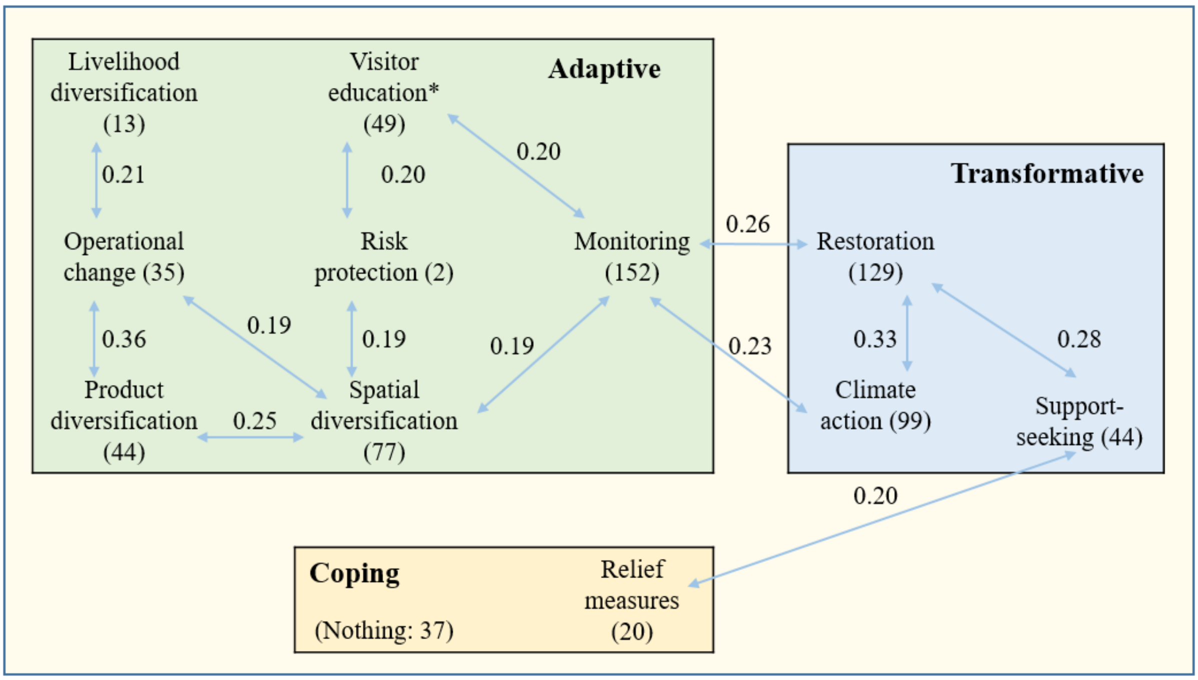
6.4.2 Adaptive Responses to Climate Disturbances on Coral Reefs

I identified three clusters that map reasonably onto theoretical developments classifying adaptation types in the adaptation literature by distinguishing (broadly speaking) between *coping*, *adaptive*, and *transformative* responses to climate change (Berrang-Ford et al., 2021; Fedele et al., 2019; Kates et al., 2012; Park et al., 2012; Pelling et al., 2015; Wilson et al., 2020). I therefore classified adaptive responses that distinguished between: (1) coping measures (e.g. doing nothing or looking for relief) (Bennett et al., 2014; A. P. Fischer, 2019); (2) adaptive measures (minor adjustments that can potentially buffer the impacts from climate disturbances, but that are unlikely to change the longer-term impacts and/or alter social-ecological system outcomes) (Kates et al., 2012; Park et al., 2012); and (3) transformative measures (actions that could affect and/or produce improved long-term social and ecological outcomes in the context of change) (Berrang-Ford et al., 2021; Kates et al., 2012; Park et al., 2012). I acknowledge that these are imperfect classifications and the concepts are still debated, yet I believe that they can be useful for understanding the potential outcomes of different actions and I therefore use them to align with existing research.

Monitoring (reefs and/or climate) and reef restoration measures were the most common adaptive responses to climate disturbances by reef tourism operators in the APAC Region, followed by climate action and spatial diversification (Figure 6.2). I classified operators that did nothing together with operators that implemented relief measures (e.g. selling assets or relieving staff) in my ‘coping’ cluster as these were likely the most vulnerable behaviors. I classified most of the other responses as ‘adaptive’ because these responses are relatively minor adjustments that can potentially buffer the impacts from climate disturbances, but will not likely change the longer-term impacts of climate change and/or alter social-ecological system outcomes. While monitoring was most strongly associated with restoration measures, conceptually it fits within the ‘adaptive’ cluster because monitoring is more of a passive response linked to observation and reporting of impacts, rather than active engagement in restoration measures. I included restoration measures, climate action, and support-seeking within my 'transformative' cluster because these could affect and produce better long-term outcomes (e.g. a more sustainable ecosystem with the ability for the tourism industry to continue thriving). While support-seeking was also significantly associated with coping measures, I found it to be more strongly associated (Spearman's rank correlation coefficient of 0.28 versus 0.20) with restoration measures. I classified support-seeking as transformative because it could involve building alliances with different stakeholders groups to address the social-ecological challenges associated with climate disturbances. For example, I found evidence in my surveys that some operators sought support from fishing communities, local citizens, government agencies, and/or non-governmental organizations to address environmental threats.

Figure 6.2

Clustering of Adaptive Responses to Climate Disturbances by 231 Asian-Pacific Reef Tourism Operators



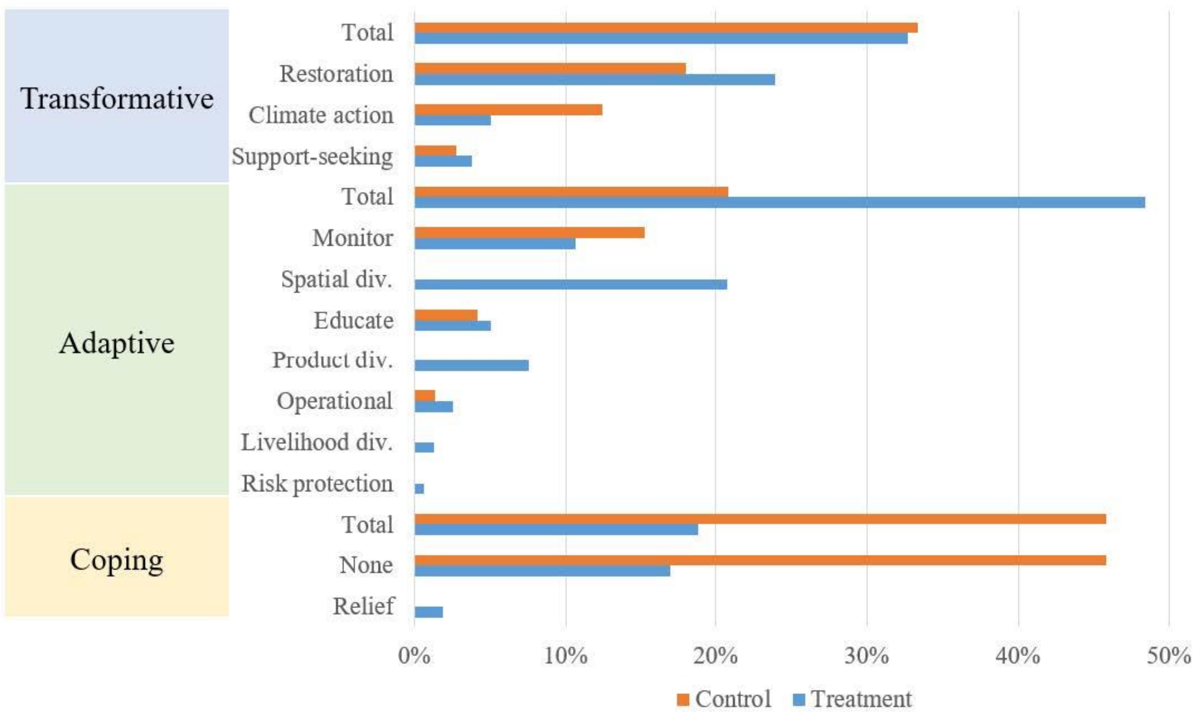
Note. Graph includes only significant partial correlation effects (Spearman's rank correlation coefficient) between responses that are significant at a p-level of 1%. Numbers in brackets indicates prevalence of adaptive response (i.e., how many operators adopted a particular response).

Visitor education was mentioned as an 'other' response by several of the operators in my sample: 14% in Indonesia, 16% in Australia, 6% on the Mariana Islands, 20% on the Hawaiian Islands, 27% on French Polynesia, and 6% in Fiji. I added this response to my surveys on the Ryukyu Islands in Japan that were started later to test whether this response might have been underestimated. I found that 79% of the operators in the Ryukyu Islands stated that they educated their visitors as a response to climate disturbance when they were explicitly asked whether they had done so (and 25% did so as primary response). While this might have introduced bias into my sample because my surveys in Japan were slightly different, this only affected my modeling results through the six operators in Japan that selected 'visitor education' as their primary response (as explained in my analysis section). The results from my analysis did not change in any meaningful way when I removed these six surveys, so I retained these in my analysis using the 'adaptive' category as primary response.

In both my treatment and control samples, about a third of the operators undertook 'transformative' measures as their primary (i.e., most important) response to a climate disturbance (Figure 6.3). Restoration was most frequently adopted as the primary response within the transformative cluster in both samples, while the fraction of operators that used climate action as their primary response was about twice as high in the control sample as compared to the treatment sample. Seven out of the eight operators that sought support as their primary response also undertook restoration measures, and this provided additional justification for including this response as a primary response within the 'transformation' rather than the 'coping' cluster. That is, if an operator would have mainly sought support (e.g. financial) as relief measure they would likely not have the resources to also participate in restoration action. In my treatment sample, almost half of the operators undertook an 'adaptive' measure as primary response, while only about 20% of operators in the control sample did so. Monitoring was the most common primary response in the control sample, while spatial diversification was the most common within the treatment sample. Almost half (45%) of operators in the control group did nothing as their primary response to a climate disturbance, while less than 20% of the operators in the treatment sample were classified in the 'coping' cluster (which included doing nothing) as their primary response.

Figure 6.3

Primary Responses to Climate Disturbances by 231 Asian-Pacific Reef Tourism Operators



Note. Graphs shows primary (i.e. most important) responses sorted by treatment and control group. Treatment group consists of operators that had at least 25% of their reef sites severely affected by the climatic disturbance (n=159). Control group consists of operators who took similar action as primary response to climate disturbance but who were not directly affected by it (i.e. none of their reefs were severely affected) (n=72).

6.4.3 Adaptive Capacity and Contextual Conditions Associated With Adaptive Responses

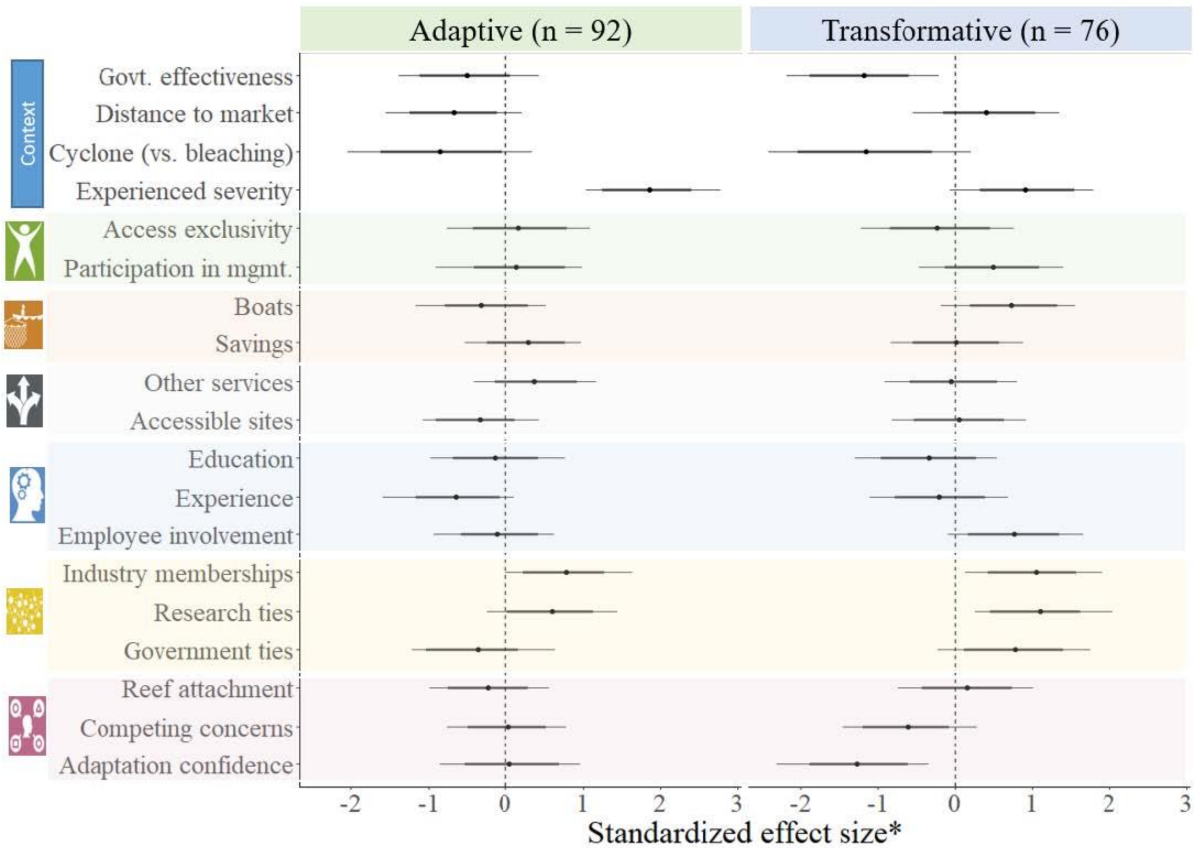
I found strong evidence, at a 95% credible interval, for six relationships in my model. In the following section, I refer to positive statistical relationships between adaptive capacity indicators and/or contextual conditions and particular response clusters as 'enablers' and negative statistical relationships as 'barriers'. However, a negative correlation is not necessarily indicative of a barrier to adaptation because it might only indicate that attributes are more frequently associated with other types of adaptive action, not necessarily because the alternatives are faced with a barrier.

More severely affected operators were more likely to take adaptive action as primary response, compared to doing nothing or taking relief measures (i.e., 'coping,' Figure 6.2). The effect size associated with disturbance severity as an enabler of adaptive action was stronger than all other effect sizes in my model. Having an *industry membership* (organization) in at least one tourism industry association had a positive effect on the likelihood that a reef tourism operator would undertake either adaptive or transformative action as their primary response as compared to a coping response, with respective mean odds ratios of 2.2 and 2.9 as compared to operators that did not have any membership. Operators that had at least some *research ties* (organization) were also more likely to take transformative action as primary response, with a mean odds ratio of 3.0. Operators in countries with higher *government effectiveness* (contextual) and operators with higher *adaptation confidence* (socio-cognitive) were less likely to undertake transformative action as primary response, both with a mean odds ratios of 0.3.

I found weak evidence, at a 80% credible interval, for *research ties* (organization) being an enabler of adaptive action and *distance to market* (contextual), *disturbance type* (contextual), and the *experience* level of the general manager (learning) being barriers to adaptive action as primary response. For transformative action, I found weak evidence for a positive effect from *disturbance severity* (contextual), *employee involvement* (learning), *boats* (assets), and *government ties* (social organization), while there is also weak evidence that *disturbance type* (contextual) and *competing concerns* (socio-cognitive) were barriers.

Figure 6.4

Caterpillar Plots Showing the Effect of Contextual Conditions and Adaptive Capacity Indicators on the Likelihood That Reef Tourism Operators (n=231) Implemented a Coping Measure, Adaptive Measure, or Transformative Measure as Their Primary Response to a Climate Disturbance



Note. Outputs are based on a multinomial logistic regression model in which estimates are based on comparison to the reference model where operators implemented a coping measures (i.e. doing nothing or relief) as their primary response to disturbance. Parameter estimates are Bayesian median highest posterior density intervals (HPDI) at 80% (thicker lines, for weak evidence) and 95% (thinner lines, for strong evidence) credible intervals (CI) respectively. CIs measure how compatible a relationship between an explanatory and response variable is with the data under the background statistical assumptions. Round dots show the parameter estimate. Lines that do not cross the ‘0’ point (either positively or negatively) could be interpreted as showing a meaningful effect within the respective CI. All estimates are on a logit scale. Non-binary indicators (i.e. distance to market and experience severity) have been standardized using z-scores so that the effect sizes are comparable to binary predictors.

6.5 Discussion

The ten adaptive responses to climate change adopted by reef tourism operators in the APAC Region could be classified into three clusters, corresponding to coping, adaptive, and transformative measures (Berrang-Ford et al., 2021; Fedele et al., 2019; Kates et al., 2012; Park et al., 2012; Pelling et al., 2015; Wilson et al., 2020). Operators in my treatment sample were more than twice as likely as operators in the control sample to take adaptive action as their primary response, while operators in the control sample were more than twice as likely as those in my treatment sample to do nothing (Figure 6.3). This is perhaps not surprising because operators in the control sample (whose reefs had not yet been severely affected by climate change) are unlikely to see the need to take adaptive measures such as spatial diversification of their reef sites. However, I found that the fraction of operators that adopted transformative measures as their primary response was about equal in my treatment and control groups (Figure 6.3). This finding demonstrates that operators that have not yet been severely affected by climate change are already becoming involved in actions that they believe can have long-term benefits for the sustainability and resilience of people and ecosystems (Berrang-Ford et al., 2021; Kates et al., 2012). Speculatively, my findings could be interpreted as saying that about one in three actors, irrespective of impacts, are beginning to prioritize transformative action in light of climate threats.

The likelihood of adopting adaptive measures as a primary response was associated mostly with the *severity* (contextual condition) of climate impacts on individual operators, and the effect size was stronger than for transformative action (Figure 6.4). I did not find any barriers towards adaptive action as a primary response within my adaptive capacity domains, and only strong evidence for one positive determinant: *industry memberships* (organization). My findings indicate that when defining adaptation in a limited sense, i.e., as relatively minor adjustments that can potentially buffer the impacts from climate disturbances, actor-specific adaptive capacity did not seem to be a reliable proxy for actual adaptation in this case—even when broadly conceptualizing adaptive capacity to include various domains (e.g. agency, socio-cognitive constructs, etc.). Irrespective of adaptive capacity (except *industry memberships*), reef operators increasingly prioritized adaptive measures as they became more severely-affected (Ilosvay et al., 2022). This is important because it shows that adaptive action might be provided autonomously by the majority of microeconomic actors (Fankhauser, 2017; Pecl et al., 2019). However, further research is required to assess whether there are differences between responses within the adaptive action cluster, as well as to assess the outcomes that are associated with such adaptive action (Figure 1.1; Berrang-Ford et al., 2021).

Unlike the mostly absent effect of adaptive capacity on adaptive action, I found that an operator's decision to prioritize transformative action was strongly and meaningfully associated with specific aspects of adaptive capacity, in particular with the domain of social organization (Figure 6.4). *Industry memberships*, *research ties*, and *government ties* all had a meaningfully positive effect on the likelihood of an operator becoming involved in transformative action as a primary response to a climate disturbance. My finding that the domain of social organization is important for transformative action is in line with one of the few quantitative empirical studies that have operationalised actor-specific adaptive capacity along multiple axes (Barnes et al., 2020). I believe my findings make sense conceptually because it is likely to be difficult to transform a social-ecological system individually; collective action and alliances are required (Gelcich et al., 2010). My results indicate that all types of social capital are important for transformative action (Dressel et al., 2020; Pelling & High, 2005), i.e., bonding ties between reef operators (through *industry memberships*) and bridging and linking ties between operators and reef-related stakeholders (through *research ties* and *government ties*).

Our categorization of spatial and livelihood diversification as adaptive rather than transformative measures could be questioned; they are also consistent with some definitions of transformation (Park et al., 2012) because they might indicate a major shift in the reef tourism operator's operations. We classified these responses as adaptive because they were correlated with other adaptive measures and because of evidence in our surveys that indicated that these responses were often incremental rather than transformational. Spatial diversification consisted mostly of switching between reef sites that were already available to operators rather than (for example) leaving a place to which they were attached. Livelihood diversification, which was only adopted by 13 out of 231 (6%) of the operators we sampled, consisted mostly of operators switching to other products and/or services that were relatively incremental (e.g. selling reef-safe products). Notably, our survey consisted for the largest part of operators that were still in operation years after a climate disturbance. While we included one operator that fully diversified away from reef tourism in response to a tropical cyclone, it is likely that our study missed some operators who stopped operations in response to a climate disturbance. The livelihood diversification response might thus be underestimated in our results. It could also be argued that the responses we classified as transformative are more associated with sustainability and reef tourism operators' environmental responsibility rather than adaptation to climate change (e.g. in the sense of reducing vulnerability). For this reason, operators in both the control and treatment group might appear to have engaged in the responses I classified as transformative, indicating that what is considered transformative adaptation may not necessarily be adaptation. The speculative conclusion that actors are engaging in transformative adaptation could thus be a bit misleading because these companies may only be engaged in pro-environmental action but not necessarily in response to the perceived need to reduce vulnerability to climate change. The definition of transformation would also depend on what is being transformed, the individual company, the reef tourism industry in which the company is embedded, the ecological system on which the company is dependent, or a combination of these three.

Research on adaptive capacity has implications for policy because it can identify which groups or sectors require adaptation support and which barriers to adaptation are most important to address (Siders, 2019). Current adaptation support programs are mainly focused on the adaptive capacity domains of assets and flexibility (Cinner et al., 2018; Lemos et al., 2013). My results suggest, however, that policies aimed at fostering collaboration and integration of policy, research, and industry decision-making may prove more effective in promoting long-term social-ecological system change. I also found some evidence that my indicator for decentralized learning (*employee involvement* in decision-making), had a positive effect on transformative action. This finding indicates that empirical learning, based on information captured by people closest to the system at hand (Gosnell et al., 2019; Hayek, 1945; Henry, 2009), could provide an important function in attempts to increase the sustainability of social-ecological systems. This finding reinforces recent evidence showing that people's direct interaction with ecosystems (i.e., social-ecological ties) was a significant determinant of transformative action (Barnes et al., 2020). Taken together these findings caution against the development of climate change adaptation strategies at higher governance levels without involving local stakeholders that have in-depth understanding of local social-ecological systems.

Government effectiveness (contextual condition) was negatively associated with transformative action on the micro-level (Figure 6.4). There are few comparative studies that compare adaptation to similar climate impacts in countries with high and low government effectiveness. Such comparative research could help quantify the 'adaptation deficit,' i.e., the assumption that people in less-affluent countries will be less able to adapt to climate change because of lower adaptive capacity (Brooks et al., 2005; Fankhauser & McDermott, 2014; Hughes et al., 2012). My study demonstrates that, counter to the 'adaptation deficit' hypothesis, reef operators in countries with lower government effectiveness were not less likely to adapt to climate change than reef operators in countries with higher government effectiveness. My findings are in line with recent empirical evidence that Indonesia had the highest percentage of households that had implemented high-effort adaptation measures in response to floods, compared to households in China, the Netherlands, and the United States (Noll et al., 2021). Moreover, I found that operators in countries with lower government effectiveness were more likely to adopt transformative action as primary response to a climate disturbance. This could indicate that microeconomic actors in countries with higher government effectiveness might expect authorities to be responsible for implementing transformative action such as reef restoration and climate action measures (Mortreux et al., 2020; Mortreux & Barnett, 2017). Conversely, in countries with lower government effectiveness, people might be relying more heavily on self-organization in terms of social-ecological system transformation (Ostrom, 2010).

Operators with higher *adaptation confidence* (socio-cognitive constructs), my proxy for self-efficacy, were less likely to take transformative action as their primary response, rather than doing nothing or taking relief measures (coping) (Figure 6.4). Prior theoretical studies have identified self-efficacy as a positive determinant of adaptive action (Bandura, 1977; Grothmann & Patt, 2005; Mortreux & Barnett, 2017) and a meta-analysis of climate change adaptation studies found evidence in line with this theory (van Valkengoed & Steg, 2019). In a fishery context, self-efficacy was positively associated with transformative responses such as engaging in other livelihoods (Béné et al., 2016). My findings indicate, oppositely, that self-efficacy was a meaningful barrier to the adoption of transformative action. The relationship between self-efficacy and transformative action might differ depending on context, for example between the fishing and tourism industry. Additionally, our transformative responses mainly consisted of coral restoration and climate action and these responses might have a different relationship to self-efficacy than livelihood diversification. Speculatively, *adaptation confidence* could be associated with people's perceptions about the (future) severity of climate change (Grothmann & Patt, 2005; Patt & Schröter, 2008) and people who feel less threatened by climate change might be less likely to take transformative action such as restoration or climate action. If transformative action is required to safeguard the ability of the wider system to adapt, my results could indicate that a more nuanced perspective on the role of self-efficacy might be required within the climate change adaptation discourse. Further research with a more detailed focus on the measurement of self-efficacy and its effects on adaptive and transformative action is required to study these effects in more detail.

Adaptive capacity has long been recognized as an element of resilience and transformation (Olsson et al., 2010). Resilience has also been operationalized as an outcome of five different 'capacities' including preventive, adaptive, absorptive, adaptive, and transformative capacities (Manyena et al., 2019). These frameworks have a clear interface with the three-fold categorization that emerged from our data for adaptive responses. Our findings contribute to the operationalization of adaptive capacity, and by extension to the operationalization of resilience theory, by identifying which domains of adaptive capacity (Cinner and Barnes, 2019) are meaningfully associated with different types of responses. Further adaptation studies might benefit from drawing on the capacities framework (Manyena et al., 2019) by also studying *preventive* and *anticipative* responses to climate change, and assessing how they relate to different domains of adaptive capacity.

The main limitations of my study were the exploratory approach that I had to use to identify the most common and important adaptive responses within a coral-reef tourism setting and the need to rely on recall data. Recall may have been particularly challenging for respondents for some socio-cognitive indicators, which could have been influenced by current rather than prior perceptions. Further research focusing on the most common responses and their social-ecological outcomes, and collecting real-time measures of adaptive capacity and responses to perturbation, would enhance our understanding of adaptation and reef decline. I also chose to focus on primary responses to climate disturbances; there may be important adaptation strategies consisting of multiple responses (both adaptive and transformative) undertaken simultaneously that were not covered here. Several authors have proposed that actors employ a bundle of strategies to prepare for, cope with, and adapt to shocks (Béné et al., 2016; Eisenack and Stecker, 2012; Vincent et al., 2013). These are often proactive, concurrent, or reactive and as such are deployed at different times during an event. Our chosen methodology allowed each operator to have only one primary response, which was consequently categorized as coping, adaptive, or transformative. Analyzing the relationship between adaptive capacity and a basket of responses that operators employed may have rendered slightly different results and could be the focus of future research. Overall, more empirical evidence is needed to provide a definitive statement about whether and how actor-specific adaptive capacity can be used to understand future responses to climate change; recent work using consistent and replicable adaptive capacity domains (Cinner & Barnes, 2019) is promising in this regard (Barnes et al., 2020; D'agata et al., 2020; Nyboer et al., 2022; Salgueiro-Otero et al., 2022).

6.6 Conclusion

Both affected and non-affected reef tourism operators in the APAC Region are already taking adaptive and transformative action in response to severe climate disturbance on coral reefs. My findings indicate that people's latent capacity to adapt (i.e., adaptive capacity) might not be a reliable proxy for measuring potential adaptation to future climate change. I found strong evidence for only one out of 15 indicators of adaptive capacity in terms of its effect on the likelihood that an operator would primarily take adaptive action to climate change rather than taking coping measures or doing nothing. Moreover the effect of the *disturbance severity* on the likelihood that an operator primarily adapted to a climate disturbance was twice as strong as the effect of the adaptive capacity indicator of *industry memberships* (organization). The priorization of adaptive action to climate disturbance is therefore strongly driven by the severity of impacts on individual operators rather than by each operator's adaptive capacity. Conversely, adaptive capacity was a reliable proxy for the likelihood that an operator would take transformative action as their primary response to a climate disturbance; several indicators of adaptive capacity had a meaningful effect. Most notably, I found evidence that all three indicators within the adaptive capacity domain of organization that I tested (*industry memberships*, *government ties*, and *research ties*) and one indicator within the adaptive capacity domain of learning (*employee involvement*), were meaningful determinants of transformative action. Thus, my results emphasize the importance of social capital, collaborative networks, and the incorporation of local knowledge. Government policies focused on promoting collective action through knowledge sharing might be more effective in terms of promoting long-term transformation of social-ecological systems than policies focused on other domains of adaptive capacity such as assets or flexibility. *Adaptation confidence* (within the domain of socio-cognitive constructs) and the country's *government effectiveness* (contextual conditions) were found to be barriers to transformative action. Further research is required to understand the causal mechanisms behind these effects before these barriers can be addressed, and to evaluate the generality of my findings in different contexts over space and time. Overall my findings suggest that a more comprehensive operationalization of adaptive capacity, including tangible and less tangible determinants, will be helpful in increasing our understanding of people's ability to take adaptive and transformative action in response to severe impacts from climate change.

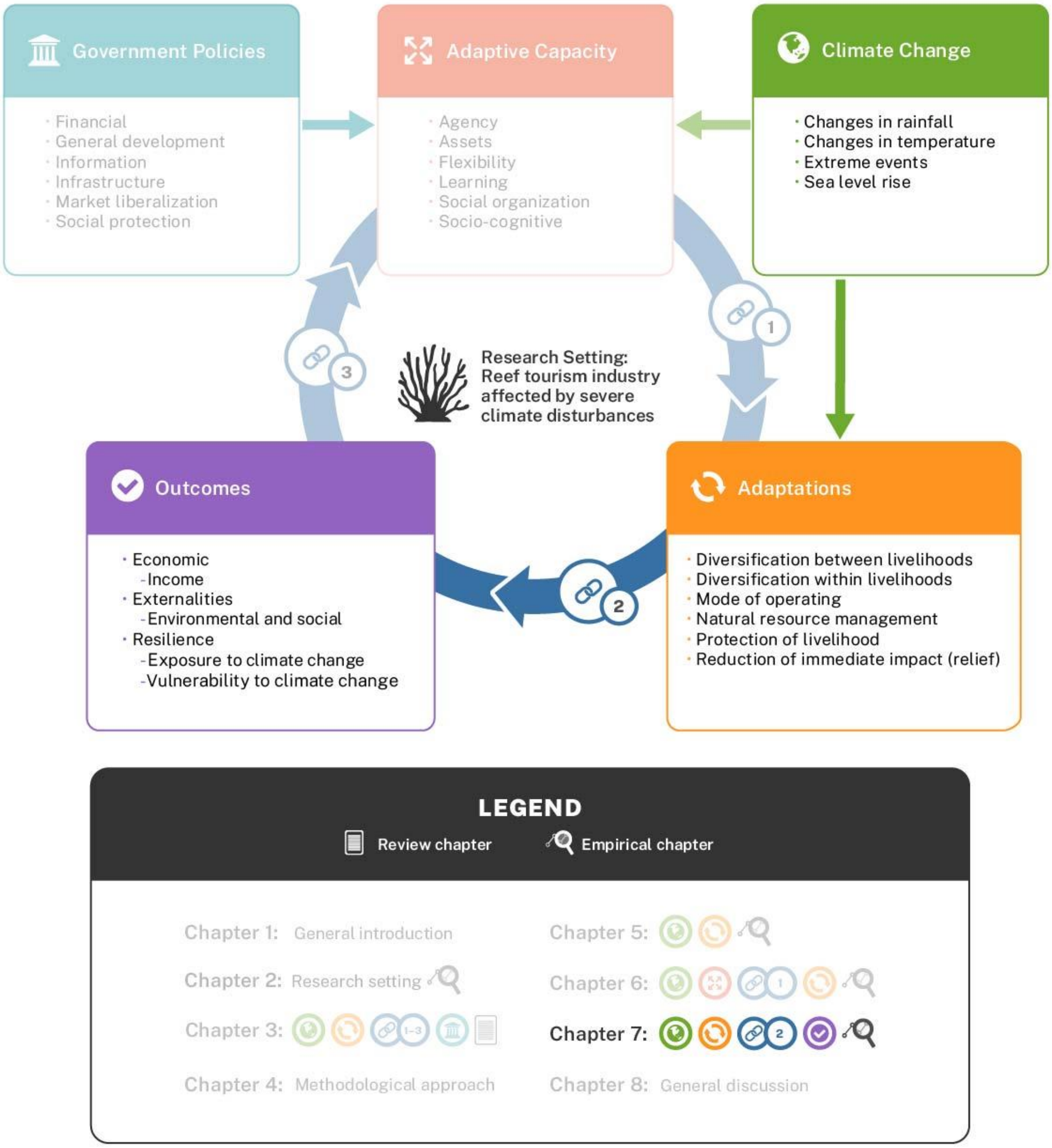
Chapter 7. Operationalizing and Measuring 'Successful' Adaptation to Climate Change

Adapted from: Bartelet, H.A., Barnes, M.L., Bakti, L.A.A., Cumming, G.S. (In review). Operationalizing and measuring 'successful' adaptation to climate change. *Environmental Science & Policy*.

In my seventh chapter, I evaluate the relationship between APAC reef tourism operators' adaptive response to climate change and the outcomes they experienced one year after a disturbance in terms of perceived climate risk, perceived climate vulnerability, and economic, environmental, and social sustainability. I used the same sample as in Chapter 6. Testing the reliability of adaptive capacity as a proxy for adaptive and transformative responses to climate change, but removed 4 operators because they had several missing data on outcomes, and 18 operators in Indonesia that I surveyed about a bleaching event in 2019, where there was potential interference on outcomes from initial COVID-19 pandemic impacts.

Figure 7.1

Research Gaps Addressed in Empirical Data Chapter 7: Reef Tourism Adaptation to Severe Climate Disturbances



Contributions

HB conceived the manuscript and developed the methodological approach with input from MB and GC. HB collected data in Australia, the Hawaiian Islands, the Mariana Islands, Japan, Fiji, and French Polynesia; HB and LB collected data in Indonesia; HB ran the analyses and wrote the first draft. MB, LB, and GC helped write and revise the manuscript.

Abstract

In a context of rapid global change, understanding whether and how adaptation to climate change can be considered 'successful' has become an important research gap within the climate change adaptation literature. While definitions of adaptation success have been formulated, how they can be operationalized and tested within an empirical context remains unclear. To address this gap, I operationalized one of the most prominent definitions of 'successful' adaptation within the academic literature, which describes it as adaptations that support reductions in risk and vulnerability without compromising sustainability (Doria et al., 2009). Specifically, drawing on data collected from 209 coral reef tourism operators across 28 locations and eight countries in the Asia-Pacific, I empirically explored how the socioeconomic outcomes that operators experienced one year after experiencing a severe climate disturbance (either coral bleaching or a cyclone) related to the particular types of adaptation they adopted in response to the disturbance. I used chi-squared tests and multivariate regression to explore the relationships between adaptive responses, adaptation outcomes, and contextual conditions. Compared to a control group with non-affected operators, operators affected by a climate disturbance were significantly more likely to have experienced an increase in perceived climate risk and reduced economic and environmental sustainability. However, my findings indicate that that at least some adaptation responses were effective in promoting desirable outcomes, such as reductions in perceived risk and vulnerability. Spatial diversification provided resilience for sustaining economic viability

despite environmental impacts, while reef restoration measures reduced perceived climate risks for some operators. Moreover, seeking support from others led to a reduction in perceived vulnerability in a coral bleaching context, while also having positive economic outcomes. My findings suggest a need for further research on the causal linkages between adaptation measures and their outcomes, experimentation with different statistical methods, and empirical tests of the generalizability of my findings in different contexts over space and time.

7.1 Introduction

Adaptation to climate change has become a topic of increasing interest as the initial impacts of contemporary warming manifest themselves (Berrang-Ford et al., 2021). Given that the world will most likely exhaust the 1.5°C carbon budget by the year 2029 (DNV, 2022), further warming and warming-related climate impacts are to be expected over the coming decades. These impacts will have an increasing impact on society in terms of human health, wellbeing and economic activity (Pörtner et al., 2022). Local and regional differences in their magnitude will depend on both the the extent to which people are affected and their ability to adapt (Auffhammer, 2018; Kahn, 2016).

Despite increasing scientific interest in ongoing human responses to impacts of climate change, we still lack knowledge of how effective they are at reducing climate-related risks (Berrang-Ford et al., 2021). Bartelet et al. (Chapter 3. Literature review) reviewed empirical evidence for microeconomic (firms and households) adaptation to climate change between 1995 and 2020. Within the 80 studies they identified, only 14 evaluated adaptation outcomes (and only four assessed outcomes quantitatively). A handful of papers published since the Bartelet et al. (Chapter 3. Literature review) review have explicitly included and evaluated the outcomes of microeconomic adaptation. Broadly speaking, these contributions have demonstrated that adaptation had a positive effect on farm and household income

(Ankrah Twumasi et al., 2022; Dhakal et al., 2022; Etwire et al., 2022; Khan et al., 2021) and reduced climate risk (Dhakal et al., 2022). In one case, adjusting farming to climate change impacts was found to produce better livelihood outcomes than abandoning farming (Islam et al., 2021). Yet there is still much we do not know about the effectiveness of different climate adaptation measures.

Measuring climate adaptation effectiveness begins with defining what outcomes (e.g. risk or vulnerability reduction) are desired. When a combination of desired adaptation outcomes are achieved, it is argued that adaptation could be judged as being ‘successful’ (Moser & Boykoff, 2013). Adaptation success can be incredibly challenging to measure in practice however, and there has been disagreement about whether the theoretical operationalization of adaptation success is even a desirable and reachable goal (Moser & Ekstrom, 2010). Some experts have argued that adaptation is grounded in a local context, and thus metrics and indicators of adaptation success can only be determined in relation to local stakeholders (Dilling et al., 2019; Owen, 2020; Piggott-McKellar et al., 2020). Others have argued for a more generic operationalization of adaptation success through evaluation criteria, targets and indicators to enable broad-scale tracking of adaptation outcomes (Bierbaum et al., 2013; Singh et al., 2022; Tompkins et al., 2010).

To extend empirical analyses of adaptation success, I operationalized one of the most prominent and widely-used definitions of ‘successful’ adaptation within the academic literature (Doria et al., 2009) and tested whether different types of adaptation in response to climate change were more or less relevant for promoting it. Specifically, I explored how the outcomes that coral reef tourism operators in the Asia-Pacific (APAC) Region experienced one year after a severe climate disturbance (either coral bleaching or tropical cyclone) related to the particular types of adaptation they adopted. My findings provide evidence that at least some adaptation responses are effective, particularly those that depend on the presence of spatial variation, but they also identify some unexpected and surprising outcomes that can inform our general understanding of how to measure adaptation success.

7.2 Methods

I conducted 209 surveys with representatives of reef tourism companies (operators) to obtain information about the actions they took in response to a specific climate disturbance and the outcomes they experienced one year after the climate disturbance. I used the definition of successful adaptation by Doria et al. (2009) to develop and quantify indicators for perceived risk and vulnerability, as well as economic, social, and environmental sustainability. These data were then used to explore the relationships between adaptive responses, adaptation outcomes, and relevant contextual variables.

7.2.1 Domains and Indicators of Adaptation Success

I developed five key actor-specific indicators (Table 7.1) to capture the three broad domains (risk, vulnerability, and sustainability) of adaptation success as identified by Doria et al. (2009) and as displayed in Figure 1.1. I collected data on the indicators in my surveys using multiple-choice categories to provide a consistent and directly comparable level of detail in the answers. I asked each respondent first about their answer for each indicator as they judged it to be one month before a specific climate disturbance. I then asked whether the indicator was different one year after a specific climate disturbance, and if so, I again asked how they judged the indicator to be one year after the climate disturbance. In two out of my 209 surveys, respondents answered that an indicator was different one year after a specific climate change, but consequently selected the same multiple-choice category as an answer, which would reflect either no change or a change that was within the same answer category. I followed up with the operators to identify whether it was a positive or negative change, and included their answer in my consequent analysis. In my dataset (Bartelet, 2023a) I have acknowledged this by decreasing the indicator category by 0.5 instead of by one or more levels. For operators that were affected by two consecutive climate disturbances (e.g. GBR in Australia), I used one year after the latest disturbance as the reference period.

For risk, my primary focus was on the perceived risk of being affected by a specific climate disturbance (either coral bleaching or tropical cyclones; Table 7.1). For vulnerability, my focus was on the perceived livelihood vulnerability (ability to prevent negative livelihood outcomes when climate impacts occur) to specific climate disturbances (Table 7.1). I used subjective indicators for risk and vulnerability, under the assumptions that operators would have an understanding of the factors that contribute to the risks and vulnerability associated with specific climate disturbances (Jones & Tanner, 2017). Quantifying objective climate risk and vulnerability indicators that could identify which reef sections and operators are most likely to be affected by (and vulnerable to) bleaching and/or tropical cyclones is difficult because even for experts, local climate risks are hard to predict as climate outcomes depend on environmental factors, such as topography and the stochastic processes involved in cloud formation (Freeman et al., 2015), as well as socioeconomic factors related to vulnerability and people's capacity to adapt (Cinner et al., 2018). For my perceived risk indicator, I realized that asking about the probability of being affected by a climate disturbance a month before it happened might have been influenced by forecasts of the disturbance. I therefore included in my pre-disturbance question the following reservation:

> We know that there were reports and forecasts (for example from NOAA) some weeks before the bleaching event that warned for it to happen. But before any official forecast came out, how likely did you think it was for your company to be affected by coral bleaching in the next 12 months?

Microeconomic reef business sustainability depends on many factors, including market demand, operational costs, debt ratios, and profit margins. Because many of these factors contain privacy-sensitive information, I focused here on each company's number of daily visitors (on reef activities/tours) as a proxy for economic sustainability. A reduction in visitor numbers could be judged as a direct sign of negative economic impacts, although this assumes constant prices and operational costs. I used the company's (average) daily number of customers in the month before a particular climate disturbance occurred, and one year after the climate disturbance. Seasonality can be important for ecosystem service provision (Grantham et al., 2022); the tourism sector in particular depends on differential holiday periods of international visitors (Duro & Turrión-Prats, 2019). By using a one year period after the disturbance, I tried to account for any seasonality effects by asking for visitor numbers around the same period the next year. It is important to note a limitation of our chosen economic sustainability indicator that focused on visitor numbers rather than absolute or relative values of revenue. Due to this approach, we were not able to capture changes in economic sustainability that came from diversification outside of tourism and/or by adaptations that led to higher market values (prices paid by tourists) for their tourist activities. Both these factors could have increased absolute and/or relative revenue without having experienced increased visitor numbers.

I used coral cover as my proxy for the environmental sustainability of the coral reef (Bellwood et al., 2004), although I acknowledged that for tourists fish and other marine life may be more important (Grafeld et al., 2016). Changes in fish assemblages on coral reefs are expected when severe climate disturbances lead to significant coral loss, although this effect on fish stocks might take years to materialize (Pratchett et al., 2011). Finally, I used the strength of social ties between reef operators [a measure of social cohesion and social capital (Barnes-Mauthe et al., 2013)] as my proxy for social sustainability, under the assumption that changes in these ties could affect people's propensity for collective action to address shared challenges (Hasanov & Zuidema, 2022; Partelow & Nelson, 2020). Negative changes in the ties between operators could indicate potential maladaptation if adaptive responses by some operators are negatively affecting others (Barnett & O'Neill, 2010; S. Eriksen et al., 2011).

Table 7.1
Multidimensional Actor-Specific Outcome Indicators

Outcome domain	Outcome indicator	Description	Variable units
Risk	(perceived) Climate risk	Perception of how likely it was that the company would be affected by specific (either bleaching or cyclone) climate disturbance in the next 12 months.	(1) 0–20% (2) 20–40% (3) 40–60% (4) 60–80% (5) 80–100%
Vulnerability	(perceived) Climate vulnerability	Perception of how much the company's revenue would be affected if specific (either bleaching or cyclone) climate disturbance were to occur in the next 12 months.	(-1) Somewhat positively (0) Not affected (1) Somewhat negatively (2) Very negatively
Sustainability	Environmental	Coverage of live coral at the reef sites the company is using.	10 multiple-choice options ranging from '0-10%' to '90-100%.'
	Economic	Company's number of daily customers going on tourism activities.	16 multiple-choice options ranging from '0-3' to '>500.'[a]
	Social	Company's ties to surrounding reef tourism operators.	(1) Weak ties (did not interact much with other operators) (2) Moderate ties (had some interaction with other operators, mainly through formal events) (3) Strong ties (frequently interacted and collaborated with other operators)

Note. Indicators were measured using recall data in two time periods: one month before and one year after a climate disturbance occurred. All variables were measured as ordinal variables using multiple-choice categories.

[a] Because of differences in scales between reef operators in different locations (e.g. in Indonesia there are more and smaller operators, while in Australia there are fewer and larger operators), I added some additional detail in the smaller multiple-choice categories, while for larger operators I mainly used increments of 50 visitors. I decided not to use an open-ended question because respondents would have to look up their (exact) visitors data from years back, and this might have had decreased specific answer or overall participation rates in the survey.

7.2.2 Analysis

Because I measured five outcome indicators (Table 7.1) for each operator, I began my analysis by testing for the pair-wise correlation between my post-disturbance outcome indicators in R software (v.4.2.1) (R Core Team, 2013) using *GGally* (Schloerke et al., 2021) and the Spearman's rank coefficient for non-parametric distributions. I conducted this test because in the case where multiple outcomes are measured and the outcomes are significantly correlated, it has been proposed that multivariate methods should be used instead of analyzing each outcome separately (Teixeira-Pinto et al., 2009). However, I found that none of the correlations between the multiple outcomes I measured exceeded the threshold of (rho >) 0.4, which was recently been proposed for deciding whether to analyze outcomes together or separately (Vickerstaff et al., 2021). I therefore followed the recommendation of Vickerstaff et al. (2021) to analyze each outcome separately.

Next, I analyzed the association between tourism-specific adaptive responses to climate disturbances (Table 4.2) and the actor-specific outcome indicators (Table 7.1) using three consecutive steps that built up my understanding from the specific to the general, which I describe in detail in the following sub-sections.

7.2.2.1 Treatment Versus Control Group (Independence of Outcomes). I first divided my sample (n = 209) into a posterior treatment and control group based on each operator's answer to a question in my survey about the fraction of reef sites that they were using on their tours before the disturbance that were severely (>30%) affected by a climate disturbance (Table 4.3). Operators that perceived that none of their reef sites were severely affected were placed in my posterior control sample (n = 60, 29%), while operators that had at least some (25%) of their reef sites severely affected (n = 149, 71%) were included in my posterior treatment sample. I first tested whether the actor-specific outcomes experienced one year after a climate disturbance were significantly different between my posterior treatment and control.

I classified each outcome indicator (Table 7.1) under one of three potential outcomes. An outcome either (1) remained the same; (2) decreased; or (3) increased as calculated one year after compared to just before a climate disturbance. I thus did not evaluate the absolute level of change (whether an outcome decreased by one or multiple levels). Because both the outcomes (same, decrease, or increase) and sample type (treatment or control) were categorical, I used Pearson's (1900) Chi-square test of independence. Chi-square analyses were performed in Microsoft Excel using contingency tables and the *CHISQ.DIST.RT()* function. I applied a significance threshold (*p*-value) of 5%. If I found an outcome (Δ) that was dependent on having been affected, I ran two pairwise tests where I compared the fraction of operators that experienced a decrease in the outcome versus the fraction of operators that experienced no change, and similarly the fraction of operators that experienced an increase in the outcome versus the fraction of operators that experienced no change.

7.2.2.2 Adaptive Responses to Climate Disturbances (Independence of Outcomes). Next, I analyzed the association between the adaptive responses implemented by individual operators in response to a climate disturbance and the outcomes they experienced. In other words, for operators that were affected by a climate disturbance, I asked whether the adaptive response(s) they adopted led to a change in perceived climate risk and vulnerability, without compromising sustainability (Doria et al., 2009). Here I first divided the posterior treatment sample by disturbance type. I had one sample with operators that were affected by severe impacts from coral bleaching ($n = 123$) and one with operators that were affected by severe impacts from tropical cyclones ($n = 26$).

Because both the outcomes (same, decrease, or increase) and adaptive responses (implemented or not) were categorical, I used Pearson's (1900) Chi-square test of independence. I did not run chi-square analyses for any of the adaptive responses that were implemented by fewer than 10% of the operators in the respective bleaching and cyclone treatment samples. Including responses that are rarely adopted would have led to low expected values within the chi-square contingency tables and this could have led to invalid statistical results (Campbell, 2007). I did not run chi-square analyses for any of the adaptation outcomes of which less than 5% of the operators experienced a decrease or increase.

7.2.2.3 Logistic Regression Models Finally, in the third step I analyzed my combined sample including both the posterior treatment and control sample and including both impacts from coral bleaching and tropical cyclones. Here I used binary logistic regression models to test which adaptive responses and contextual variables had most predictive power in terms of explaining adaptation outcomes. A regression model conflates the question of whether any specific adaptive response leads to a reduction in climate risk and/or vulnerability without compromising economic, and, social, and environmental sustainability (Doria et al., 2009) because the responses are now competing with each other to determine what most predicts outcomes when controlling for the other responses. On the other hand, a regression model helps to identify marginal effects when different operators adopted various combinations of responses, whereas it is difficult to understand which response contributed most to a particular outcome using the chi-square analyses. Additionally, in the regression models I used the full sample because I had the ability to control for the disturbance type and severity, thereby giving us higher statistical power and the ability to find synergistic relationships. For example, particular adaptive responses might have had outcome effects in the same direction in both the bleaching and cyclone samples, but these effects might not have been significant using a chi-square analysis. Finally, the regression models gave me the ability to control for different baseline values on the outcome indicators. For example, operators that perceived higher climate risk before a disturbance occurred might have been less likely to experience an increase in perceived climate risk compared to operators that started out on a low climate risk level.

I used binary logistic regression models for all outcomes, mostly because of skewedness in the outcomes data (Table 7.2), as explained in more detail in Table 7.7. In the binary logistic regression models, I used as dependent variable a one-sided change in an outcome (e.g. a decrease in environmental sustainability), and compared the likelihood of that outcomes versus the rest of the sample that experienced any other outcome. Logistic regression models were fitted in the R modelling software (R Core Team, 2013) using the *glm* function. The logistic regression models were validated via DHARMa residuals (Hartig, 2018). All predictors had a variance inflation factor (VIF) below 2, calculated using the *performance* package in R (Lüdecke et al., 2021), indicating no collinearity in my models. For all outcome models I used the same set of explanatory variables (Table 4.3), and I also controlled for the baseline value on each respective outcome indicators.

7.3 Results

7.3.1 Sample Description (Adaptation Outcomes)

The pre-disturbance outcomes, as well as the observed changes on the different outcomes of operators in my different study locations is summarized in Table 7.2. Other sample description details were presented in Table 4.4. The data indicate that perceived climate risk and environmental sustainability changed over time for the largest fraction of operators in the sample, while social sustainability for the most part did not change at all.

Table 7.2

Sample Description for Asia-Pacific Reef Tourism Operators by Location

Indicator	Units	Indonesia	Australia	Japan	Mariana islands	Fiji	Hawaiian islands	French Polynesia	Total
Respondents	#	68 (33%)	55 (26%)	23 (11%)	17 (8%)	16 (8%)	15 (7%)	15 (6%)	209 (100%)
Risk (pre-disturbance)	0–20%	32 (47%)	21 (38%)	10 (43%)	5 (29%)	2 (13%)	7 (47%)	3 (20%)	80 (38%)
	20–40%	18 (26%)	14 (25%)	2 (9%)	6 (35%)	2 (13%)	3 (20%)	4 (27%)	49 (23%)
	40–60%	13 (19%)	9 (16%)	4 (17%)	4 (24%)	4 (25%)	4 (27%)	4 (27%)	42 (20%)
	60–80%	4 (6%)	8 (15%)	5 (22%)	1 (6%)	3 (19%)	0 (0%)	2 (13%)	23 (11%)
	80–100%	1 (1%)	3 (5%)	2 (9%)	1 (6%)	5 (31%)	1 (7%)	1 (7%)	14 (7%)
	NA	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (7%)	1 (0%)
Risk (Δ)	Same	43 (63%)	28 (51%)	10 (43%)	13 (76%)	7 (44%)	11 (73%)	10 (67%)	122 (58%)
	Decrease	12 (18%)	16 (29%)	5 (22%)	2 (12%)	5 (31%)	1 (7%)	2 (13%)	43 (21%)
	Increase	13 (19%)	11 (20%)	8 (35%)	2 (12%)	4 (25%)	3 (20%)	2 (13%)	43 (21%)
	NA	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (7%)	1 (0%)
Vulnerability (pre-disturbance)	-1 (positive)	2 (3%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	2 (1%)
	0 (not)	16 (24%)	18 (33%)	8 (35%)	5 (29%)	0 (0%)	3 (20%)	6 (40%)	56 (27%)
	1 (some)	32 (47%)	24 (44%)	13 (57%)	10 (59%)	11 (69%)	10 (67%)	6 (40%)	106 (51%)
	2 (very)	17 (25%)	13 (24%)	2 (9%)	2 (12%)	5 (31%)	1 (7%)	3 (20%)	43 (21%)
	NA	1 (1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (7%)	0 (0%)	2 (1%)
Vulnerability (Δ)	Same	54 (81%)	40 (73%)	21 (91%)	11 (65%))	14 (88%)	13 (93%)	13 (87%)	166 (79%)
	Decrease	6 (9%)	6 (11%)	0 (0%)	1 (6%)	0 (0%)	1 (7%)	0 (0%)	14 (7%)
	Increase	7 (10%)	9 (16%)	2 (9%)	5 (29%)	2 (13%)	0 (0%)	2 (13%)	27 (13%)
	NA	1 (1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (7%)	0 (0%)	2 (1%)

Coral cover (pre-disturbance)	Median	7 (60–70%)	8 (70–80%)	7 (60–70%)	7 (60–70%)	8 (70–80%)	6 (50–60%)	8 (70–80%)	7 (60–70%)
	MAD	2 (20–40%)	1 (10–20%)	1 (10–20%)	1 (10–20%)	1 (10–20%)	1 (10–20%)	1 (10–20%)	2 (20–40%)
Coral cover (Δ)	Same	40 (60%)	28 (51%)	17 (74%)	9 (53%)	4 (25%)	9 (60%)	7 (47%)	114 (55%)
	Decrease	24 (36%)	26 (47%)	5 (22%)	8 (47%)	11 (69%)	5 (33%)	8 (53%)	87 (42%)
	Increase	3 (4%)	1 (2%)	1 (4%)	0 (0%)	1 (6%)	1 (7%)	0 (0%)	7 (3%)
	NA	1 (1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Daily visitors (pre-disturbance)	Median	3 (5–10)	4 (10–20)	3 (5–10)	3 (5–10)	4 (10–20)	4 (10–20)	3 (5–10)	4 (10–20)
	MAD	1	1	1	1	2	1	1	1
Daily visitors (Δ)	Same	51 (75%)	36 (65%)	22 (96%)	10 (59%)	10 (63%)	11 (73%)	12 (80%)	152 (73%)
	Decrease	4 (6%)	12 (22%)	0 (0%)	4 (24%)	6 (38%)	3 (20%)	2 (13%)	31 (15%)
	Increase	13 (19%)	7 (13%)	1 (4%))	3 (18%)	0 (0%)	1 (7%)	1 (7%)	26 (12%)
Operator ties (pre-disturbance)	Weak	16 (24%)	11 (20%)	10 (43%)	10 (59%)	8 (50%)	2 (13%)	9 (60%)	66 (32%)
	Moderate	30 (44%)	24 (44%)	7 (30%)	5 (29%)	4 (25%)	7 (47%)	2 (13%)	79 (38%)
	Strong	22 (32%)	20 (36%)	5 (22%)	2 (12%)	4 (25%)	6 (40%)	4 (27%)	63 (30%)
	NA	0 (0%)	0 (0%)	1 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Operator ties (Δ)	Same	65 (96%)	53 (96%)	22 (100%)	16 (94%)	15 (94%)	15 (100%)	14 (93%)	200 (96%)
	Decrease	1 (1%)	1 (2%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	2 (1%)
	Increase	2 (3%)	1 (2%)	0 (0%)	1 (6%)	1 (6%)	0 (0%)	1 (7%)	6 (3%)
	NA	(0%)	(0%)	1 (4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (0%)

Note. For environmental (coral cover) and economic (visitor numbers) sustainability I have indicated the median value (and median absolute deviation: MAD) because these indicators consisted of respectively 10 and 16 levels. Detailed fractions for each level can be estimated from the input data (Bartelet, 2023a). Percentages might not add up to 100% due to rounding in two decimals.

7.3.2 Treatment Versus Control Group (Independence of Outcomes)

Almost a third (29%, n = 60) of the operators had none of their reef sites severely affected by a climate disturbance [these operators were thus included in my posterior control sample (Table 7.2)]. The fraction of operators in the posterior control sample was relatively even across locations, ranging from 19% of the sampled operators in Fiji to 36% in Australia. Outcomes in terms of perceived climate risk, environmental sustainability, and economic sustainability were significantly different in my posterior treatment and control samples (

Table ***7.3***). Perceived climate vulnerability outcomes were not significantly different between out treatment and control samples. Post-hoc analyses showed that operators in my treatment sample were significantly more likely than operators in my posterior control sample to experience an increase in perceived climate risk (26% vs. 8%, p = 0.001), decreased environmental sustainability (54% vs. 12%, p = 0.000), and decreased economic sustainability (21% vs. 0%, p = 0.000) one year after being affected by a climate disturbance.

Table 7.3

Test of Independence Between Multidimensional Actor-Specific Outcome Indicators and Being Affected (Treatment Sample) or not (Control Sample) by a Climate Disturbance

	0	**-**	+	**X^2 (*p*-value)**
Climate risk				
Treatment	51%	23%*	26%**	12.19
Control	77%	15%	8%	(0.002)
Climate vulnerability				
Treatment	80%	7%	13%	0.01
Control	80%	7%	13%	(0.997)
Environ. Sustainability				
Treatment	42%	54%***	4%	33.40
Control	86%	12%	2%	(0.000)
Econ. Sustainability				
Treatment	68%	21%***	11%	14.99
Control	83%	0%	17%	(0.001)

Note. Outcomes, measured as the number of operators that experienced a change in each indicator, are presented as either no change (0), a decrease (-), or an increase (+). Posterior treatment sample consisted of (n =) 148 reef tourism operators and the posterior control sample consisted of (n =) 60 reef tourism operators. I used a p-level threshold for significance of 5% for the multinomial outcomes (same, decrease, increase) versus the test variable (df = 2). If a significant association was found, I used posthoc analysis comparing decrease vs. same and increase vs. same.

Note. Significant results for the *post hoc* pairwise analysis are highlighted in yellow with asterisk presenting significant results (*p*-values) at respectively <0.05 (*), <0.01 (**), and <0.001 (***).

7.3.3 Adaptive Responses by Control Group (Independence of Outcomes)

Only four out of the ten adaptive responses that I surveyed were adopted by at least 10% of the operators in my posterior control sample: monitoring activities (50%), restoration measures (35%), climate action (30%), and support-seeking (10%). Within the control sample, operators that undertook monitoring activities were significantly more likely to have experienced a decrease in perceived climate risk one year after a climate disturbance occurred that did not severely affect them (27% vs. 3%, $p = 0.018$, $n = 30/60$) (Table 7.4). Within the control sample, operators that undertook monitoring activities were also significantly more likely to have reported a reduction in environmental sustainability (20% vs. 3%, $p = 0.049$), and those that sought support (e.g. from government, local communities, and/or relatives) were significantly more likely to have experienced increased economic sustainability (50% vs. 13%, $p = 0.021$, $n = 6/60$).

Table 7.4

Test of Independence Between Multidimensional Actor-Specific Outcome Indicators and Adaptive Responses Adopted in Response to Coral Bleaching and Tropical Cyclones by Reef Tourism Operators That None of Their Reef Sites Severely-Affected (n = 60)

	Climate risk				**Climate vulnerability**			
	0	**-**	**+**	**X^2 (*p*-value)**	**0**	**-**	**+**	**X^2 (*p*-value)**
Monitoring								
Yes	70%	27%*	3%	7.59	77%	7%	17%	0.58
No	83%	3%	13%	(0.022)	83%	7%	10%	(0.747)
Restoration								
Yes	67%	29%	5%	4.88	76%	10%	14%	0.48
No	82%	8%	10%	(0.087)	82%	5%	13%	(0.788)
Climate action								
Yes	83%	11%	6%	0.65	83%	6%	11%	0.18
No	74%	17%	10%	(0.724)	79%	7%	14%	(0.915)
Support-seeking								
Yes	83%	17%	0%	0.61	83%	0%	17%	0.51
No	76%	15%	9%	(0.738)	80%	7%	13%	(0.775)

	Environmental sustainability [a]			**Economic sustainability [b]**		
	0/+	**-**	**X^2 (*p*-value)**	**0**	**+**	**X^2 (*p*-value)**
Monitoring						
Yes	80%	20% *	3.86	83%	17%	0.00
No	97%	3%	(0.049)	83%	17%	(1.000)
Restoration						
Yes	85%	15%	0.28	76%	24%	1.19
No	90%	10%	(0.594)	87%	13%	(0.276)
Climate action						
Yes	82%	18%	0.79	72%	28%	2.29
No	90%	10%	(0.375)	88%	12%	(0.131)
Support-seeking						
Yes	83%	17%	0.15	50%	50%*	5.33
No	89%	11%	(0.701)	87%	13%	(0.021)

Note. Outcomes, measured as the number of operators that experienced a change in each indicator, are presented as either no change (0), a decrease (-), or an increase (+). I used a p-level threshold for significance of 5% for the multinomial outcomes (same, decrease, increase) versus the test variable (df = 2). If a significant association was found, I used posthoc analysis comparing decrease vs. same and increase vs. same. Adaptive responses are sorted from most frequently to least frequently adopted.

Note. Significant results for the posthoc pairwise analysis are highlighted in yellow with asterisk presenting significant results (*p*-values) at respectively <0.05 (*), <0.01 (**), and <0.001 (***).

[a] 2% of the operators in the control sample experienced an increase in environmental sustainability and this outcome was merged with the 'no change (0)' category.

[b] None of the operators in the control sample experienced a decrease in economic sustainability.

7.3.4 Adaptive Responses by Bleaching-Affected Operators (Independence of Outcomes)

In my treatment sample of operators who were affected by coral bleaching, support-seeking was the only adaptive response that was significantly associated with experienced adaptation outcomes. Specifically, operators that sought support ($n = 25/123$, or 20% of the bleaching treatment sample) were significantly ($p = 0.025$) more likely to have experienced a decrease in perceived climate vulnerability one year after being affected by coral bleaching (Table 7.5). Operators affected by coral bleaching that sought support were also significantly ($p = 0.006$) more likely to have experienced increased economic sustainability one year after the disturbance.

Table 7.5

Test of Independence Between Multidimensional Actor-Specific Outcome Indicators and Adaptive Responses Adopted in Response to Severe Impacts From Coral Bleaching by Asian-Pacific Reef Tourism Operators (n = 123)

	Climate risk				**Climate vulnerability**			
	0	**-**	**+**	**X^2 (*p*-value)**	**0**	**-**	**+**	**X^2 (*p*-value)**
Monitoring								
Yes	52%	20%	29%	1.89 (0.388)	80%	8%	12%	2.12 (0.346)
No	61%	23%	16%		87%	10%	3%	
Restoration								
Yes	47%	23%	30%	5.02 (0.081)	80%	9%	11%	0.72 (0.699)
No	68%	15%	17%		86%	7%	7%	
Climate action								
Yes	52%	23%	25%	0.48 (0.785)	77%	11%	13%	1.78 (0.410)
No	56%	18%	26%		86%	6%	8%	
Spatial diversif.								
Yes		15%	29%	1.62 (0.445)	78%	10%	12%	0.68 (0.712)

No	56% 53%	24%	23%		84%	7%	9%	
Product diversif.								
Yes	62%	17%	21%	0.98 (0.614)	76%	7%	17%	2.31 (0.314)
No	52%	22%	27%		84%	9%	8%	
Support-seeking								
Yes	72%	12%	16%	4.06 (0.131)	79%	21%*	0%	8.72 (0.013)
No	49%	23%	28%		82%	5%	12%	
Oper. Change								
Yes	61%	11%	28%	1.15 (0.564)	78%	6%	17%	1.20 (0.548)
No	53%	22%	25%		83%	9%	9%	

	Environmental sustainability [a]			**Economic sustainability**			
	0/+	**-**	**X² (*p*-value)**	**0**	**-**	**+**	**X² (*p*-value)**
Monitoring							
Yes	48%	52%	2.83	69%	18%	13%	2.56
No	66%	34%	(0.092)	81%	6%	13%	(0.278)
Restoration							
Yes	49%	51%	1.14	72%	14%	15%	0.79
No	60%	40%	(0.285)	74%	17%	10%	(0.672)
Climate action							
Yes	47%	53%	1.28	70%	16%	14%	0.25
No	58%	42%	(0.258)	74%	14%	12%	(0.881)
Spatial diversif.							
Yes	51%	49%	0.14	75%	9%	15%	2.16
No	54%	46%	(0.713)	70%	19%	11%	(0.340)
Product diversif.							
Yes	50%	50%	0.13	83%	10%	7%	2.47
No	54%	46%	(0.720)	69%	16%	15%	(0.291)
Support-seeking							
Yes	64%	36%	1.57	52%	20%	28%**	7.84
No	50%	50%	(0.211)	78%	13%	9%	(0.020)
Oper. Change							
Yes	50%	50%	0.07	67%	17%	17%	0.37
No	53%	47%	(0.794)	73%	14%	12%	(0.831)

Note. Outcomes, measured as the number of operators that experienced a change in each indicator, are presented as either no change (0), a decrease (-), or an increase (+). Adaptive responses are sorted from most frequently to least frequently adopted.

Note. Significant results for the posthoc pairwise analysis are highlighted in yellow with asterisk presenting significant results (*p*-values) at respectively <0.05 (*), <0.01 (**), and <0.001 (***).

[a] 4% of the operators in the bleaching sample experienced an increase in environmental sustainability and this outcome was merged with the 'no change (0)' category.

7.3.5 Adaptive Responses by Cyclone-Affected Operators (Independence of Outcomes)

Three of the adaptive responses adopted in response to severe impacts from tropical cyclones were significantly associated with experienced climate vulnerability outcomes (Table 7.6). Specifically, operators that adopted measures to improve the health of the coral reef (n = 14/26), used relief measures (n = 11/26), and/or sought support (n = 7/26) in response to cyclone impacts were also significantly (respective p-values of 0.048, 0.007, and 0.035) more likely to have experienced an increase in perceived climate vulnerability one year after being affected. Operators that spatially diversified their reef sites were significantly more likely to have also experienced a decrease in environmental sustainability (p = 0.037, n = 18/26). Finally, operators that used relief measures, and/or diversified their products (n = 9/26) were significantly (respective p-values of 0.048 and 0.039) more likely to have also experienced a decrease in economic sustainability.

Table 7.6

Test of Independence Between Multidimensional Actor-Specific Outcome Indicators and Adaptive Responses Adopted in Response to Severe Impacts From Tropical Cyclones by Reef Tourism Operators in Australia and Fiji (n = 26)

	Climate risk				**Climate vulnerability** [a]		
	0	**-**	**+**	**X^2 (*p*-value)**	**0**	**+**	**X^2 (*p*-value)**
Spatial diversif.							
Yes	33%	39%	28%	0.72	72%	28%	0.02
No	50%	25%	25%	(0.696)	75%	25%	(0.883)
Monitoring							
Yes	41%	24%	35%	3.12	71%	29%	0.15
No	33%	56%	11%	(0.211)	78%	22%	(0.694)
Restoration							
Yes	29%	43%	29%	1.40	57%	43%*	3.91
No	50%	25%	25%	(0.497)	92%	8%	(0.048)

Climate action							
Yes	25%	42%	33%	3.51	67%	33%	0.47
No	58%	33%	8%	(0.173)	79%	21%	(0.495)
Relief measures							
Yes	27%	36%	36%	1.27	45%	55%**	7.39
No	47%	33%	20%	(0.530)	93%	7%	(0.007)
Product diversif. [d]							
Yes	67%	22%	11%	4.74	67%	33%	0.29
No	24%	41%	35%	(0.094)	76%	24%	(0.592)
Support-seeking				0.16			
Yes	43%	29%	29%	(0.924)	43%	57%*	4.45
No	37%	37%	26%		84%	16%	(0.035)
Livelihood diversif.							
Yes	50%	50%	0%	1.76	100%	0%	1.74
No	36%	32%	32%	(0.415)	68%	32%	(0.187)
	Environmental sustainability [b]				**Economic sustainability** [c]		
	0/+	**-**	**X² (*p*-value)**		**0**	**-**	**X² (*p*-value)**
Spatial diversif.							
Yes	6%	94%*	4.34		56%	44%	0.72
No	38%	63%	(0.037)		38%	63%	(0.395)
Monitoring							
Yes	12%	88%	0.49		59%	41%	1.53
No	22%	78%	(0.482)		33%	67%	(0.216)
Restoration							
Yes	7%	93%	1.58		43%	57%	0.62
No	25%	75%	(0.208)		58%	42%	(0.431)
Climate action							
Yes	8%	92%	0.85		50%	50%	0.00
No	21%	79%	(0.356)		50%	50%	(1.000)
Relief measures							
Yes	9%	91%	0.58		27%	73%*	3.94
No	20%	80%	(0.446)		67%	33%	(0.047)
Product diversif. [d]							
Yes	0%	100%	2.50		22%	78%*	4.25
No	24%	76%	(0.114)		65%	35%	(0.039)
Support-seeking							
Yes	14%	86%	0.01		43%	57%	0.20
No	16%	84%	(0.925)		53%	47%	(0.658)

Livelihood diversif.	0%	100%	0.86	50%	50%	0.00
Yes	18%	82%	(0.354)	50%	50%	(1.000)
No						

Note. Outcomes, measured as the number of operators that experienced a change in each indicator, are presented as either no change (0), a decrease (-), or an increase (+). Adaptive responses are sorted from most frequently to least frequently adopted.

Note. Significant results for the posthoc pairwise analysis are highlighted in yellow with asterisk presenting significant results (*p*-values) at respectively <0.05 (*), <0.01 (**), and <0.001 (***).

[a] None of the operators in the cyclone sample experienced a decrease in climate vulnerable.

[b] 4% of the operators in the cyclone sample experienced an increase in environmental sustainability and this outcome was merged with the 'no change (0)' category.

[c] None of the operators in the cyclone sample experienced an increase in economic sustainability.

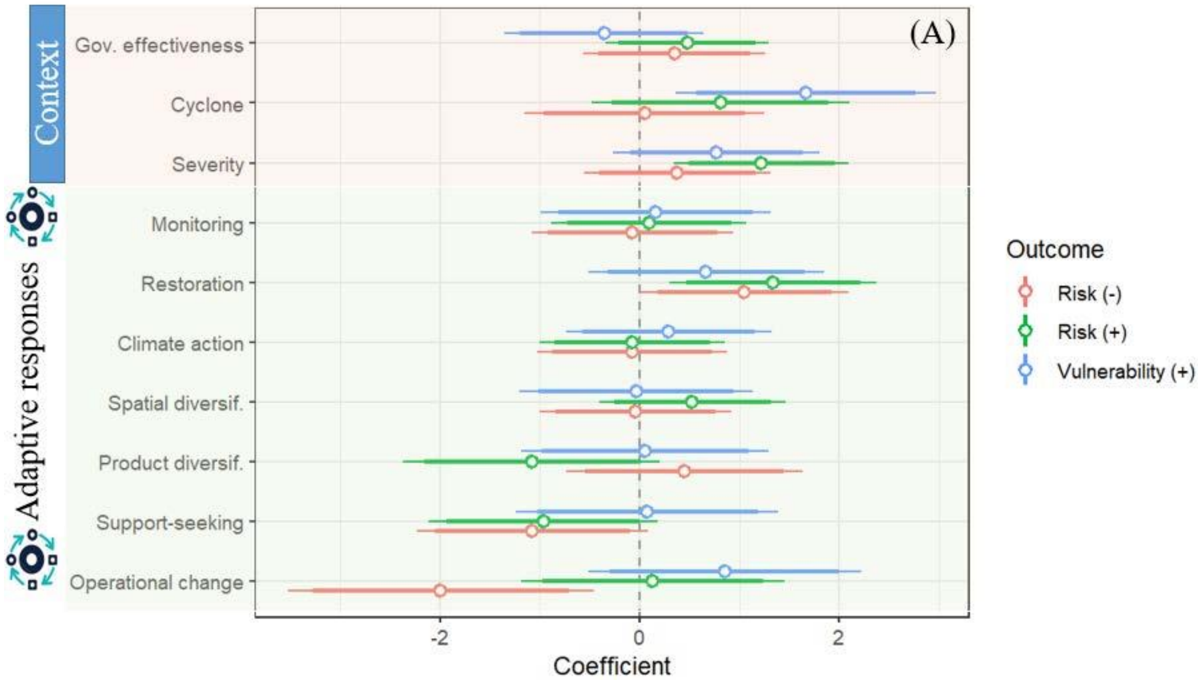
[d] All operators in the cyclone sample that diversified their products also changed their mode of operating and the chi-square analysis results for both adaptive responses are identical.

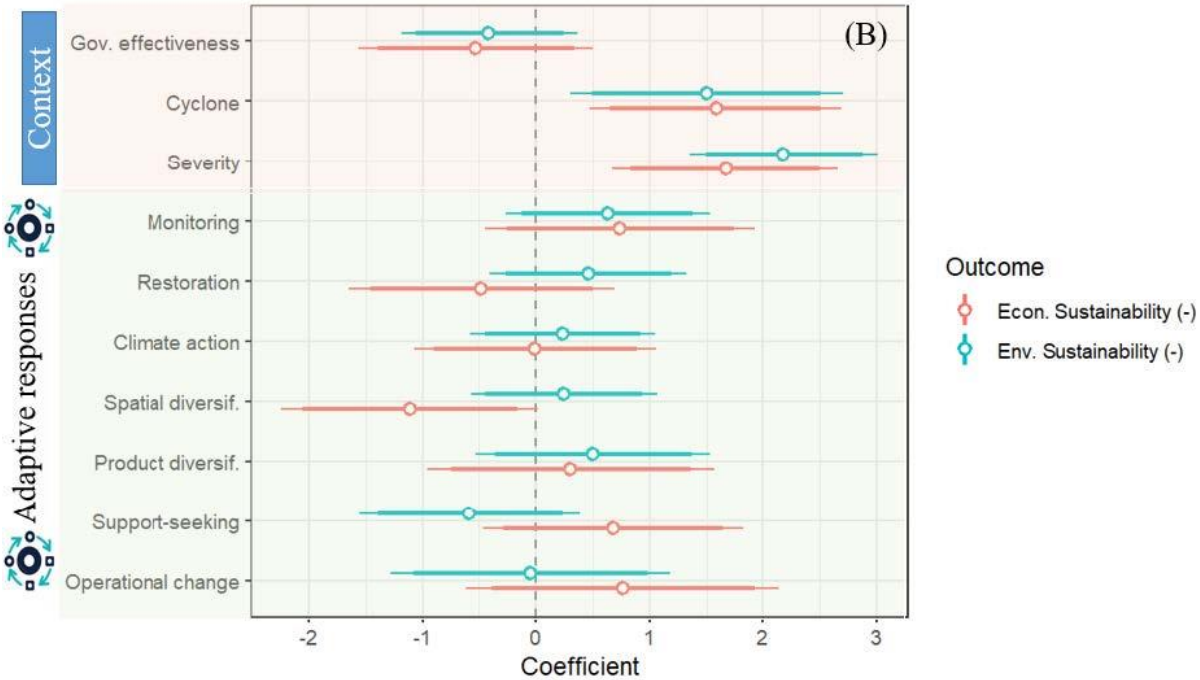
7.3.6 Logistic Regression Models (Full Sample Analysis)

I found that operators that were affected by tropical cyclone impacts, rather than coral bleaching, were significantly more likely to experience (1) an increase in perceived climate vulnerability ($\beta = 1.67$, $p = 0.013$); (2) a decrease in environmental sustainability ($\beta = 1.50$, $p = 0.014$); and (3) a decrease in economic sustainability ($\beta = 1.58$, $p = 0.005$) (Figure 7.2 and Table 7.7). Operators that had a higher fraction of their reef sites affected (experienced severity) were significantly more likely experience (1) an increase in perceived climate risk ($\beta = 1.22$, $p = 0.006$); (2) a decrease in environmental sustainability ($\beta = 2.18$, $p = 0.000$); and (3) a decrease in economic sustainability ($\beta = 1.67$, $p = 0.001$). Operators that undertook measures to improve the health of the coral (restoration) were significantly more likely to experience either a decrease ($\beta = 1.05$, $p = 0.048$) or an increase ($\beta = 1.34$, $p = 0.011$) in perceived climate risk. Operators that changed their mode of operating were significantly ($\beta = -2.00$, $p = 0.011$) less likely to experience a decrease in perceived climate risk. Finally, operators that changed their reef sites (spatial diversification) in response to a climate disturbance were significantly (β = -1.11, p = 0.055) less likely to experience a decrease in economic sustainability.

Figure 7.2

Multidimensional Outcomes (Displayed in Panel A and B) Associated With Adaptive Responses Taken by Asian-Pacific Coral Reef Operators to Climate Disturbances, Controlling for Contextual Factors





Note. Panel A shows perceived climate risk and vulnerability outcomes, while panel B shows sustainability outcomes. Figures show the effect sizes (log-odds), and the 95% (for stronger evidence) and 90% (for weaker evidence) confidence intervals. Results are based on individual logistic regression models. Coefficient for disturbance severity was based on z-scored variable to make its effect size comparable to the other binary predictors, and should be interpreted as the effect of a one-standard deviation change in the predictor variable on the response variable.

7.4 Discussion

My results show that climate impacts from coral bleaching and tropical cyclones led to changes in actor-specific outcomes, in particular to reductions in environmental sustainability and changes in perceived climate risk (Table 7.2). Changes in outcomes (except perceived climate vulnerability) were significantly more likely for operators who had been directly affected by a climate disturbance. Almost half of the operators I surveyed (including the control group, with non-severely affected operators) lost at least 10% of coral cover one year after a climate disturbance. None of the adaptive responses taken by operators were able to significantly reduce the likelihood of coral cover loss (my environmental sustainability measure) one year after the event. This could be interpreted as evidence for a scale mismatch (Bellwood et al., 2019; Cumming et al., 2006); individual reef operators cannot directly influence the processes that are the major drivers of climate-induced coral loss, most notably the increasing heat content in our oceans (Cheng et al., 2020), and the coral's ability to adapt to this heating (Hughes, Kerry, et al., 2017; Logan et al., 2021). While measures to improve the health of the coral reef (restoration measures) were adopted by more than half (56%) of the operators in my combined sample (Table 4.4), these measures were not significantly associated with a lower likelihood of coral loss one year after a climate disturbance occurred (Figure 7.2). The positive effects of restoration measures on environmental sustainability may take more than a year to materialize. I also did not know exactly when an operator adopted restoration measures. For example, if restoration measures were adopted six months after a disturbance, the effective evaluation period for that response would have been six months instead of one year. While small-scale successes in coral restoration have been reported (Boström-Einarsson et al., 2020; Howlett et al., 2023), it remains a question whether the restoration methods and scale will be able to dampen the severe effects of ocean heating on coral reef sustainability, even on smaller scales such as tourism areas (Bellwood et al., 2019; Kleypas et al., 2021).

Despite severe climate disturbances and their impacts on coral reefs (Hughes, Kerry, et al., 2017), the majority (85%) of operators did not experience a substantial reduction in economic sustainability (visitor numbers). The results suggest that most operators (at least among those that I surveyed) were not severely economically affected (in terms of visitor numbers) by the climate disturbances I focused on here, but those that had a larger fraction of their reef sites affected did have a higher chance of negative economic outcomes. My results provide evidence for feedback between environmental change and economic output, at least within a reef tourism context (**Chapter 2**. The effect of coral bleaching on the recreational value derived from the GBR; Lin et al., 2023). My results illustrate both economic damage from climate change (Auffhammer, 2018) and the disproportionately high effect of this damage on a small fraction of actors within the system that are most severely-affected by a climate disturbance (Ilosvay et al., 2022).

7.4.1 Operationalizing Adaptation Success

My study is one of the first to operationalize and test Doria et al's (2009) definition of successful adaptation. I found that all domains of 'adaptation success' could be captured and applied to a micro-level where I specifically focused on perceived climate risk, perceived climate vulnerability, and sustainability outcomes as perceived from an individual reef tourism operator. I identified two major challenges associated with the measurement of adaptation success. First, following the definition of adaptation success by Doria et al. (2009), I decided to use chi-square analyses to test whether specific adaptive responses were able to reduce perceived climate risk and/or vulnerability without compromising social, economic, and environmental sustainability. While the chi-square analyses are able to tease out the individual relationships between adaptive responses and outcomes, the findings produced from these analyses cannot fully capture the fact that most operators used multiple adaptive responses to the same disturbance. Moreover, the relationship between adaptive responses and outcomes is likely mediated by other factors such as the baseline outcome levels (e.g. perceived risk pre-disturbance) and/or the experienced severity of climate effects. Supplementing my chi-square analyses for individual climate disturbances and individual responses with multiple-predictor regression models where I tested for the effect of all adaptive responses on individual outcomes within the same model provided useful, but different insights. Most notably, the combined model revealed significant associations between responses and outcomes that were consistent over my three separate samples (control, bleaching, and cyclone), such as the association between spatial diversification and economic sustainability and the association between restoration and perceived climate risk. However, pooling the samples obscured some effects, such as the association between support-seeking and vulnerability; support-seeking decreased perceived climate vulnerability in my bleaching sample, but increased perceived climate vulnerability in my cyclone sample. The relationships between adaptive responses and outcomes can be complex and multi-faceted (Adger et al., 2005; Tubi & Williams, 2021), and will need to be investigated from multiple angles using large sample sizes and a range of alternative statistical approaches. Second, the interpretation of the statistical results and specifically unravelling the question of cause and effect was challenging. Because I measured outcomes at two points in time, I could not describe the behaviour of each indicator in the intervening period. For example, economic sustainability (visitor numbers) might have decreased one month after the disturbance without recovering in the following 11 months. Thus, some adaptive responses (implemented within one year after a disturbance) might have been (partly) caused by a change in the outcome, rather than the outcome being caused by the adaptive response. For example, I found that relief measures and product diversification were significantly associated with reduced economic sustainability for cyclone impacts. However, it remains unclear whether a loss of economic sustainability was the cause or the consequence of these adaptive responses. Similar questions could be asked for some of my other findings, as discussed below. Qualitative research approaches could contribute to a better understanding of causality within the climate change adaptation process (Bennett et al., 2016; Simpson et al., 2021), although people might not consciously understand all the ways in which their values, background, and other attitudes (e.g. risk perceptions) influence their behaviour (Schlüter et al., 2017; Simon, 1990). I also did not account for whether some operators might have been better prepared for the impacts from climate disturbance. Because of their preparedness, particular operators might have experienced lower risk and/or vulnerability before a disturbance and still had lower levels after a disturbance.

7.4.2 Successfulness of Specific Adaptive Responses

I did not find a strong association between most of the adaptive responses implemented in response to coral bleaching and the outcomes experienced by individual operators (Table 7.5). The one exception was the finding that operators who sought support from others were more likely to experience a reduction in perceived climate vulnerability and an increase in economic sustainability. Support-seeking might thus be identified as a 'successful' response in a coral bleaching context (Doria et al., 2009). My findings could be linked to the importance of collective action, with actors collaborating to address common problems, for successful climate change adaptation (Barnes et al., 2016; Carr & Nalau, 2023; Karlsson & Hovelsrud, 2015; Rodima-Taylor, 2012). It is unclear why the support-seeking response was also associated with higher economic sustainability. Speculatively, actors that sought support from others in response to bleaching might also cooperate on other topics such as finding ways to increase visitor numbers to their reef locations (Partelow & Nelson, 2020). Interestingly, operators in my control sample that sought-support (10% of control sample) were also significantly associated with higher economic sustainability (Table 7.4). This could indicate that these non-affected operators also reaped the benefits associated with collective action.

My findings indicated that for impacts from tropical cyclones, the support-seeking response was associated with an increase in perceived climate vulnerability one year post-disturbance. This indicates that the support-seeking response may be qualitatively different between bleaching and cyclones; more relief-based for cyclones and perhaps more focused on collective action (transformative) for bleaching (Figure 6.2). Operators that took relief measures and that diversified their products in response to impacts from tropical cyclones were more likely to have experienced a loss in visitor numbers on their tours (my economic sustainability measure) one year after the event. This could, for example, refer to operators who sold their reef boat (relief measure) and switched to land-based tour activities (product diversification). Land-based tour activities might have had a lower carrying capacity because operators could transport less visitors per day in a tour van as compared to their former reef boats. This finding raises the question of whether diversifying in response to climate change will necessarily be associated with positive outcomes (Goulden et al., 2013; Islam et al., 2021; Mohammed et al., 2021). Thus, we need a better understanding of the strengths and weaknesses of different kinds of response diversity (Bartelet & Mulder, 2020; Grêt-Regamey et al., 2019; Walker et al., 2023).

7.4.3 Predicting Adaptation Outcomes

I found significant empirical evidence that spatial diversification (changing reef sites used on tours) can alleviate negative economic outcomes from climate change, at least within a reef tourism sector affected by severe climate disturbances. Spatial diversification might thus be a key adaptation response associated with social resilience (Gonzalez-Mon et al., 2021; Goulden et al., 2013; Tengö & Belfrage, 2004)—in my case, it provided the ability to for operators to retain visitor numbers despite coral loss. Adaptation is a critical component of resilience (Folke et al., 2010; Janssen et al., 2007; Nelson, 2011; Walker et al., 2004), so operationalising it is necessary as part of a broader framework for understanding social-ecological resilience (Allen et al., 2016; Cumming et al., 2005). My findings provide clear empirical evidence that spatial diversification responses contribute to operator resilience to climate-related disturbances. Whether this resilience can be sustained over the long term depends partially on the amount of ecological redundancy in respective social-ecological systems (Allen et al., 2011; R. Biggs et al., 2015) and whether operators have the flexibility to relocate their activities to other reef areas (Hoegh-Guldberg et al., 2019; Lin et al., 2023).

Measures to improve the health of the coral reef (restoration) were strongly associated with perceived risk outcomes. Operators that implemented restoration measures were significantly more likely to either see an increase or decrease in the perceived risk of being affected again by a similar climate disturbance in the next year. This finding provides empirical evidence that human responses to climate change can potentially affect risk thresholds (Berrang-Ford et al., 2021; Carr & Nalau, 2023). While spatial diversification helped to absorb disturbance (resilience), restoration-focused responses were associated with attempts to influence and manage resilience by reducing disturbance risks (adaptability) (Folke et al., 2010; Walker et al., 2004). Restoration-focused responses, however, were also significantly associated with increase in perceived climate risk after a disturbance. This indicates that similar responses might have different outcomes on perceived risks, or that my response type of ‘restoration’ consisted of different actions that affected risk outcomes in opposite ways. Thus a more detailed understanding of people’s restoration-focused responses is required.

7.5 Conclusion

Evaluating the outcomes, effectiveness, and success of climate change adaptation measures and programs implemented around the world has become a topic of increasing academic and public interest. My research operationalized and tested whether different adaptation measures, adopted by reef tourism operators in response to climate change impacts on coral reefs, had a positive or negative association with different indicators of adaptation success (risk, vulnerability, and sustainability). I found several meaningful relationships. Seeking support from others helped reef tourism operators to reduce their perceived climate vulnerability to future impacts and was positively associated with economic sustainability. Taking relief measures in response to cyclone impacts was associated with increased vulnerability and reduced economic sustainability one year post-disturbance, although pinpointing the cause-effect relationships between this response and the experienced outcomes will require further in-depth research. Reef restoration measures were associated (both positively and negatively) with perceived risk levels, indicating that climate risks can potentially be addressed by adaptation measures (adaptability, managing resilience). Spatial diversification (of reef sites) was positively associated with resilience, i.e. the ability to retain visitor numbers despite environmental change. My findings thus suggest that human adaptation to climate change addresses several elements of adaptation success, in particular climate risks, vulnerability, and economic sustainability. Further improvements in the operationalization and measurement of adaptation success, empirical testing in different contexts, longer time series, and integration with social-ecological systems theory, could further contribute to attempts to better understand whether and how climate change adaptation can be considered successful.

Appendix 7A.

Logistic Regression Models: Results Table

Table 7.7

Regression Statistics (Odds Ratios) for Multidimensional Outcomes Associated With Adaptation to Climate Disturbances on Asian-Pacific Coral Reefs

	Climate risk [a]		**Climate vulnerability** [b]	**Environmental sustainability** [c]	**Economic sustainability** [d]
	Decrease (21%)	***Increase (21%)***	***Increase (13%)***	***Decrease (42%)***	***Decrease (15%)***
R-squared	0.28	0.22	0.23	0.32	0.28
(Intercept)	-2.20 (0.000)	-2.85 (0.000)	-3.41 (0.000)	-1.30 (0.006)	-2.45 (0.000)
Baseline (pre-disturbance) [e]	2.73*** (0.000)	-2.90*** (0.000)	-3.06*** (0.000)	1.48*** (0.000)	1.34** (0.002)
Government effectiveness	0.35 (0.456)	0.48 (0.255)	-0.36 (0.484)	-0.41 (0.300)	-0.53 (0.313)
Cyclone (vs. bleaching)	0.05 (0.937)	0.81 (0.219)	1.67* (0.013)	1.50* (0.014)	1.58** (0.005)
Experienced severity [e]	0.38 (0.426)	1.22** (0.006)	0.77 (0.146)	2.18*** (0.000)	1.67** (0.001)
Monitoring (66%)	-0.07 (0.891)	0.09 (0.852)	0.16 (0.784)	0.63 (0.167)	0.74 (0.219)
Restoration (56%)	1.05* (0.048)	1.34* (0.011)	0.67 (0.268)	0.46 (0.298)	-0.48 (0.419)
Climate action (42%)	-0.08 (0.877)	-0.08 (0.872)	0.29 (0.581)	0.24 (0.569)	-0.01 (0.983)
Spatial diversif. (34%)	-0.04 (0.931)	0.53 (0.270)	-0.04 (0.950)	0.25 (0.554)	-1.11. (0.055)
Product diversif. (20%)	0.45 (0.455)	-1.08 (0.100)	0.05 (0.934)	0.50 (0.336)	0.30 (0.640)
Support-seeking (18%)	-1.08. (0.070)	-0.97 (0.100)	0.08 (0.909)	-0.58 (0.242)	0.68 (0.244)

Operational change (15%)	-2.00* (0.011)	0.13 (0.845)	0.85 (0.223)	-0.05 (0.935)	0.77 (0.275)

Note. Outcomes, measured as the number of operators that experienced a change in each indicator, are presented as either no change (0), a decrease (-), or an increase (+). The percentages reflect the fraction of the sample that experienced a particular outcome or adopted a particular adaptive response. Regression coefficient (β) are on a log-odds (logit) scale. Evidence against the null hypothesis of 'no effect' for each predictor is estimated using *p*-values with a 10% significance level (*p*-value provided between brackets). R-squared calculated in R by 1 minus (Residual/Null deviance).

Note. Significant results for the posthoc pairwise analysis are highlighted in yellow with asterisk presenting significant results (*p*-values) at respectively <0.10 (.), <0.05 (*), <0.01 (**), and <0.001 (***).

[a] For climate risk, I used a binary logistic regression model comparing either an decrease or increase in climate risk verus the rest of the sample. I used binary instead of multinomial logistic regression to be consistent with the models used for other outcomes (see below).

[b] For climate vulnerability, I used a binary logistic regression model because none of the cyclone-affected operators experienced a decrease and this outcome was merged with the 'no change (0)' category.

[c] For environmental sustainability, I used a binary logistic regression model because 3% of the sampled operators experienced an increase and this outcome was merged with the 'no change (0)' category.

[d] For economic sustainability, I used a binary logistic regression model because none of the cyclone-affected operators experienced an increase and this outcome was merged with the 'no change (0)' category.

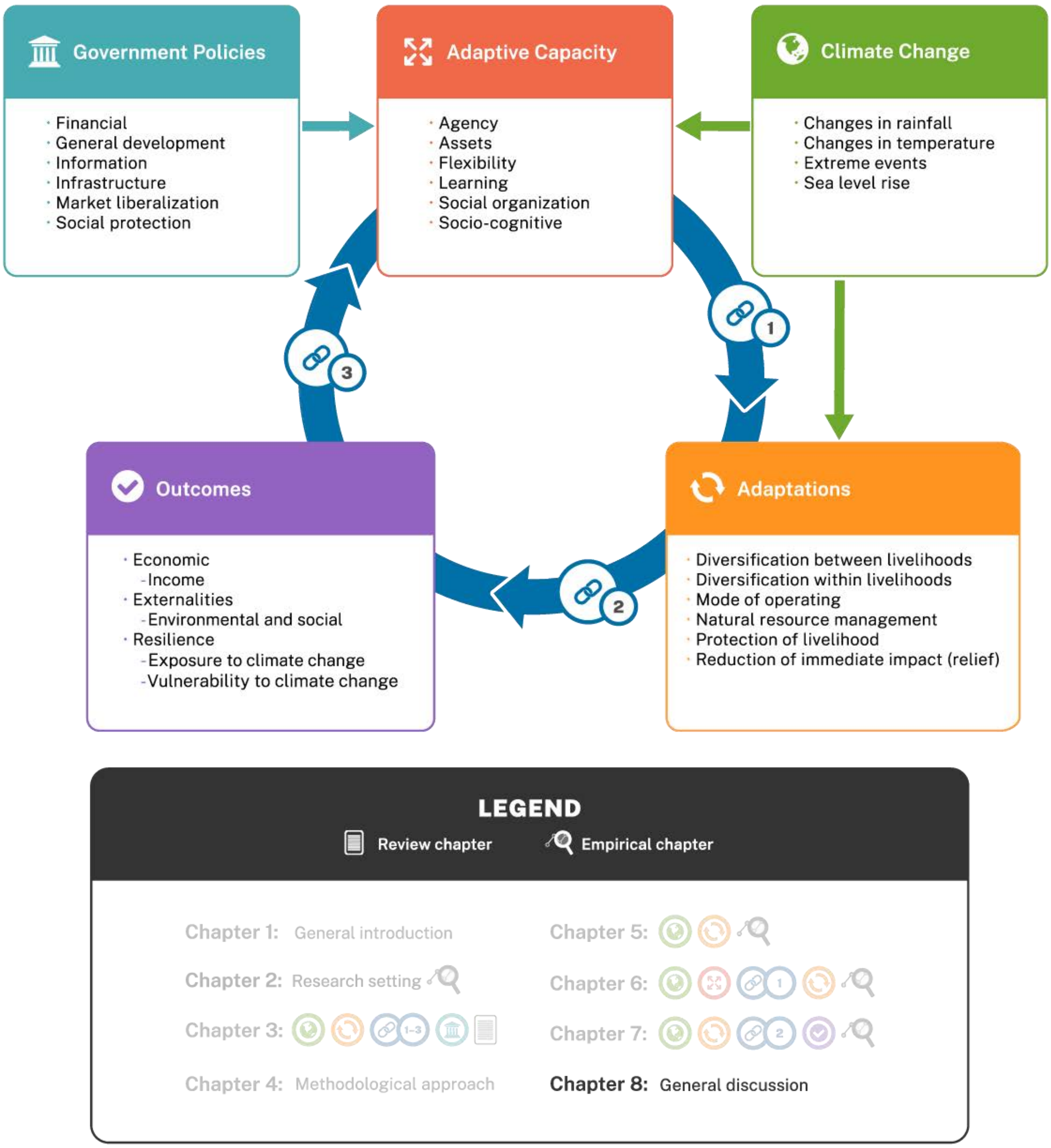
[e] Coefficients for outcome baseline and experienced severity are based on z-scored variables to make their effect size comparable to the other binary predictors, and should be interpreted as the effect of a one-standard deviation change in the predictor variable on the response variable.

Chapter 8. Discussion and Conclusions

8.1 General Discussion

Figure 8.1

Summary of Chapter 8



Amidst the expected 21st century climate change impacts on human livelihoods and wellbeing around the globe (Pörtner et al., 2022), adaptation is a topic of growing public and scientific interest. My thesis contributes to the adaptation literature by refining existing theories and providing solid empirical evidence of how adaptation plays out in action. Adaptation will be a shared responsibility between public and private actors. Microeconomic adaptation entails adaptation by the smallest units within economies: Individual households and firms. While the scientific literature on adaptation to climate change is growing rapidly, relatively few published studies provide evidence for adaptation that has already taken place rather than potential actions or vulnerability assessments (Berrang-Ford et al., 2021). In my thesis I provide a critical review of the scientific literature on microeconomic adaptation that has already taken place with most of the reviewed papers focused on African and Asian smallholder farms (**Chapter 3**. Literature review). The following chapters (**Chapter 4** to **Chapter 7**) explore microeconomic adaptation by communities that are economically dependent on coral reefs, an ecosystem that is one of the first and most iconic victims of climate change. I focused on communities dependent on coral reef tourism because they will likely experience the most immediate impacts from climate change. I first explored the effect of climate change on visitor numbers and tourist satisfaction, i.e. demand-side adaptation by reef tourism consumers (**Chapter 2**. The effect of coral bleaching on the recreational value derived from the GBR). The remaining chapters (**Chapter 4** to **Chapter 7**) focus on better understanding, through a systems lens, how individual reef tourism operators adapt to climate disturbances on coral reefs (i.e. supply-side adaptation by reef tourism producers).

The identification of social barriers and limits on climate change adaptation has become a major research stream within the adaptation literature (Adger et al., 2009; Biesbroek et al., 2013; Eisenack et al., 2014; Nielsen & Reenberg, 2010).This research has led to a re-emergence of the theoretical concept of 'adaptive capacity,' a concept adopted from evolutionary biology and complexity theory (Angeler et al., 2019; Seaborn et al., 2021) that has also been used in other fields including the health sciences (Janssen & Osnas, 2005) and sociology (Fullan & Loubser, 1972). Within the specific context of contemporary climate change, the concept of adaptive capacity seeks to synthesize the most important determinants of people's latent ability to adapt to climate change and other stressors. In my thesis, I build upon the holistic adaptive capacity framework developed by Cinner and Barnes that consists of both tangible (e.g. assets) and intangible (e.g. agency and psychological factors) determinants of adaptive capacity (Barnes et al., 2020; Cinner et al., 2018; Cinner & Barnes, 2019). In my critical review (**Chapter 3**. Literature review), I found that three of the six domains of adaptive capacity (agency, social organization, and socio-cognitive constructs) are under-represented in the current empirical adaptation literature. My case study on reef tourism (**Chapter 6**. Testing the reliability of adaptive capacity as a proxy for adaptive and transformative responses to climate change) is therefore one of the first studies that have operationalised actor-specific adaptive capacity along multiple axes (Barnes et al., 2020; D'agata et al., 2020; Datta & Behera, 2022; Mortreux et al., 2020; Nyboer et al., 2022; Salgueiro-Otero et al., 2022) and test for its effect on different adaptive responses to climate change.

My thesis extends the traditional two-way approach (adaptive capacity as enabler of adaptation) into a three-way approach by including a measurement of adaptation success that is associated with particular adaptive responses. Here I am one of the first authors to operationalize one of the most prominent definitions of 'successful' adaptation within the academic literature (Doria et al., 2009). Measuring adaptation outcomes, for example whether adaptation is successful in terms of reducing climate risk and vulnerability, is important because currently most of the existing literature includes an implicit assumption that all adaptations are beneficial. Indeed, few studies evaluate the outcomes of adaptation (Berrang-

Ford et al., 2021). Through my analysis (**Chapter 7**. Operationalizing and measuring 'successful' adaptation to climate change), I learned that one of the major challenges in evaluating adaptation success is the difficulty in pinning down the causal pathways between adaptations and the outcomes of adaptation.

Overall, my thesis contributes to conceptualizing and simplifying some of the complexity inherently involved in the process of human adaptation to climate change, in particular on a microeconomic level. I provide a theoretically-grounded and empirically applied conceptual framework to understand the consequential linkages between adaptive capacity (social barriers and determinants), adaptive responses (through a novel six-category categorization), and adaptation success.

8.2 Key Findings and Contributions

Within the climate change adaptation literature, there are roughly three interrelated avenues of enquiry that try to understand and explain climate change adaptation in terms of (1) responsive diversity; (2) barriers and determinants; and (3) outcomes (success). First, there are enquiries and theories about people's adaptive behaviour that try to explain and predict how people will respond to climate change. Second, there are enquiries and theories about people's ability to adapt to climate change that explain adaptation as a consequence of whether they have the adaptive capacity needed to respond when they are affected. Third, there are enquiries and theories about how adaptations work and thus about whether they will be successful or not. For each avenue of enquiry I discuss the key theoretical developments as well as the theoretical contributions made through my thesis.

8.2.1 Adaptation (response diversity)

There have been some higher level (or conceptual) ideas about how people will respond to climate change. For example, from an eco-centric perspective there is an emerging literature that classifies adaptation to environmental change as either ‘dampening’ or ‘amplifying’ environmental degradation (Cinner et al., 2011; Green et al., 2021). Another emerging literature has started to distinguish adaptive responses (incremental changes) from transformative responses (fundamentally altering systems or processes) to climate change (Fedele et al., 2019; Park et al., 2012; Pelling et al., 2015; Termeer et al., 2017; Wilson et al., 2020). Some prior categorizations of adaptation measures based on empirical data also exist. For example, Thomas et al. (2007) distinguished between short-term coping measures and longer-term adaptations, and Agrawal (2008) focused on the adaptation elements of mobility, storage, diversification, communal pooling, and market exchange. Finally, a specific typology for household adaptation to coastal flooding was developed by Koerth et al. (2014). However, a comprehensive framework (or typology) with adaptation alternatives has not yet been developed. The lack of an adaptation framework can be partly explained by a lack of synthesis of empirical evidence of people’s adaptations to the actual impacts from climate change. I contributed to adaptation theory by synthesizing the empirical evidence for adaptation to the actual impacts from climate change within the academic literature from 1995 to 2020. I proposed a conceptual typology of six types of adaptive responses microeconomic actors may potentially take in response to the impacts from climate change (Table 3.3). My adaptation typology can be challenged and refuted (Popper, 1935) if common and important adaptation measures to actual climate change impacts are identified that cannot be properly included within my six-type categorization. A limitation of my novel, and existing, adaptation typologies is that there is no strict delineation between different ‘types’ of adaptation, meaning that different adaptive responses could conceptually be included in different adaptation ‘types’. Further development of adaptation typologies could focus on having less ambiguously classified response types.

I tested my conceptual adaptation typology in an empirical case study on adaptation to climate change by coral reef tourism operators in the Asia-Pacific Region. I found that similarly to my reviewed studies (Table 3.3), the most common adaptation types were ‘diversification within livelihood’ and ‘natural resource management.’ However, making ‘changes in the mode of operating’ were not that frequently adopted in response to climate change impacts by reef tourism operators. This finding could indicate that operational changes that are common in agriculture (changing harvesting dates or farm management) might be less applicable in a reef tourism context. My study identified only one adaptation measure that was commonly mentioned as an ‘other’ response by my study participants: the education of visitors about climate change impacts. This educational response might be tourism-specific, as other microeconomic actors such as farmers might have less directly interaction with the consumers of their products, and the consumers of these products less direct interaction with the impacts from climate change. The visitor education response could conceptually be included as a product diversification (diversification within livelihood), but my results indicated that it was correlated with actions to reduce carbon emissions (Figure 5.2). Visitor education could potentially have an effect on future carbon emissions similar to a company taking climate action itself. Given the large number of visitors to Australian coral reefs, about 2 million annually (**Chapter 2**. The effect of coral bleaching on the recreational value derived from the GBR), evaluating the long-term impact of education on visitors’ environmental behaviors is an important future research avenue (Becken, 2005; Salim et al., 2022). My analysis of visitor experiences through Tripadvisor reviews (Figure 2.4) identified that visitor satisfaction is positively associated with knowledge about the ecosystem. Thus, educating visitors about climate change impacts on coral reefs (or other ecosystems) might lead to both higher satisfaction levels and potential positive impacts on future carbon emissions.

When I analyzed which adaptive responses were most commonly implemented together (or correlated) by the same operators, I found that my ten responses could be classified into three distinct response clusters (Figure 6.2). The three response clusters mapped well into the theoretical distinctions between coping, adaptive and transformative responses (Fedele et al., 2019; Park et al., 2012; Pelling et al., 2015; Termeer et al., 2017; Wilson et al., 2020). I overlaid these three response clusters based on existing theory and my empirical evidence to identify what type of individual response could be classified as adaptive and transformative in my reef tourism context. I found that, counter to expectation, diversification between livelihoods was more strongly associated with responses typically considered adaptive in nature. This could potentially be explained by our observation (based on qualitative evidence in our surveys) that the types of other products and services reef operators diversified towards were often relatively incremental (e.g. selling reef-safe products). Support-seeking, on the other hand, was classified as ‘coping’ response in my typology, but my data showed that it was more strongly associated with responses that were more transformative in nature, most notably with restoration measures (natural resource management). We therefore included the support-seeking response within the transformative cluster, as a response linked to collective action (for which we found some qualitative evidence in our surveys). Our later finding (discussed below) that support-seeking led to positive risk and environmental sustainability outcomes in a coral bleaching context strengthened our decision to classify this response as transformative.

8.2.2 Adaptive Capacity (barriers and determinants)

The evaluation of adaptive capacity is important because it differs from evaluating adaptation by its focus on aiming to understand whether people will have the ability to adapt, before they are actually affected. This can be important for policy-making as potential negative impacts from climate change might be prevented by strengthening people’s adaptive capacity before they are (severely) affected (Engle, 2011; Engle & Lemos, 2010). My thesis builds specifically on the adaptive capacity theory and domains developed by Cinner and Barnes (2019), building on earlier work by Cinner et al. (2018). My review of empirical adaptation studies (Figure 3.3) found that three of the adaptive capacity domains (the most intangible) are currently under-represented: *agency*, *social organization*, and *socio-cognitive constructs*. My study (**Chapter 6**. Testing the reliability of adaptive capacity as a proxy for adaptive and transformative responses to climate change) complements other recent studies that have tested for the effect of all different domains of adaptive capacity on the responses implemented in response to climate change (Barnes et al., 2020; D'agata et al., 2020; Nyboer et al., 2022; Salgueiro-Otero et al., 2022). My study is among the first to include three indicators within the domain of *socio-cognitive constructs* that were based on the disaster risk reduction and behavioural science literature: competing concerns, self-efficacy, and place attachment (Mortreux & Barnett, 2017). My findings indicated that, accounting for all adaptive capacity domains, self-efficacy (adaptation confidence) was negatively associated with transformative responses to climate change. Prior theoretical studies have identified self-efficacy as a positive determinant of adaptive action (Bandura, 1977; Grothmann & Patt, 2005; Mortreux & Barnett, 2017) and a meta-analysis of climate change adaptation studies found evidence in line with this theory (van Valkengoed & Steg, 2019). As discussed in Chapter 6, the observed transformative responses mainly consisted of coral restoration and climate action and these responses might have a different relationship to self-efficacy than livelihood diversification. Adaptive responses were mainly driven by the experienced severity of climate impacts on individual operators. Self-efficacy might thus be more important for the adoption of proactive/preventive adaptation measures towards climate change (Truelove et al., 2015; van Valkengoed & Steg, 2019), while reactive adaptation measures are driven by impact severity, at least within our specific study setting. In adaptation settings where transformative action is necessary, self-efficacy could pose a barrier. A better causal understanding of this effect is required. My findings also emphasized the importance of one of the other under-represented domains of adaptive capacity, namely social organization. Indicators within the adaptive capacity domain of social organization, specifically ties between operator and with research institutes, within were meaningful predictors of adaptation to climate change. This has important implications for policy making, as many climate change adaptation programs are focused on the adaptive capacity domains of assets and flexibility (Cinner et al., 2018; Lemos et al., 2013). Policies focused on improving social capital, could potentially be more effective in promoting bottom-up transformative action for sustainable social-ecological systems (Girard et al., 2015; Pisor et al., 2022; Urwin & Jordan, 2008). Further research is required to identify what kind of government policies can have positive effects on the adaptive capacity domain of social organization.

If and how adaptive capacity is a good proxy for adaptation is a key theoretical research question (Barnes et al., 2020; Daw et al., 2012; Green et al., 2021; Mortreux et al., 2020). My findings propose a refinement of existing theories about the complex relationship between adaptive capacity and adaptation. That is, I found that the prioritization of adaptive (incremental) responses to climate change (over doing nothing) are only weakly associated with underlying levels of adaptive capacity, and they are mostly driven by the experienced severity of climate change impacts (Figure 6.4). The prioritization of transformative responses to climate change (over doing nothing) were strongly associated with the underlying levels of social organization for individual actors. Reef operators that were more socially connected (in particular with other operators and research institutions) were more likely to prioritize transformative responses such as coral restoration and climate action. My refinement of existing theories, about a differential relationship between adaptive capacity, adaptive, and transformative responses can be tested and corroborated by further empirical studies. My findings are relevant for policy making in a climate change adaptation context because they indicate that adaptive action might be provided autonomously by the majority of microeconomic actors when they are affected by climate change (Fankhauser, 2017; Ilosvay et al., 2022; Pecl et al., 2019).

A final discussion point is that there is a possibility that the adaptive capacity indicators I used in my analysis were not the most appropriate for the specific industry I studied. An inductive stakeholder-driven approach to identify what specific metrics of capacities (within the framework used) might be most salient for the industry might have led to alternative conclusions.

8.2.3 Adaptation Outcomes (success)

My thesis builds specifically on the definition of adaptation success developed by Adger and colleagues (Adger et al., 2005; Doria et al., 2009): risk and vulnerability reduction without compromising social, economic, or environmental sustainability. My review of empirical adaptation studies (Figure 3.3) found that most empirical adaptation studies do not evaluate the outcomes of people's adaptation measures. There are currently no prominent theories about different adaptation measures and what outcomes they are most likely to lead to (Berrang-Ford et al., 2021; Owen, 2020). Some higher level conceptual ideas exist, for example that transformative responses to climate change can have long-term benefits for the sustainability and resilience of people and ecosystems (Fedele et al., 2019; Pelling et al., 2015; Wilson et al., 2020).

My findings indicate that adaptive responses classified (Figure 6.2) as transformative (specifically, coral restoration and support-seeking) were significantly associated with changes in perceived climate risk and vulnerability, while responses classified as adaptive (specifically, spatial diversification) were significantly associated with sustaining economic benefits received from climate-affected natural systems. My findings could be associated with the distinction in the social-ecological systems literature between resilience, adaptability, and transformability (Folke et al., 2010; Walker et al., 2004). Adaptive responses (spatial diversification) contribute to resilience in terms of absorbing disturbances while retaining the same function and outcomes (that is, sustaining visitor numbers after environmental impacts). While resilience is mainly associated with absorbing disturbance and recovering from it, adaptability is associated with attempts by human actors to influence and manage resilience (Folke et al., 2010; Walker et al., 2004). Influencing and managing resilience was associated with transformative responses that can affect the risk and vulnerability levels of microeconomic actors. An important caveat here is that the significant relationship I found between transformative responses (restoration and support-seeking) and risk and vulnerability outcomes were based on *perceived* risk and vulnerability. Transformative responses affecting *perceived* risk and vulnerability outcomes do not necessarily translate to *objective* risk and vulnerability thresholds being changed. Instead, it might only indicate that engaging in these transformative responses provided socio-cognitive benefits to reef tourism operators (Curll et al., 2022; Keniger et al., 2013).

Transformability (within social-ecological system theory) is defined as actors creating fundamentally new systems (Folke et al., 2010; Walker et al., 2004), which was not commonly observed in my system of interest, the Asian-Pacific coral reef tourism industry affected by climate change. My study thus contributes to interdisciplinary science by building a bridge between climate change adaptation outcomes theory and social-ecological systems theory. My findings posit a theory that relates adaptive responses to climate change with resilience (absorbing but not managing disturbance) and transformative responses with adaptability (managing disturbance through risk and vulnerability reduction). My synthesis of two different theoretical fields, about the associative relationships between different kinds of responses to climate change and the expected outcomes can be tested and corroborated by further empirical studies. Future research should more clearly conceptualize the relationships between individuals and their actions (which was the focus of my thesis) and the system-level outcomes and dynamics that were not explicitly included in my research design. For example, if an individual reef tourism operator spatially diversified their reef sites, this could be seen as resilient if it helps them retain visitor numbers. However, if all operators diversified spatially by moving tourists to a limited number of remaining healthy reef sites, their collective and uncoordinated response could lead to undesired fragilities in the system. The question of how individual (adaptive) actions support or undermine social-ecological resilience is complex and my thesis does not provide much system-level evidence independent of the operator responses to assess these linkages.

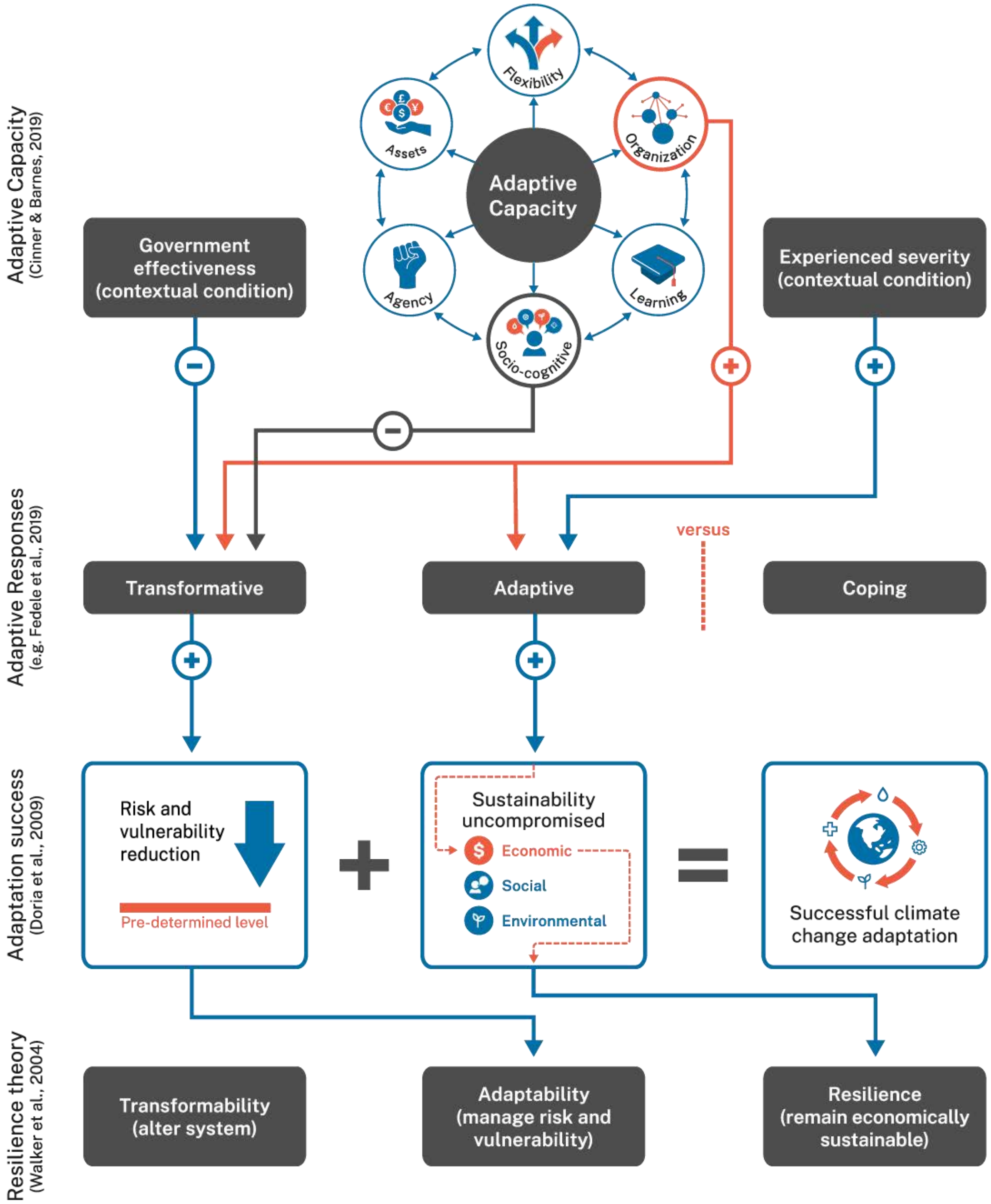
8.2.4 Dynamic Adaptation Framework (Synthesis)

In my thesis I studied the consecutive relationships between people's pre-existing levels of adaptive capacity, the adaptation measures they implemented in response to impacts from climate change, and the outcomes they experienced one year after a climate disturbance occurred. These three dynamic steps provide the baseline required for going towards a feedback approach in evaluating climate change adaptation (Figure 1.2 and Figure 3.5). That is, over time, outcomes are expected to have an effect on people's adaptive capacity (Dilling et al., 2023). The main contribution of my thesis is thus that I have brought ideas and a way of thinking that originates within the system sciences to the complex field of microeconomic climate change adaptation. The importance of the dynamic aspects of human adaptation studies has been acknowledged widely (Eisenack et al., 2014; Engle, 2011; Schill et al., 2019), but seldom implemented and operationalized. My thesis makes a contribution to the emerging research stream focused on the dynamic complexities and feedbacks within the climate change adaptation process (Barnes et al., 2017; Fedele et al., 2020; Laborde et al., 2016).

My thesis also builds a bridge between climate change adaptation theory and social-ecological system resilience theory. Impacts from climate change, such as the climate disturbances I have studied in my thesis (coral bleaching and tropical cyclones), are considered as environmental perturbations within a resilience context (Cumming et al., 2005; Walker et al., 2004). Adaptive capacity is now a common framework used within a climate change adaptation context (Siders, 2019; Smit & Wandel, 2006), but its relationship to resilience remains debated (Gallopín, 2006). My thesis has, without explicitly focusing on it, identified that the associations between adaptive capacity and resilience can be better understood when analysing the (social-ecological) outcomes of adaptation. Within resilience and social-ecological systems theory, resilience is mainly associated with the ability of a system to restore functioning after a perturbation (Folke et al., 2010; Walker et al., 2004). In a microeconomic context, this could be achieved by a quick recovery of economic output after an environmental perturbation. Within a climate change outcomes context, resilience can be measured through the economic sustainability indicator. In my case study, it was spatial diversification that significantly contributed to (economic) resilience (Figure 7.2). Within resilience theory, adaptability is associated with the ability of system actors to manage resilience, thus the ability to reduce exposure and vulnerability (Folke et al., 2010; Walker et al., 2004). This adaptability is strongly associated with the climate risk and vulnerability measures that were identified by Doria et al. (2009) to test adaptation success. In my case study, the transformative response of restoration measures (natural resource management) was significantly associated with perceived climate risk reduction in some cases (Figure 7.2). Thus my findings indicate that transformative responses as identified within a climate change adaptation context (Figure 6.2) are associated with adaptability in a social-ecological system resilience context. Transformability in a resilience context relates to the ability of a system to completely transform itself into something with a new functioning (Folke et al., 2010; Walker et al., 2004). It is unclear how this type of transformability is associated with the adaptation success definition in a climate change context, although it might be represented and measured by economic sustainability in a wider sense, e.g. from a regional rather than a microeconomic point of view. Novel indicators might be required to measure the successfulness of climate change adaptation in terms of transforming the functioning of a system. Within my case study, while some operators adopted livelihood diversification measures, these measures were mainly incremental. Thus, I did not find strong evidence for transformability within a climate change impacts on reef tourism context.

Figure 8.2

Microeconomic Adaptation Dynamics: Summary of Main Thesis Results



Note. This figure describes the meaningful relationships that were found in my analysis of the consecutive relationships between adaptive capacity, adaptation, and adaptation outcomes ('success'). Within an APAC reef tourism industry context, the adaptive capacity domain of social organization enabled both transformative (industry memberships and ties to research institutes) and adaptive responses (industry memberships) to climate disturbances. One indicator within the adaptive capacity domain of socio-cognitive constructs (adaptation confidence) was negatively associated with transformative response. Adaptive response were primarily enabled by the experienced severity of climate impacts (contextual condition). Operators in countries with higher government effectiveness (contextual condition) were less likely to prioritize transformative responses. The adaptive response of spatial diversification enabled economic sustainability by helping operators maintain visitor numbers despite environmental impacts. Social sustainability was not affected by climate disturbances, while none of the responses was able to dampen negative impacts on environmental sustainability (coral cover). The transformative responses of coral restoration and support-seeking were associated with perceived climate risk and vulnerability reduction in some cases. Economic sustainability is associated with resilience in social-ecological systems theory context, while perceived risk and vulnerability reduction are linked with adaptability. Design by Eileen Siddins.

8.3 Caveats and Critiques

One limitation to this dissertation is the limited ability to generalize my specific results, e.g. on the relationships between adaptive capacity and adaptations, and adaptation and adaptation outcomes. I investigated these relationships in a very particular research setting: Asian-Pacific coral reef tourism affected by climate disturbances. However, within my research setting I included several culturally, economically, and institutionally different research locations. I thereby provided the ability to generalize my findings to other reef tourism settings. While the specific findings might not be directly replicable towards other microeconomic sectors, such as farming, the main contribution of my thesis was conceptual and methodological: applying a dynamic approach to study the adaptation process. These conceptual and methodological concepts can be directly applicable to other research settings, including farming, fisheries, and urban systems.

A second caveat is that my thesis was for the most part based on data from surveys, focused on getting a relatively large sample size with standardized responses that are directly comparable in terms of the level of detail. My results are thus mainly quantitative, and findings are based on statistical rather than causal associations. The focus on quantitative research is on identifying the relationships between different processes that are shared among different actors. Qualitative research focuses on what is unique to a particular actor or system of interest. More importantly, qualitative research can help answer the why questions that are less evident with quantitative associations among variables and can provide the needed insight into causal relations. Qualitative work is also often critical in the scoping stages of research design to ensure construct validity in any indicators considered for quantitative analysis.

Third, the way in which I measured reef operators' adaptive responses to climate disturbance was exploratory. That is, I had a long list with potential responses, without prior information on what kind of responses would have been most common in their situation. I thus was not able to investigate in more detail what operators exactly did within each of the responses that I asked about in my surveys. For example, I asked operators whether they implemented measures to improve the health of the coral reef (that is, reef restoration measures), but if an operator selected 'yes,' I did not know exactly what their response entailed. Given my finding that restoration measures had opposite effect on perceived risk outcomes, there could have been different types of restoration responses (with different outcomes). My results thus provided the basis for more detailed future investigations.

Finally, a major critique is the time period used in my surveys, specifically the fact that I asked about adaptive response over the same time period as the evaluation period of the outcomes. This made it more difficult to interpret cause-and-effect. Because we measured outcomes at two points in time, we could not describe the behaviour of each indicator in the intervening period. For example, economic sustainability (visitor numbers) might have decreased one month after the disturbance without recovering in the following 11 months. Thus, some adaptive responses (implemented within one year after a disturbance) might have been (partly) caused by a change in the outcome, rather than the outcome being caused by the adaptive response. Our time period of measuring outcomes one year after a disturbance occurred also limited our ability to understand the longer-term outcomes associated with different adaptation measures.

8.4 Future Directions

Future research could focus on replicating my dynamic adaptation method in other settings, for example within an agricultural or fisheries setting. Through replication studies some of the theories I posited, for example about potential response types and linkages between adaptive capacity and responses, could be corroborated and new hypotheses could be developed. It would also be interesting to test my dynamic adaptation model in a setting that is less associated with climate disturbances and more with gradual changes in the environment caused by climate change, for example groundwater depletion. Adaptation to gradual climate impacts might be fundamentally different from adaptation to extreme climate events (Kates et al., 2012; Lee & Zhao, 2021; Linnenluecke & Griffiths, 2010; Travis & Huisenga, 2013).

Future research could help improve the methods I used in my thesis. Survey questions can be improved to get a more detailed response about the type and timing of implemented adaptation measures, while more open-ended questions could help establish causal links, for example whether outcomes are the cause of consequence of particular adaptation measures. Improvements can also be made to the statistical methods I used to analyse the consecutive relations between adaptive capacity, adaptive responses, and adaptation outcomes. For example, these consecutive links might be explored in a combined model using structural equations modelling. Novel statistical methods might also be applied to study the interrelationships between different adaptation outcomes and the different adaptive responses in one coherent model. Cross-verification of some of my findings using qualitative methods (structured interviews) could provide some more explanative insights into my research findings.

Finally, future research could complete the adaptation feedback cycle (Figure 1.2 and Figure 3.5), by studying whether the adaptation outcomes are a meaningful predictor of changes over time in different adaptive capacity domains. Such studies can also test for the effect of different government policies to facilitate microeconomic adaptation on the adaptation feedback cycle. I have collected data on these relationships during my thesis and hope to contribute to this future research avenue.

Theoretically, further research could focus on studying interactions between public sector and private sector (microeconomic) adaptation to climate change. For example, I found that transformative responses to climate change were more frequently adopted by reef tourism operators located in countries with lower government effectiveness (Figure 6.4). This finding could be explained by the assumed responsibility of public authorities in countries with higher government effectiveness to undertake transformative responses to climate change (Mortreux et al., 2020). My thesis thus might have provided evidence for the 'crowding out' (Ostrom, 2000) of microeconomic climate change adaptation by the presence and/or actions of government institutions. For example, in Australia the Great Barrier Marine Park Authority is mainly responsible for reef conservation measures, and microeconomic actors might thus be less inclined (or permitted) to become involved in such measures. Interestingly, we did not find significant differences in social-ecological outcomes between operators located in countries with lower versus higher government effectiveness (Figure 7.2). Thus it remains a question whether public or private adaptation efforts to climate change are more successful, at least over short periods such as the one studied here (Grothmann & Patt, 2005; Klein et al., 2018; Wamsler, 2016). There could potentially be synergies between public and private adaptation, however it is also possible that the two types of adaptation might hinder each other. For example, public crop insurance programs have in some cases reduced the incentive for farmers to adapt to climate change (Mendelsohn, 2006; Repetto, 2008). Public policies can also be influenced by power dynamics rather than market failures, favouring the protection of the status quo and special interest groups rather than creating a level playing field for cost-efficient adaptation (Cinner & Barnes, 2019). There might also be co-benefits associated with an increased focus on bottom-up adaptation efforts (e.g. by microeconomic actors), such as an increase in collective action (Ostrom, 1990) and benefits in terms of social sustainability. Overall, better theories are needed to understand the holistic advantages and disadvantages of adaptation by public and private sectors. Novel frameworks are needed to determine when, and in which context, each type of adaptation is most applicable, and how different combinations of responsibilities could lead to different outcomes.

8.5 Concluding Remarks

My thesis has contributed to making sense of some of the complexity associated with adaptation to environmental change, specifically within a climate change context. Through the progressive chapters of my thesis, I have provided a number of theoretical contributions that could help progress the climate change adaptation literature and practice. These contributions include (1) a typology of the six most commonly observed types of adaptation among microeconomic actors to climate change; (2) a binary explanation for when and where adaptive capacity has been a good proxy for adaptation, based on findings within a specific research setting of reef tourism operators affected by severe climate disturbances; (3) an understanding of how adaptive and transformative responses can provide resilience and adaptability in a social-ecological system resilience context; and (4) an overall feedback perspective on the adaptation process that could be used to evaluate the effectiveness of policies to facilitate microeconomic adaptation to climate change.

My thesis raises more new questions than it has answered, as every theoretical advancement raises "new problems; problems of reconciliation, problems of how to conduct new and previously unthought-of observational tests" (Popper, 1963, p. 301). Individual human behaviour and the collective behaviour of groups of people are notoriously complex.

Additionally, people depend on nature and our understanding of people's interactions with and responses to environmental change is in its infancy. While a strong growth in action and initiatives to help people adapt to climate change is expected, my thesis provides a critique against intervention in human adaptation processes without understanding the dynamic implications. Local people often have the best information about their specific adaptation needs and combined with their ability to innovate and address problems through collective action, it is clear that they will play a key role in successful adaptation.

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