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Effects of Climate Change on Corals Relevant to the Pacific Islands

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EXECUTIVE SUMMARY

In the Pacific island region, anthropogenic-induced ocean warming is impacting coral reefs through thermal coral bleaching (Adjeroud *et al*., 2009; Cumming *et al*., 2000; Davies *et al*., 1997; Kleypas *et al*., 2015; Lovell *et al*., 2004; Mangubhai, 2016; Obura and Mangubhai, 2011; Rotmann, 2001) and by reducing coral calcification rates (high confidence) (De'ath *et al*., 2009; Nurse *et al*., 2014). Ocean acidification is also affecting calcification rates (low confidence) (Barros and Field, 2014; IPCC, 2014; Johnson *et al*., 2016b), while tropical cyclones (TC) are becoming more intense (low confidence) (Elsner *et al*., 2008; Nott and Walsh, 2015), causing widespread coral damage (Johnson *et al*., 2016a; Mangubhai, 2016). Accelerating climate change is currently the strongest driver affecting coral dynamics (Aronson and Precht, 2016) exacerbating other non-climate pressures, such as pollution from land-based activities and coastal development, eutrophication, overfishing, crown-of-thorns starfish outbreaks, direct physical impacts (e.g. tourism-related impacts, trampling and anchor damage), and coral diseases, which together are causing changes in coral communities not previously recorded (high confidence) (Brown *et al*., 2017a; Hoffmann, 2002; Johnson, 2017; Maata and Singh, 2008; Maynard *et al*., 2015b; Mayor, 1924; Morris *et al*., 2008; Morrison, 1999; Movono *et al*., 2018; Singh *et al*., 2009; Sykes and Morris, 2009; Zann, 1994). Predicted increase in atmospheric carbon dioxide (CO_2) concentrations will continue to increase ocean temperatures and acidity (high confidence) (Gattuso *et al*., 2015; Newman *et al*., 2018) as well as increase the intensity of TC (low confidence) (Elsner *et al*., 2008).

Climate pressures will exacerbate non-climate pressures (high confidence) (Aronson and Precht, 2016; Sheridan *et al*., 2014; Wild *et al*., 2011), thus increasing the frequency and severity of coral bleaching, disease incidence, and mortality (high confidence) (IPCC, 2014; Langlais *et al*., 2017; Reisinger *et al*., 2014; Ruiz-Moreno *et al*., 2012; Sheridan *et al*., 2014). Declines in coral reef habitat will cause negative social-economic and ecological effects (high confidence) (IPCC, 2014; Morrison, 1999). Traditional

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systems of resource governance in the Pacific are often associated with healthy reefs (Hoffmann, 2002) and coastal communities depend heavily on coral reefs for food, income and livelihoods. Therefore, management and adaptation options must consider and build on the regional diversity of governance systems to enable community-based initiatives and cross-sectoral cooperation, taking into account traditional knowledge that can inform sustainable solutions to problems (Aswani *et al*., 2017; Morrison, 1999; Remling and Veitayaki, 2016; Veitayaki, 2014) and allow the involvement of a broader section of the community. Such an inclusive approach will offer enhanced opportunities to develop and implement measures to reduce non-climate pressures and develop early warning systems, to identify potential refuges for coral reef communities (Karnauskas and Cohen, 2012) and also to test coral farming, assisted colonisation and shading or other climate mitigation techniques (Barros and Field, 2014; Coelho *et al*., 2017).

Introduction

Coral reefs are the dominant coastal habitat in the tropical Pacific, representing more than 25% of reefs globally – nearly 66,000 km^2 (Wilkinson, 2004; Wilkinson, 2008). Many Pacific Islands and Territories (PICTs), including French Polynesia, Kiribati and Palau have at least double the reef area than land area (SPC data). Corals are the fundamental reef ecosystem engineers because they construct the framework that supports over 600 species of calcifying corals, 4,000 species of fish, as well as a high diversity of invertebrates, macroalgae and marine megafauna totalling approximately 830,000 species of multi-cellular animals and plants worldwide, or 32 percent of all named marine species (Allen, 2008; Fisher *et al*., 2015; Wilkinson, 2008). Coral reefs form a mosaic of habitats along with mangroves and seagrasses, which sustains a diversity of organisms, greater fish productivity, a variety of industries (e.g. fisheries and tourism), also more effectively protecting the coastline against erosion (Veitayaki *et al*., 2017) when these habitats are adequately inter-connected (Guannel *et al*., 2016; Moberg and Folke, 1999; Zann, 1994).

The distribution of corals is limited by physical and biological factors. Physical factors include water temperature, pH, light, turbidity/sedimentation, salinity, and water depth (Aronson and Precht, 2016), while biological factors include predation (e.g. the Crown-of-Thorns-Starfish (COTS) and *Drupella* spp.; both well-known coralivores (Berthe *et al*., 2016; Bruckner *et al*., 2017)), intra and inter-specific competition (e.g. competition between corals and algae, and between different coral species for space), reproductive and regenerative capacity, and the ability to cope with pollutants, nutrients and sediments (Guinotte *et al*., 2003; Kleypas *et al*., 1999; Rogers, 1990). This means that alterations to any of these factors can seriously threaten the existence of corals.

Growing human populations in most PICTs, along with changes in lifestyle put enormous pressure on coral reefs and connected habitats. In addition to an increasing demand for food, people also want increased standards of living and, to do so, they build infrastructure such as piped water and sewerage facilities, but also better housing, roads and a range of foodstuffs and consumer goods. Despite the beneficial effects on corals of sewerage systems and better housing, increased land clearing and alteration of riverine and littoral vegetation for construction, waste disposal, and mining, negatively affect water quality, coral reefs and connected habitats, leading to the decline of corals and associated organisms (Morrison, 1999; Remling and Veitayaki, 2016; Veitayaki and Holland, *in press*; Zann, 1994).

Since the 1970s there has been a growing body of evidence showing the deterioration of coral populations around the world and in the Pacific Ocean due to both climatic and non-climatic drivers. Widespread temperature-related bleaching events have been recorded world-wide and in the Pacific Ocean (Hughes *et al*., 2017b; Lough, 2012; Mangubhai, 2016; Obura and Mangubhai, 2011). Cyclones are becoming stronger (low confidence (Elsner *et al*., 2008)), oceans are becoming more acidified (medium confidence) (Barros and Field, 2014; Bates *et al*., 2014; Dore *et al*., 2009; IPCC, 2014; Johnson *et al*., 2016b), and sea level is gradually rising (Dean and Houston, 2013; Jevrejeva *et al*., 2009). These events cause negative effects on coral reefs and adjacent ecosystems upon which corals depend (e.g. seagrasses and mangroves) (Albert *et al*., 2017; Guannel *et al*., 2016; Hassenruck *et al*., 2015), and are expected to increase in the future due to increased carbon dioxide (CO_2) emissions and consequent global warming (high confidence) (Gattuso *et al*., 2015).

The most important non-climatic drivers affecting Pacific corals include overfishing (Hughes *et al*., 2007; Jackson *et al*., 2001; Rasher *et al*., 2012), human-induced pollution, shore modification (Bell *et al*., 2011), nutrification (Wiedenmann *et al*., 2013), increase in sedimentation and turbidity (Dadhich and Nadaoka, 2012; De'ath and Fabricius, 2010; Haywood *et al*., 2016; Sheridan *et al*., 2014), and increase in the incidence of COTS outbreaks (Berthe *et al*., 2016; Hughes *et al*., 2017a; Uthicke *et al*., 2015). Other impacts include recreational and tourism-related impacts, such as the construction of resorts, water catchment dams, roads, and even man-made islands, along with trampling, tourism handling, and anchor damage, which have brought substantial ecological shifts in coral communities over time, but also unprecedented social, economic and cultural changes within Pacific communities (Ayala, 2005; Engelhardt, 2005:176; Kininmonth *et al*., 2014; Morris *et al*., 2008; Morris, 2009; Movono *et al*., 2018; Sykes and Morris, 2009). Climatic drivers can work synergistically with other non-climate pressures such as nutrient enrichment to further impact corals (Chazottes *et al*., 2017; Wiedenmann *et al*., 2013; Wooldridge *et al*., 2017). Coral growth depends on the intrinsic immune response and repair mechanisms in reef-building corals (D'Angelo *et al*., 2012). Increase in temperature and nutrient enrichment, along with ocean acidification can affect corals' immune response, thus increasing the susceptibility of corals to diseases and affecting coral survivability and growth (Aronson and Precht, 2016; Hassenruck *et al*., 2015; Maynard *et al*., 2015a). Moreover, synergistic effects between ocean acidification (low aragonite saturation) and nutrient loading are far more effective at driving coral macrobioerosion than ocean acidification alone (DeCarlo *et al*., 2015). This has important consequences for corals and reefs because it diminishes coral growth rates, thus compromising reef structures.

Coral responses to climatic and non-climatic pressures are similar and include bleaching (expulsion of zooxanthellae that live in their tissue (Aronson and Precht, 2016; Chazottes *et al*., 2017)), reproductive and growth impairments (Albright and Mason, 2013; Fabricius *et al*., 2017; Sheridan *et al*., 2014), and coral-algal phase shifts (from coral-dominated to algae-dominated reefs) (Done, 1992; Hughes *et al*., 2007). The end result of sustained stresses on corals is a simplification of coral community structure and reductions in live coral cover (Bruno and Selig, 2007) and species coral trait diversity (Darling *et al*., 2013), which have resulted in habitat losses (Aronson and Precht, 2016; Brown *et al*., 2017a). The rate and extent of coral loss in the Pacific is greater than expected (Bruno and Selig, 2007) and have caused negative social-ecological consequences, such as decreased fish catches and coastal protection, and biodiversity loss (Adam *et al*., 2014). These consequences are very relevant to PICT due to the reliance of the majority of their population on coastal and marine resources for cultural reasons, income and food (Morrison, 1999).

It is clear from the literature that the widespread and deleterious effects of non-climate drivers on corals, climate change is currently the strongest driver affecting coral dynamics (Aronson and Precht, 2016) exacerbating non-climate pressures, which together are causing unprecedented changes in coral communities and connected habitats (high confidence) (Brown *et al*., 2017a; Hoffmann, 2002; Johnson, 2017; Maata and Singh, 2008; Maynard *et al*., 2015b; Mayor, 1924; Morrison, 1999; Singh *et al*., 2009; Zann, 1994).

Scope and aims of the review

This review will discuss impacts of climate change on corals according to standardised metrics. We use the Representative Concentration Pathways (RCP) scenarios, which provide socio-economic, technological, land-use, emissions of greenhouse gases, and environmental descriptions of possible futures. RCP are used as input for climate model runs and as a basis for assessment of possible climate impacts and mitigation options (van Vuuren *et al*., 2011).

This chapter is limited in scope to a desktop literature review on the impacts of climate change on corals relevant to the Pacific Island Countries and Territories (PICTs). The review also deals with non-climate drivers because of the synergistic effects they have with climate drivers affecting Pacific corals. The geographical focus of the review centres on Fiji, Kiribati, Nauru, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu. The review is structured as follows: firstly, we provide a general overview of observed changes on corals associated with non-climate drivers; secondly, we present observed changes on coral populations related to climate drivers, followed by the observed synergistic effects of non-climate and climate drivers on corals; thirdly, we offer the qualitative level of confidence in the science for current and future changes on corals; and, lastly we offer pressing knowledge gaps, risks and socio-economic impacts and an overview on adaptation options relevant to the Pacific islands.

What is Already Happening?

1. Observed changes: non-climate pressures on corals

Pollution, overfishing and direct physical impacts have been degrading coastal coral reefs in the Pacific for centuries (Hughes *et al*., 2017a). Globally, over eighty-percent of marine pollution originates from land-based wastewater, sediment and nutrients delivered via waterways (UNEP 2008). In PICTs, most of the pollutants relevant to corals are associated with sewage, domestic and industrial waste, marine debris, ship-based pollution (e.g. oil, antifouling paints, dumped or abandoned waste from fishing vessels) (Richardson *et al*., 2017), agricultural fertilizers, sediment, pesticides and organochlorine compounds, trace metals, and a range of emerging pollutants such as pharmaceuticals, personal care products, and microplastics (Lovell *et al*., 2004; Morrison, 1999; Nuttall and Veitayaki, 2015; South *et al*., 2004). These pollutants are known to have adverse effects on corals, even when released at low levels (Haynes and Johnson, 2000; Pinto *et al*., 2010; United Nations Environment Programme, 2017). Below we present a summary of the effects of each of these on corals.

Physical impacts: trampling, anchor damage, aquarium trade, and dynamite impacts

Tourism-related and fishing impacts, such as trampling and coral breakage due to reef gleaning and coral manipulation by SCUBA and skin divers and fishers are known to have decreased live coral cover and growth, which causes also a reduction in fish abundance (Rodgers and Cox, 2003; Sulu, 2004; Tilmant, 1987). The problem is aggravated when large numbers of tourists are taken to the reefs during snorkelling activities, such as the case in Fiji (e.g. Yasawa and Mamanuca Islands) (Lovell and Sykes, 2004:34). The construction of tourism infrastructure (e.g. resorts, roads, dams, artificial islands) also influence catchment dynamics and may increase sediment and nutrient runoff into coral reefs (refer to land-based runoff section).

Anchor damage impacts are associated with the deployment and retrieval of anchors, as well as the movement of the anchor rode, which can cause damage to corals, seagrasses and other benthic ecosystems (Kininmonth *et al*., 2014). Overall, data suggests that anchor damage in the Southwest Pacific is relatively low (Sulu, 2004), but it is recognised that in reefs heavily used for subsistence fishing, anchors can cause some damage to small sections of the reef due to the use of ‘reef hook’ grapple anchors and concrete blocks (Lovell and Sykes, 2004:34).

The aquarium trade is an important economic activity in the Pacific (Morris, 2009; Sulu, 2004). It involves the collection of fish and corals and is largely carried out using best practices on a small scale and does not pose a major threat to corals. However, the collection of ‘live rock’ involves the breakage of the reef framework in order to collect coralline algae, which are also exported. This is a more damaging activity that needs to be properly managed (Morris *et al*., 2008; Morris, 2009; Sykes and Morris, 2009).

Dynamite fishing exists but is not frequently used in the Pacific. Its use has been diminishing in PICTs due to its relative high costs, legislation in place to ban it, and growing awareness about the damage it causes on marine life (Morris, 2009; Samuelu and Sapatu, 2009; Sykes and Morris, 2009).

Both tourism-related and anchor damage impacts have caused ecological shifts in coral communities, also affecting social, economic and cultural issues in the Pacific (Ayala, 2005; Engelhardt, 2005:176; Kininmonth *et al*., 2014; Morris *et al*., 2008; Morris, 2009; Movono *et al*., 2018; Sykes and Morris, 2009). If properly managed such impacts can be mitigated or contained (Hall, 2001).

Domestic and Industrial waste

Sewage disposal leads to increase in nutrients and organic matter (Dubinsky and Stambler, 1996). Nutrients act as fertilisers for macroalgal growth, which can outcompete corals for space, while organic matter stimulates proliferation of oxygen-consuming microbes. These may negatively impact corals and other reef organisms, either directly by anoxia, or by related hydrogen sulphide production (Dubinsky and Stambler, 1996). Sewage contamination was considered a serious problem in Pohnpei (Federated States of Micronesia) (Morrison, 1999), Fanga’uta Lagoon (Tonga) (Morrison, 1999; Zann, 1994), and Suva Lagoon (Fiji) (Morrison *et al*., 2013; Naidu *et al*., 1991; Veitayaki, 2010; Zann, 1994), leading to increased macro and turf algae biomass, high abundances of herbivorous sea urchins (*Echinometra matheae* and *Tripneustes gratillus*) and detrital-feeding holothurians, and decline of corals (Zann, 1994). Other areas in Fiji with known water quality problems are Nadi Bay and Lautoka harbours (from shipping, domestic and industrial wastes, organic wastes from a sugar mill) and Levuka harbour (discharges from a tuna cannery) (Zann, 1994). In the 1990s lead, pesticides, hydrocarbons, chemical wastes from industries, and PCBs from old transformers were considered as potentially serious problems in Tonga (Zann, 1994), while in Port Vila (capital of Vanuatu) low organochlorine contamination in sediments was reported (Morrison, 1999).

Marine debris and plastics

Large concentration of marine debris and plastics (mainly sourced from land) occur in the centre of the Pacific Ocean Gyres (Howell *et al*., 2012; Maes and Blanke, 2015; Martinez *et al*., 2009). In the ocean, plastic litter will fragment in smaller particles termed microplastics (particles less than 5 mm, even though no scientific definition has been established) (Hall *et al*., 2015; Reichert *et al*., 2018). In the early 1990s, marine debris, including plastic waste and litter, was identified as a major and growing hazard to fish, marine mammals, turtles, sea birds, coral reefs, and even human activities in PICTs (Morrison, 1999; Pichel *et al*., 2007; Veitayaki, 2010; Zann, 1994). However, little action has been taken to deal with this threat.

Plastic marine debris threaten corals (Reichert *et al*., 2018) because they ingest particles such as microplastics leading to either malnourishment/starvation or the plastic may be toxic to the corals (Hall *et al*., 2015). This can cause negative effects on coral health, through bleaching and tissue necrosis (Reichert *et al*., 2018). It is known that entanglement with plastic debris increases coral susceptibility to diseases (Lamb *et al*., 2018). However, coral responses to microplastic ingestion vary due to different cleaning mechanisms and feeding interaction (Lamb *et al*., 2018; Reichert *et al*., 2018). The condition of microplastics (presence/absence of microfilms) also influence coral ingestion rates and thus, their response to microplastics (Allen *et al*., 2017). Microplastic pollution occurs all over the Pacific with records including New Caledonia and Chesterfield Islands (Maes and Blanke, 2015), as well as Fiji's main Island Viti Levu, where all samples collected from the water column, sediment traps, fish guts and bottom sediments between 2015-17 contained microplastic (Ferreira, M. unpublished data).

Ship-based pollution (e.g. oil and antifouling paints)

Sea transport that relies on fossil fuels is crucial for PICT as it moves people, goods and resources (Holland *et al*., 2014; Newell *et al*., 2017; Nuttal *et al*., 2014). Oil spills are therefore a constant risk in the region. The effects of oil spills (and dispersants used in clean-up operations) on corals include extensive death of corals and prolonged cessation of growth and reproduction, through the decrease in the number of female gonads per polyp, impairment of reproduction due to planulae abortion, change in tentacle motion, and in mucus excretion and photosynthesis of zooxanthellae, defective reproductive tissue, degeneration and loss of zooxanthellae, and degeneration of mucus excretion cells and muscle bundles, inhibition of planulae settlement and metamorphosis (Dubinsky and Stambler, 1996).

The exposure of corals to antifouling paints (Tributyl tin (TBT) and copper-based) can cause decreased growth rates and reduced abundance of branching species (Dubinsky and Stambler, 1996), inhibit coral fertilization and larval metamorphosis (Negri and Heyward, 2001). Antifoulant contamination is thought to cause major mortality of resident coral communities and have a negative impact on the recovery of adult populations to other stressors (Smith *et al*., 2003). Suva (capital of Fiji) is the main commercial, shipping and industrial centre of the South Pacific (Morrison *et al*., 2013), where TBT from antifouling paints, and other pollutants have contributed to the decline of coral reefs in the region since the 1990s (Zann, 1994). In fact, in the 1990s, Suva Harbour had the highest levels of TBT in sediments among PICTs (Lovell *et al*., 2004; Morrison, 1999).

Land-based runoff

In PICTs, the modernisation of traditional villages via transition from semi-subsistence to commercial-oriented activities is often associated with the increased and unregulated use of pesticides and other farming chemicals, such as fertilisers, along with land clearing, changes in land use, introduced trees, and infrastructure construction, which increase sediment and nutrient runoff into coastal waters thereby causing coral reef decline (McCauley *et al*., 2012; Nuttall and Veitayaki, 2015; Remling and Veitayaki, 2016; Veitayaki, 2018). Agricultural runoff threatens approximately 25% of the total global reef area with further increases projected for the coming decades (Fowler *et al*., 2013). Rangeland grazing, mining and logging (extensive clearing), along with land clearing for urban development (housing, roads, etc.) are the main contributors of sediment, while intensive cropping (e.g. sugarcane) and horticulture are the main contributors of nutrients, herbicides and pesticides (e.g. carbaryl, naphthol, chloropyrifos and organochlorine pesticides) (Dubinsky and Stambler, 1996; Erftemeijer *et al*., 2012). Most of these pollutants are delivered through waterways during periods of high flows, and flood plumes often carry elevated concentrations of several pollutants, simultaneously exposing near-shore reef systems to toxic combinations of chemicals (van Dam *et al*., 2011).

Increased sedimentation can negatively affect corals through direct burial, which depletes oxygen and leaves corals in darkness, abrasion and by reducing light penetration, which is essential for photosynthesis by zooxanthellae (Dubinsky and Stambler, 1996; Rogers, 1990). This results in reduced skeletal growth rates, species diversity, and recruitment, and reproductive impairment (Haywood *et al*., 2016; Rogers, 1990; Wicks *et al*., 2012). Increased sediment runoff may also expose corals to a variety of other contaminants, such as nutrients and heavy metals, which interfere with coral fertilisation (copper and zinc sulphates), larvae development and cause coral bleaching (Dubinsky and Stambler, 1996). Poor agricultural land-use practices (e.g. land clearing and slash-and-burn agriculture, logging, and slope cultivation of sugar cane and ginger) have resulted in serious erosion of topsoil in many agricultural areas, leading to increased sedimentation in coral reef areas (Zann, 1994). For example, coral reefs in inner Vava'u (Tonga) have been affected by sediment run-off from coastal roads and earth works and the construction of causeways (Zann, 1994). The almost total clearing of Upolu's coastal forests (Samoa) for copra (coconut) plantations between 1870 and 1960 caused serious soil erosion of steep cultivated slopes in catchments of Western Samoa; the death of some of the leeward reefs in Western Samoa may date from this period (Lovell *et al*., 2004; Zann, 1994).

There has been some research to determine whether or not Marine Protected Areas (MPAs) have the ability to offer some protection to corals from indirect stressors, such as increased sedimentation, through enhanced resilience. However, a five-year study in the Solomon Islands comparing the response of fish and corals to increased sedimentation both inside and outside MPAs showed management afforded little benefit (Halpern *et al*., 2013).

Release of excess nutrients into coastal waters causes eutrophication (Cloern, 2001), resulting in macroalgae proliferation, algal blooms (Kuffner and Paul, 2004), and the creation of hypoxic or anoxic 'dead zones' (Diaz and Rosenberg, 2008), which can kill large numbers of organisms, such as fish (Lotze *et al*. 2006). Nutrients, herbicides and pesticides can kill or impair corals (through abnormalities, blemishes, necrotic patches, and increased incidence of diseases) (Al-Moghrabi, 2001; Bruno *et al*., 2003; Furby *et al*., 2014; Haapkyla *et al*., 2011; Kuta and Richardson, 2002; Redding *et al*., 2013; Sato *et al*., 2016; Voss and Richardson, 2006), and have been linked to declines in coral cover in reef ecosystems around the world (Dubinsky and Stambler, 1996; Restrepo *et al*., 2016). The direct effects of nutrients (nitrogen (N) and phosphorous (P)) on corals are diverse. Nutrients can increase a) the amount of chlorophyll *a* within zooxanthellae cells, b) zooxanthellae density within coral hosts, and c) chlorophyll *a* density per unit area of coral (Shantz and Burkepile, 2014). N reduces calcification and increases photosynthetic rates, while P alone can increase calcification with little effect on photosynthetic rates. The effects of nutrients on coral communities depend on taxa, enrichment source and nutrient identity (Shantz and Burkepile, 2014). Poor water quality is also related to COTS outbreaks (Berthe *et al*., 2016; De'ath *et al*., 2012; Vanhatalo *et al*., 2017). In Fiji, increased erosion associated with land clearing, and poor agriculture practice has led to increased nutrient levels resulting in seagrass and macroalgae expansion in less flushed, leeward reefs (Zann, 1994). The coral decline in the Fanga'uta Lagoon (Tonga) was associated with high levels of DDT (Morrison, 1999; Zann, 1994) and eutrophication, which also contributed to the advance of seagrasses and mangroves (Zann, 1994).

Overfishing

Coral reef overfishing reduces the abundance and size of fish with consequences for reproduction. Effects of overfishing on coral reefs include reduction in: a) live coral cover, b) calcareous and coralline algae cover, c) diversity of substratum, and d) topographic complexity. In countries that target herbivorous species (as is the case in many PICTs), overfishing can also accelerate bioerosion, facilitate the growth of macroalgae, and reduce biodiversity and fish productivity (Doropoulos *et al*., 2013; McManus and Polsenberg, 2004; Sandin *et al*., 2008; Stuhldreier *et al*., 2015) (see Science Review 2018: Fish and Shellfish and Coastal Fisheries, and Oceanic Fisheries papers).

Population growth, increased commercialisation, promotion of fisheries development projects and the live reef fish trade are currently increasing demand for reef fish in PICTs and thus increasing reef fishing pressure in the region (Cinner and McClanahan, 2006; Nuttall and Veitayaki, 2015; Veitayaki, 1995, 2018; Veitayaki and South, 1997). Available data indicate that more than two thirds of the reef fishes and invertebrates are taken for subsistence (Bell *et al*., 2017; Zeller *et al*., 2015) and overfishing of reef resources is common throughout the Pacific (Pinca *et* *al*. 2010; see also Science Review 2018: Fish and Shellfish and Coastal Fisheries, and Oceanic Fisheries papers). The primary driver of the decline in reef fisheries is small-scale local fisheries that target reef fish and invertebrates for food, with the demand for fish growing as populations increase in most PICTs (Bell *et al*., 2017; Veitayaki and Ledua, 2016; Williams *et al*., 2015).

Conclusion on effects of non-climate drivers on corals

It is widely acknowledged that non-climate drivers are damaging corals all over the world (Halpern *et al*., 2008; Rasher *et al*., 2012). Increased land-based pollution (sediments, nutrients, chemicals) is a key driver of coral degradation worldwide (Rogers, 1990) and in the Pacific (Lal, 2016), along with overfishing (Jackson *et al*., 2001) and increase in the incidence of COTS outbreaks (Berthe *et al*., 2016). In addition to causing the decline of coral communities, these non-climate drivers also limit the recovery capacity of coral assemblages (Aronson and Precht, 2016; Jackson *et al*., 2001). The synergistic effects of overfishing, excessive nutrients and sediments, and pollution on corals are extremely negative (Dubinsky and Stambler, 1996; Haywood *et al*., 2016; Rasher *et al*., 2012; Rogers, 1990; Wicks *et al*., 2012).

One of the major concerns in PICTs is the lack of baseline data and long-term monitoring programmes addressing water quality and (over)fishing effects on corals for adequate system understanding on cause-effect relationships and proper assessment of non-climate impacts on corals and management actions (Zann, 1994). It is important to note that by effectively managing non-climate impacts on corals, communities can boost the capacity of reef ecosystems to survive climate change (Hughes *et al*., 2017a).

2. Observed changes: climate pressures on corals

Despite the detrimental effects of non-climate drivers on coral communities, accelerating climate change is currently the strongest driver affecting coral dynamics (Aronson and Precht, 2016). Sea level rise, high ocean temperatures, ocean acidification and the synergistic effects that climate drivers have with one another and with non-climate drivers are currently causing widespread negative effects on PICT corals. For example, calcification rates are affected by both ocean pH and temperature. Current maximum calcification rates are just 2-3 ^{o}C below the maximum temperature corals can withstand before thermal bleaching (Evenhuis *et al*., 2015). When corals bleach, calcification is further supressed because photosynthetic products from the zooxanthellae are essential for the calcification process (Evenhuis *et al*., 2015).

Sea level rise

Despite the evident negative effect of sea level rise (SLR) on Pacific islands and atolls (Nurse *et al*., 2014), it may also provide some opportunities to corals. SLR effects on corals are complex and not straightforward to understand because corals grow vertically and, in principle, additional depth provides extra 'accommodation space', in which corals could expand in intertidal areas and also colonise new inundated areas – provided that suitable substrate is available (van Woesik *et al*., 2015; Woodroffe and Webster, 2014) – thus increasing live coral cover (Albert *et al*., 2017). Evidence from Tuvalu strongly suggest that Pacific islands can persist on reefs under SLR rates around 4mm.yr^{-1} (commensurate with RCP 2.6 scenario) (Kench *et al*., 2018). However, it is unclear whether islands will continue to maintain their sizes under rising seas of up to 0.82m by 2100 (RCP 8.5) (Kench *et al*., 2018). Under such scenario it is more likely than not that rising seas will inundate coastal areas and promote coastal erosion (Barros and Field, 2014; Kench *et al*., 2018), thus increasing turbidity and sedimentation in coastal waters negatively affecting corals and other reef organisms (Brown *et al*., 2017a; Brown *et al*., 2017b; De'ath and Fabricius, 2010). In addition to this, a recent study comparing the accretion rates of coral reefs in the Indian and Atlantic Oceans showed that without sustained ecological recovery, very few reefs in either ocean would be able to track the projected sea level rise under RCP4.5 or RCP8, potentially resulting in reef submergence. This will lead to changes in wave energy regimes, increasing sediment mobility, shoreline change and island overtopping (Perry *et al*., *in press*). Human-induced SLR is associated with the melting of polar ice sheets and water expansion as a result of increased water temperatures (IPCC, 2014), which itself cause negative effects to corals (see below) and have already caused the displacement of PICT people (Reuters, 2017).

Increase in Ocean Temperatures

Sea surface temperature (SST) plays an integral role in the growth of corals by influencing their skeletal density, extension and calcification rate (Carricart-Ganivet, 2004). Scientists have high confidence that anthropogenic-induced ocean warming is impacting coral reefs through thermal coral bleaching (Adjeroud *et al*., 2009; Cumming *et al*., 2000; Davies *et al*., 1997;

Kleypas *et al*., 2015; Lovell *et al*., 2004; Mangubhai, 2016; Obura and Mangubhai, 2011; Rotmann, 2001) and by increasing bioerosion (Chaves-Fonnegra *et al*., 2017), reducing coral calcification rates (De'ath *et al*., 2009; Nurse *et al*., 2014) and influencing mass coral spawning events over large geographical areas (Keith *et al*., 2016).

Coral bleaching impacts coral species differently depending on the species of the coral host affected and its zooxanthellae symbiont (Hoadley *et al*., 2015). This means that coral species and their symbionts respond and adapt differently to rising SST (Barshis *et al*., 2013; Berkelmans and van Oppen, 2006; Oliver and Palumbi, 2011). Bleaching also affects colony size (favours smaller size corals), the time of coral spawning (Paxton *et al*., 2016), slows down swimming of coral larvae and reduces the number of viable recruits (Singh, 2018).

Coral reef bleaching events have increased dramatically since the early 1980s. Most of these have been caused by anomalous increases in SST, reduced cloud cover, higher than average air temperatures and higher than average atmospheric pressures (Glynn, 1983; Hoegh-Guldberg, 1999; Hoegh-Guldberg *et al*., 2007; Hughes *et al*., 2003; McGowan and Theobald, 2017; Nunn, 1990), which are associated with El Niño or La Niña events. Six distinct peaks in bleaching have occurred worldwide between 1976 and 2016 (Le Nohaic *et al*., 2017; Oliver *et al*., 2009). The 1997-98 El Niño and the 1998-99 La Niña were the most severe and spatially extensive on record (Oliver *et al*., 2009). The recent severe thermal coral bleaching events in 2015-16 have caused extensive habitat and biodiversity losses around the world and in the Pacific (Anthony *et al*., 2017; Gardner *et al*., 2017; Le Nohaic *et al*., 2017). Interestingly, the south-western Pacific islands were little affected by the mass coral bleaching resulting from the 1998 El Niño – possibly due to under-reporting (Oliver *et al*., 2009) – but were heavily impacted by the subsequent strong La Niña event in 2000 (Cumming *et al*., 2000) and the 2015-16 El Niño (Mangubhai, 2016; Wolanski *et al*., 2017).

Some examples of coral bleaching for locations relevant to this review include the northern and southern parts of Papua New Guinea (PNG) in early 1998 (Goreau *et al*., 2000), Lihir Island group in March 1996 (Done, 1996), February-March 2001 (Rotmann, 2001) and February 2006 (Flynn, 2006). Also in PNG, coral bleaching was recorded in the Milne Bay Province in February 1996 (Davies *et al*., 1997). Thermal coral bleaching was registered throughout the Fijian archipelago during the first half of 2000 (Cumming *et al*., 2000), and around Gau Island and the Vatu-i-ra seascape in 2015-16 (Mangubhai, 2016). In 2016, increased thermal stress reduced oxygen concentrations in seawater promoting mass fish kills on the Coral Coast of Fiji, where water temperatures were as high as 35 °C (Singh, 2018). In Samoa, bleaching and extensive coral mortality were recorded at Ofu Island in 1994 and 2015 (Craig *et al*., 2001; Thomas and Palumbi, 2017), Palolo Deep Marine Park (Western Samoa) in 1987-1988, and a major episode occurred around Upolu and Savai'i between April and July 1991 (unpublished data) (Zann, 1994). In Kiribati, the greatest thermal stress event reported in the coral reef literature occurred at the Phoenix Islands in January 2003, which persisted for 4 years causing extensive coral bleaching and mortality (Obura and Mangubhai, 2011). Still in Kiribati, extensive coral bleaching occurred at the Gilbert Islands in 2004 and 2009 (Carilli *et al*., 2012). In Moorea (French Polynesia), extensive coral bleaching and mass mortality were registered in 1978, 1982, 1998, and 2003 (Riegl *et al*., 2015). Seawater temperatures as high as 30 °C were reported in Vanuatu causing widespread fish kills (Johnson *et al*., 2016a).

SST acts synergistically with nutrients and sediments amplifying bleaching effects and also influencing the recovery period from bleaching. As a result, corals currently sheltered from effects of excessive nutrients and elevated temperatures will be the most at risk from ocean acidification (Riegl *et al*., 2015).

Ocean acidification

Ocean acidification is the increase of partial pressure of CO_2 and associated decline in seawater pH (Enochs *et al*., 2016) (see Science Review 2018: Ocean Acidification paper). For scleractinian corals, probably the most significant consequence of ocean acidification is the decrease in the concentration of carbonate ions (CO_3^{2-}). As coral's skeletons are made from the mineral phase of calcium carbonate, called aragonite, the saturation state of aragonite (Ωarg) is often related to rates of calcification (Evenhuis *et al*., 2015). Increases in atmospheric CO_2 concentrations are negatively correlated with Ωarg, which decreases the rates of coral calcification (Pandolfi *et al*., 2011).

Present-day aragonite saturation levels are postulated to be close to the point where it can weaken coral skeletons and slow coral growth. Weaker reef systems will be far more susceptible to other pressures including bioerosion, eutrophication, coral disease, intense storms and bleaching because coral skeletons become more fragile (Meissner *et al*., 2012; Nuttall and Veitayaki, 2015; van Hooidonk *et al*., 2014).

Our review did not identify any field studies pointing to conclusive cause-effect relationships attributable to anthropogenic ocean acidification and weakening of coral skeletons in the Pacific Ocean. However, there is emerging evidence of the impacts of ocean acidification on coral reefs (Barros and Field, 2014). It is likely that, in many places, responses of corals to more acidified waters are not yet outside natural variability and may be influenced by local issues and mechanisms (e.g. circulation patterns and pollution) (Barros and Field, 2014).

Field observations of reefs growing in more acidified waters suggest that reduced pH promotes changes in the abundance and structure of coral communities (Enochs *et al*., 2015; Enochs *et al*., 2016; Fabricius *et al*., 2011), threatening the ecosystem functioning of coral reefs (Done, 1992; Hughes *et al*., 2007; Mumby, 2009; Wild *et al*., 2011). However, the literature offers mixed responses of corals to more acidified waters. For instance, a reef in Palau (Nikko Bay) growing in waters with pH of 7.8 has coral cover 2 to 6 times higher than other coral reefs around the island growing in waters with higher pH (Golbuu *et al*., 2016), whereas in PNG a recent decrease of 0.1 units in pH may have affected coral diversity and recruitment (Fabricius *et al*., 2011), and the abundance of crustose coralline algae (CCA) – an inducer of coral larvae settlement (Fabricius *et al*., 2015). These negative effects on corals most likely facilitate macroalgae growth, causing a shift from a coral-dominated to algal-dominated state (Enochs *et al*., 2015). In PNG massive *Porites* dominate reefs with pH > 7.8 and no distinct evidence of calcification exists in places with pH ≤ 7.7 (Fabricius *et al*., 2011), which is consistent with a switch from net calcification to net dissolution of coral reefs at a pH of roughly 7.8 (Enochs *et al*., 2016). Similar effects of more acidified waters on corals were also registered in waters of Japan and the Northern Mariana Islands (Enochs *et al*., 2015; Enochs *et al*., 2016; Fabricius *et al*., 2011).

Several laboratory studies suggest that more acidified waters impair calcification and accelerate the dissolution of coral skeletons thus weakening coral skeletons, and triggering stress-response mechanisms, which affect the rates of tissue repair, feeding rate, reproduction, and early life-stage survival (D'Angelo *et al*., 2012; Enochs *et al*., 2015; Fabry *et al*., 2008; Kroeker *et al*., 2010). Possible responses of reef building corals to reduced calcification include a) decreased linear extension rate and skeletal density (Cooper *et al*., 2008), b) the maintenance of physical extension rate, but reduced skeletal density, leading to greater erosion (Szmant and Gassman, 1990), and c) maintenance of linear extension and density but greater investment of energy diverting resources from other processes such as reproduction (Albright and Mason, 2013; Szmant and Gassman, 1990).

Extreme events

In PICTs, cyclones regularly contribute to changes in island geomorphology (Duvat and Pillet, 2017), causing extensive damage to corals by exacerbating nearshore biogeochemical changes associated with land-use, runoff, and human activities (Levin *et al*., 2015). These include physical damage through wave action which breaks corals (with branching and foliose growth forms being more vulnerable to wave damage), and associated flood events which cause substantial soil erosion leading to increased sediment and nutrient runoff into coral reefs (Veitayaki, *in press*), which creates a non-optimal environment for coral recovery (Gardner *et al*., 2005; Guillemot *et al*., 2010; Zann, 1994). Since most of the coral fragments are washed into unfavourable environments, and these scleractinian corals take years to reach spawning age, breaking them off often results in the death of the coral fragment (Cheal *et al*., 2002; Gardner *et al*., 2005). Reefs stressed by pollution, overfishing and other human influences may be slower to recover after cyclones (Zann, 1994).

Despite the fact that cyclones are part of ocean-atmosphere tropical dynamics, there is evidence of a correlation between an increase in SST and associated increase in the intensity of tropical cyclones, and increased coral stress (Elsner *et al*., 2008; Nott and Walsh, 2015; Terry, 2007). The proportion of intense tropical cyclones (category 4-5) versus weaker cyclones (category 1-2) has increased substantially in the last 40 years, which coincides with most of the current anthropogenic warming (Holland and Bruyere, 2014).

The physical destruction associated with cyclones has been identified as an important feature of coral reef ecosystems, because it opens up space in the reef for new settlement which increases biodiversity (Adjeroud *et al*., 2009; Connell, 1978; Connell, 1997). Some of the observed impacts of high-intensity cyclones in PICTs include the loss of coral reef and mangrove areas after TC Pam in Vanuatu (Johnson *et al*., 2016a), and TC Winston in Fiji (Mangubhai, 2016). In 1991 cyclone Val caused widespread damage to the coral reefs around American Samoa and a subsequent increase in coral recruitment following the cyclone (Mundy, 1996). Widespread coral destruction was seen in New Caledonia after TC Erica (1993), where the reefs took more than 3 years to recover (Guillemot *et al*., 2010). Although the same trend of coral destruction was expected on all reefs that lay in the path of the category 5 TC Winston in Fiji, this was not the case. Winston, caused widespread physical damage to coral reefs around the Vatu-i-ra passage (Mangubhai, 2016), and Navakavu reefs near Suva (K.J. Brown and L.X.C Dutra, pers. obs.) resulting in a severe decline in fish and coral assemblages, while in other sites surveyed in the Coral Coast (Singh, 2018), there was little or no damage to the reefs. The coral reefs that were not directly on the path of the eye of the cyclone but that have been affected indirectly, seemed to have recovered better and more rapidly (Singh, 2018).

Conclusions on impacts of climate drivers on corals

Simultaneous climate change drivers, such as sea-level rise, ocean warming, acidification and more frequent high-intensity cyclones, act together with local changes (e.g., pollution, eutrophication, overfishing) (high confidence), leading to interactive, complex and amplified impacts for species and ecosystems, which complicates marine management regimes (Barros and Field, 2014; Valmonte-Santos *et al*., 2016). The ability of corals to adapt naturally to changes in community composition and structure appears limited and insufficient to offset the detrimental effects of climate change (Barros and Field, 2014). Our review indicates that the current understanding of climate change effects on corals and adaptation mechanisms is very limited and requires additional field and laboratory studies to fully comprehend adaptation mechanisms, tolerance and ecological consequences of climate drivers, especially under low emission scenarios (RCP2.6).

What Could Happen?

Future climate change and impacts on corals

The extent of impacts of climate change on corals will depend on how close reality will be to future RCP CO_2 emission scenarios (Gattuso *et al*., 2015). However, common across all RCP scenarios is that atmospheric CO_2 concentrations will continue to rise, at least in the coming decades, thus increasing ocean temperatures and acidity (high confidence) (see Science Review 2018: Fish and Shellfish and Coastal Fisheries, and Oceanic Fisheries, Sea Level Rise, Sea Surface Temperature, Ocean Acidification and Extreme Events papers for predictions, Evenhuis *et al*., 2015; Gattuso *et al*., 2015; Hoegh-Guldberg *et al*., 2011; IPCC, 2014). Increased temperatures are also expected to increase the intensity of TC (low confidence) (Elsner *et al*., 2008). By 2100, the greatest impacts from climate change on corals will likely occur as the result of increased temperature stress, ocean acidification, increased sedimentation and turbidity from more extreme events (e.g. rainfall and cyclones), rising sea level, and physical damage from the combination of rising sea levels and more severe cyclones (Johnson *et al*., 2017; United Nations Environment Programme, 2017).

The future is uncertain but PICT coral reefs will most likely substantially change – rather than completely disappear – as a result of climate change and associated changes in the sea- and landscape, which will impact livelihoods (Hughes *et al*., 2003). As most of the impacts of climate change on corals from the literature are related to increased SST, ocean acidification and cyclone damage, we detail these three major threats below, followed by a review on synergistic effects of climate and non-climate drivers on corals.

Sea surface temperature

Higher SST predicted in all RCP scenarios will increase the extent, frequency and severity of coral bleaching events (van Hooidonk *et al*., 2016), the incidence of coral diseases, and the potential for mass coral mortality (high confidence) (IPCC, 2014; Langlais *et al*., 2017; Maynard *et al*., 2015a; Reisinger *et al*., 2014; Ruiz-Moreno *et al*., 2012; Sheridan *et al*., 2014). In addition, increased SST can alter growth patterns, body size, immune defence, feeding behaviour, and reproductive success of corals (Bonesso *et al*., 2017; Riegl *et al*., 2015; Ruiz-Moreno *et al*., 2012), and may even affect mesophotic, deep-sea and cold-water coral distribution (although evidence of the direct effect of climate change is less clear) (Hoegh-Guldberg *et al*., 2017). Changes are expected to become substantial from 2050 (or earlier) under a high emission scenario (Figure 1). Hence, higher SST will potentially lead to declines in coral populations, which will cause unprecedented changes in coral reefs and associated habitats (high confidence) (Figure 1, Hughes *et al*., 2017a; IPCC, 2014; Morrison, 1999). A similar phenomenon occurred in Espiritu Santo (Vanuatu) during the early Holocene (Beck *et al*., 1997).

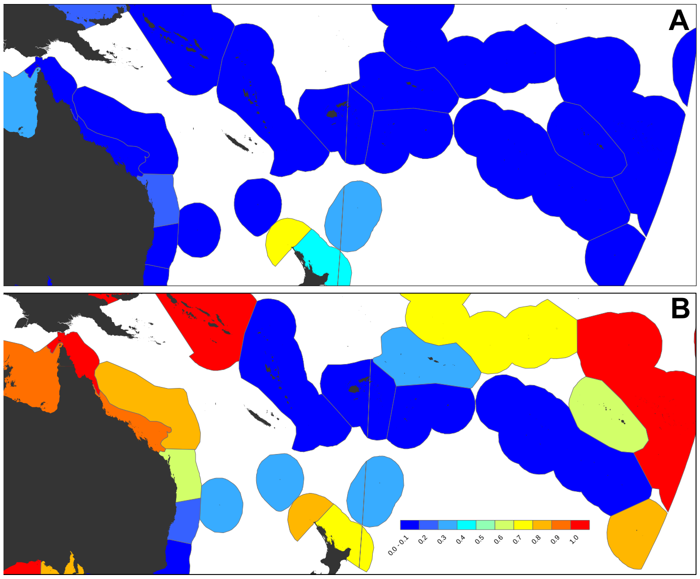


Figure 1. The vulnerability of marine communities to species loss due to warming in the Pacific Ocean. Proportion of fish and invertebrate species in present-day communities likely to exceed their upper realised thermal limit by 2025 (A) and 2115 (B) based on regional IPCC warming rates (RCP8.5 scenario). Sites with confidence scores <2.5 were excluded from most ecoregion means (details in Stuart-Smith *et al*., 2015).

The literature offers, however, some potential benefits of warmer waters to corals. For example, although highly speculative, in the short term, rising average temperatures could promote coral growth and compensate partially for long-term shifts in aragonite concentration, as some corals (e.g. *Porites*) have shown an increase in calcification rates associated with an increase in ocean temperature (~0.10 °C per decade) between 1990 and 2010 (Hughes *et al*., 2017a). Warmer waters may also facilitate the expansion of the geographical range of corals into higher latitudes, and cause shifts in species composition in response to differences in susceptibility to climate and non-climate drivers (Hughes *et al*., 2017a; Woodroffe *et al*., 2010).

Ocean acidification

Ocean acidification is expected to increase in the future under all RCP scenarios (IPCC, 2014). Variability in responses due to local environmental conditions and species composition is likely to be substantial (Chan and Connolly, 2013), which along with lack of evidence of contracting geographical range of calcifying species towards the Equator (Hughes *et al*., 2017a) contribute to the low confidence on the effects of ocean acidification on corals (Barros and Field, 2014; IPCC, 2014; Johnson *et al*., 2016b).

Recent modelling suggests that under RCP2.6, CO_2 concentrations are expected to be around 450 ppm by 2100, where pH will likely be between 7.9 and 8.1 (an average decline of 0.07 pH units from Present day mean ocean pH (Gattuso *et al*., 2015)) in most tropical oceanic waters. For medium- to high-emission scenarios (RCP4.5, 6.0, and 8.5), ocean acidification poses far more risks to coral reefs. For example, under RCP8.5, CO_2 concentration in the sea is expected to reach 450 ppm by 2030 – 2050 (Salvat and Allemand, 2009) and a decline of 0.33 units of pH is expected by 2100 (Gattuso *et al*., 2015), which would seriously threaten corals and other calcifying organisms. Such an increase in ocean acidification is expected to impact on coral physiology (calcification rates, ability to repair tissues and growth), behaviour (feeding rate), reproduction (early life-stage survival, timing of spawning) as well as weaken calcified structures, and alter coral stress-response mechanisms (Fabricius *et al*., 2015; Fabricius *et al*., 2011), with impacts on population dynamics of individual species from phytoplankton to animals (medium to high confidence). The vulnerability of reef-building corals to ocean acidification has potentially detrimental consequences for fisheries and livelihoods (Barros and Field, 2014).

Sea level rise and cyclones

Rising sea level would allow minimum shore zone for mangrove development or shore stability; with an early period of increased coastal erosion and destabilizing sedimentation as catchment streams and shorelines adjusted to new and changing base levels, thus negatively affecting corals (Dutra and Haworth, 2008). Therefore, widespread degradation of corals is expected due to coastal erosion associated with SLR.

The observed destruction that high intensity tropical cyclones have caused to corals in PICT is well known (Adjeroud *et al*., 2009; Guillemot *et al*., 2010; Mangubhai, 2016). However, the observed increase in Category 4–5 cyclones may not continue at the same rate with future global warming. Following an initial climate increase in intense cyclone proportions a saturation level will be reached beyond which any further global warming will have little effect (Holland and Bruyere, 2014).

Synergistic climate and non-climate drivers

Climate change impacts, such as increased SST and sea level, and changes in ocean chemistry, ocean circulation, rainfall and storm patterns are expected to compound existing anthropogenic pressures on coral reefs from habitat degradation due to development, resource extraction, overfishing and pollution. Interactions between climate and localized stressors such as pollution are expected to create particularly damaging synergies, adding to concerns about coral reefs globally (Bridge *et al*., 2013). For example, corals exposed to nutrients, turbidity, sedimentation, or pathogens have been shown to be more susceptible to thermal bleaching, or less able to survive and recover a bleaching episode, or an acute disturbance, such as a cyclone (Hoegh-Guldberg *et al*., 2007). This is because fertilization and larval recruitment in corals are particularly sensitive to environmental conditions (Lam *et al*., 2015), and because macroalgal growth rates increase in nutrient-rich waters, thus outcompeting corals (McCook, 1999).

Predicted changes in drought and flood regimes may exacerbate nearshore biogeochemical changes associated with land-use, runoff, and human activities (Levin *et al*., 2015), increasing nutrient and sediment loads to corals. Warmer waters will potentially increase the incidence and extent of COTS outbreaks in the Pacific (Zann, 1994) because it likely 'pushes' well-fed larvae faster to settlement (Uthicke *et al*., 2015). Ocean warming and acidification may also enhance the success of COTS juveniles, because more acidified waters facilitate growth and feeding rates on coralline algae (Kamya *et al*., 2016; Kamya *et al*., 2017; Uthicke *et al*., 2015) although the affects have been shown to be variable depending upon the genetic makeup of the COTS (Sparks *et al*., 2017). Warmer and more acidified waters can also facilitate the poleward migration of COTS (Kamya *et al*., 2017) following the expected migration of corals, but in contrast to their coral prey, COTS juveniles appear to be highly resilient to future ocean change (Kamya *et al*., 2016).

Coral bleaching is exacerbated by ocean acidification, which impairs coral calcification and the recovery potential of coral species (Anthony *et al*., 2017). Coral bleaching also facilitates bioerosion by sponges (Carballo *et al*., 2013). Plastic pollution can act alone or synergistically with increased SST and more acidified waters to increase the incidence of coral diseases (Lamb *et al*., 2018). Coastal reef fisheries are generally considered overexploited in most PICT (Matthews *et al*., 1998; Valmonte-Santos *et al*., 2016), which negatively affect coral reef ecology due to ongoing pressures as a result of human population growth, which further increase fishing effort and catch, thus facilitating macroalgal growth.

The literature offers very little information on climate change impacts on corals associated with a low-emission scenario (RCP2.6), due to technical and other issues (Hughes *et al*., 2017a). Climate change impacts on corals are often tested in the laboratory using values associated with a high emission scenario (RCP8.5) (Hughes *et al*., 2017a), which are summarised below.

Higher SST will increase the incidence of thermal coral bleaching with some Pacific nations experiencing annual severe bleaching before 2040 (e.g. Nauru, Guam, Northern Marians Islands) and all nations experiencing severe annual bleaching by 2050 under RCP8.5 (van Hooidonk *et al*., 2016). This trend is already evident with the largest coral bleaching event in the Pacific documented in many nations during the 2016 summer, and the Great Barrier Reef experiencing two successive severe bleaching events in 2016 and 2017.

While a lower emissions scenario (RCP4.5) adds 11 years to the global average year of severe annual bleaching, 75% of reefs will still experience annual bleaching before 2070. Spatial patterns of bleaching are variable, with high latitude reefs faring better than reefs near the equator (van Hooidonk *et al*., 2016). Only significant mitigation of greenhouse gas emissions (RCP2.6) will delay the onset of annual bleaching until 2100.

The area of the Pacific Ocean with suitable chemistry for coral growth will decrease by 15% by 2050, with conditions declining to marginal and only some areas in the Central Pacific being 'adequate' for coral growth by 2100 (Johnson *et al*., 2017; Lenton *et al*., 2015). By 2050, Ω is expected to be ~3 (Johnson *et al*., 2016b), which will result in poor conditions for coral growth across much of the region (Chan and Connolly, 2013; Hoegh-Guldberg *et al*., 2007).

The combined effects of increased coral bleaching and ocean acidification are expected to reduce live coral cover by 50–75% by 2050, and as much as 90% by 2100 using RCP8.5 (Freeman *et al*., 2013; Hoegh-Guldberg *et al*., 2011). Global reef habitat loss was predicted to be 60% by 2100 using RCP4.5(Freeman *et al*., 2013). This will intensify the competition between reef-building corals and non-calcareous macroalgae as coral cover, growth and calcification continue to decrease (Cooper *et al*., 2008; De'ath *et al*., 2009). Macroalgae are likely to outcompete corals for space and become a dominant feature of reefs by 2100 (De'ath *et al*., 2012).

Coral reefs and adjacent ecosystems such as mangroves and seagrasses are intrinsically linked through sediment capture, localised pH buffering and linked life cycles of some fish species (Albert *et al*., 2017; Atkinson *et al*., 2016). Together, the three habitats substantially improve coastline protection than any one habitat alone (Guannel *et al*., 2016). Therefore, any declines in any of the three ecosystems will most likely affect the other two. Mangrove areas in some locations are projected to decline due to sea-level rise (where there are barriers to landward migration) (Veitayaki *et al*., 2017), more intense cyclones, and changes in rainfall patterns (Waycott, 2011). Seagrasses have already shown sensitivity to the effects of increased turbidity due to flooding (McKenzie *et al*. 2012) and their area is expected to decrease by 5–35% by 2050 due to increased runoff from more extreme rainfall as well as increases in cyclone intensity (Waycott, 2011).

Recent research has demonstrated that the combination of ocean acidification (low aragonite saturation) and nutrient loading is ten times more effective at driving coral macrobioerosion than ocean acidification alone (DeCarlo *et al*., 2015). This has significant implications for corals and reefs, resulting in slower growth rates and compromised reef structures. The Pacific island region will experience similar changes and, if emissions are not seriously curbed and restricted to the levels of a ‘low-emission’ scenario (RCP2.6) coral calcification is expected to decline along with reef area and structural integrity.

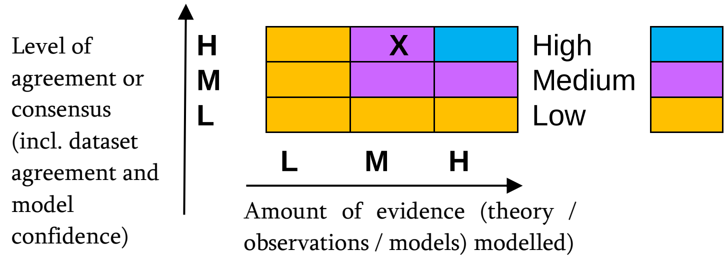
Despite the heterogeneity in responses of coral to ocean acidification (Comeau *et al*., 2014), even a slight decrease in aragonite saturation level may weaken the skeletons of calcareous organisms and shells. In this state, reef systems will be far more susceptible to other pressures including eutrophication, coral disease, storms and bleaching, which are also projected to increase in frequency due to climate change (Meissner *et al*., 2012; van Hooidonk *et al*., 2014). The interaction between ocean acidification and locally high nutrient loading also accelerates coral reef loss (DeCarlo *et al*., 2015).

Chapter Conclusions

The synergistic and cumulative impacts of extreme events caused by climate change, such as thermal coral bleaching, floods and tropical cyclones, and the chronic impacts of poor water quality, will continue to be major drivers of future reef degradation in the Pacific Ocean (Johnson *et al*., 2013). Impacts of climate change drivers in isolation, or in combination with non-climate drivers, include reduced areas of living coral, increased macroalgal cover, compromised reef structure, higher incidence of COTS and disease outbreaks, reduced species diversity, and lower fish abundance.

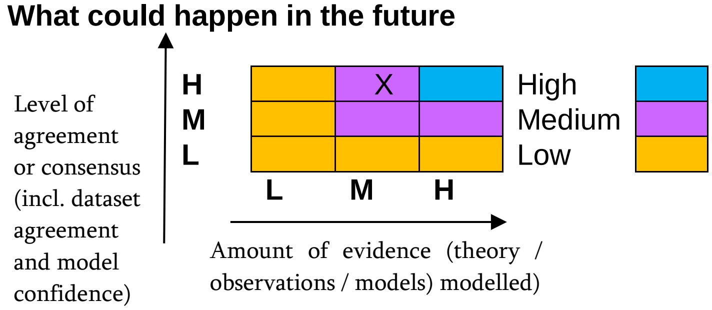
Confidence Assessment

What is already happening



The scores are based on the significant body of experimental and in situ evidence and scientific consensus on how corals are: (i) sensitive to different climate variables; (ii) responding to changing climate variables, particularly to increased SST, intense storms and reduced pH; and (iii) how they are likely to respond to future climate change. The consensus is very high with minimal disagreement that climate change is happening and affecting corals in PICT, in particular with regards to evidence of increased thermal-induced coral bleaching and COTS outbreaks, and increased incidence of high-intensity cyclones. The data used in global projections is still strong however, with limitations with regards to a) data specific for PICTs to couple regional and global scale models, b) lack of baseline data for climatic and non-climatic drivers. Overall, this results in substantial uncertainties around the level and extent of impacts of ocean acidification. As instrumentation is deployed and effects are enhanced this will rapidly change.

What could happen in the future



The future remains relatively uncertain because it is still impossible to predict the exact amount of CO_2 emissions in the next decades, and thus the exact extent of impacts associated with higher SST, ocean acidification, and cyclones. Most of the studies about coral responses to climate change use values from ‘worse case scenarios’ (RCP8.5) and very few deal with projections associated with a low-emission scenario (RCP2.6). This leaves important knowledge gaps on how corals can cope with or adapt to human-induced climate change under a low emission scenario.

Knowledge Gaps

1. Socioecological linkages to complex changes in environment. This is a recent trend but there is relatively high consensus about socio-economic and governance issues affecting resource sustainability and adaptation.
2. Species tolerance within a multidimensional non-stationary niche. This was a priority identified by the authors of this chapter.

Models of the likely shifts in coral species distributions, and the effects of climate-induced changes in species composition on ecosystems and maintaining coral-dominated reefs to identify refugia and potential areas of habitat losses and to assist in regional and community planning. There is high consensus on the influence of climate change on coral reef ecosystems but there is still high uncertainty on how the reef ecosystem will cope with these changes, especially when non-climate drivers are considered.

Socio-economic Impacts

Our review identified that climate pressures will exacerbate non-climate pressures (e.g. pollution and overfishing) (high confidence) (Aronson and Precht, 2016; Sheridan *et al*., 2014; Wild *et al*., 2011) and negatively affect corals. Predicted coral decline will cause unprecedented socio-economic changes with consequences to human populations from across the Pacific Ocean in coral reef and associated habitats (high confidence) (Hughes *et al*., 2017a; IPCC, 2014; Morrison, 1999).

There are significant socio-economic implications in PICTs from the combined effects of population growth and reef degradation due to climate change (Johnson *et al*., 2016b). Coral degradation directly affects the livelihoods of Pacific Islanders through reduced local income and inflow of foreign exchange due to the decline of fisheries. Current projections anticipate declines in reef fisheries productivity of as much as 10-20% in the western Pacific under climate change due primarily to habitat degradation (Pratchett *et al*. 2011, Bell *et al*. 2016). Decline in fisheries will increase food insecurity (given the high levels of dependency Pacific Islanders have on reef fishes for subsistence) (Zeller *et al*., 2015). Reef degradation will also affect reef-based tourism (Sajjad *et al*., 2014), reduce coastal protection, increase the risk of property damage (Guannel *et al*., 2016), and promote negative effects on aesthetics, cultural connections between traditional communities and their marine environments, spiritual values, and other ecosystem services that contribute to human wellbeing (Hughes *et al*., 2017a; Johnson *et al*., 2016b).

A regional assessment of all 22 PICTs (Johnson *et al*., 2016b) found that nations with large reef areas and predominately coastal communities had the highest relative vulnerability to climate change impacts on reefs because of high reef to land area, dependence of household incomes on coastal fisheries (for food and livelihoods), aquaculture (for jobs) and tourism (for jobs and contribution to GDP), and low education standards. Based on this assessment, the most vulnerable PICTs to climate change are: Solomon Islands, Kiribati, Papua New Guinea (PNG), Federated States of Micronesia (FSM), Tonga and Tuvalu. The PICTs that had the lowest relative vulnerability to climate change impacts on reefs and the goods and services they provide are: Niue, Commonwealth of the Northern Mariana Islands (CNMI), Tokelau, New Caledonia and Guam.

Adaptation Options

The history of coral reef evolution shows that they are resilient and adaptable to environmental changes, for example in sea level and sedimentation (Albert *et al*., 2017; Camoin and Webster, 2015; Done *et al*., 2007). Similarly, human communities in PICTs have been adapting to changes and managing reef ecosystems through traditional practices, such as temporal closures and seasonal bans, for centuries (Reenberg *et al*., 2008; Remling and Veitayaki, 2016; The Locally-Managed Marine Area (LMMA) Network, 2014; Veitayaki, 2014; Veitayaki and Holland, *in press*). However, the capacity of the coupled human-reef ecosystems to persist and adapt is under threat because non-climate threats will be exacerbated with changes in climate (Bellwood *et al*., 2004; Hoffmann, 2002).

Acclimatisation or adaptation of corals to climate change depends on intrinsic characteristics of both coral and zooxanthellae species (Dandan *et al*., 2015), as well as on governance and other social-economic characteristics, such as education and poverty. For the sake of presentation and summarising information we divide adaptation options in two main groups. These are: a) direct interventions to reduce non-climate stresses, and b) socio-economic, governance, and technological interventions, which are discussed in detail below.

Direct interventions to reduce non-climate stresses

Decisions about the most appropriate options for PICTs to adapt to the effects of climate change must take into account the many other drivers that affect the ability of coral reefs to maintain their structure and function, and support local communities (Gillett and Cartwright, 2010). A range of practical adaptation options have been identified by Bell *et al* (2013; 2011) and Johnson (2013), unless otherwise specified. These include managing land use and vegetation in catchments to reduce the transfer of sediments and nutrients into coral reefs, the prevention of marine pollution, and improve waste management. Also, as corals are impacted by climate change, their functioning and recovery mechanisms will depend on the abundance and diversity of fish that support coral recruitment and settlement, such as herbivores. At the same time, sustainable reef fisheries depend on healthy coral reef habitats to support fish and invertebrates. Actively managing reef fisheries via reducing fishing effort and improving enforcement on gear, catch restrictions and quantity, and enforcement of non-take areas (Edgar *et al*., 2014) are therefore essential to improve overall coral health and support reef resilience (Clua and Legendre, 2008; Jackson *et al*., 2001). This can be enhanced through the combination of Natural Resource Management and aquaculture techniques to reduce wild fish catches, increase the supply of fish to the wild (seeding), and support food production to PICT (Dey *et al*., 2016).

Direct manipulation of species, via the alteration of the composition of ecosystems to increase the proportion of species that are more tolerant to climate drivers, such as heat-tolerant species that bleach and die at higher temperatures or species that recover faster, can be potentially beneficial to corals in a changing world (Hughes *et al*., 2017a). Assisted colonisation and shading have been proposed but remain untested at scale (Barros and Field, 2014).

Mangrove and seagrass habitats re-vegetation facilitate their migration landward as sea level rises, while the removal of barriers to migration, such as infrastructure is beneficial to corals due to their connectedness (Albert *et al*., 2017; Guannel *et al*., 2016). Assisted recovery of corals through measures that facilitate genetic adaptations and/or physical interventions, such as coral farming and transplantation may also be necessary to improve coral conditions across the Pacific (Hughes *et al*., 2017a; van Oppen *et al*., 2015)}. Improving water quality to minimise COTS outbreaks, and developing alternative control measures, could prevent further coral decline, but would probably only be successful in localised areas (Nakamura *et al*., 2016). Such strategies can, however, only be successful if climatic conditions are stabilised, as losses due to bleaching and cyclones will otherwise increase (De'ath *et al*., 2012).

Direct socio-economic, governance, and technological interventions

Future human and ecosystem adaptation can only be achieved when population growth is addressed in some PICTs (Butler *et al*., 2014). Reducing poverty or encouraging shifts in social norms, improving governance systems, and using modern approaches to reef conservation that merge traditional knowledge and practices with scientific and technological advances can produce positive social and ecological outcomes (Hughes *et al*., 2017a; Veitayaki, 2014; Veitayaki and Holland, *in press*). Hughes *et al*. (2017a) propose that options include the introduction of technological innovations such as the introduction of social norms to reduce pollution and harmful practices on coral reefs, and encourage voluntary compliance with formal and informal environmental rules. In social systems, shifts in the composition of society — for example, through enhanced education and a reduction in poverty — can also increase resilience to strong drivers such as climate change (Hughes *et al*., 2017a).

Climate change can be partially offset by collective action and cooperative measures in local and regional management interventions that help minimise pollution and overfishing, control human population size, consumption and access to markets (McCook *et al*., 2010). Cooperation between governments, organisations and communities will improve human-reef resilience to climate change (Morrison, 1999).

At the community level, adaptation must build on local knowledge and be integrated with science, which will be of great value for environmental management, particularly when scientific data are lacking (Aswani and Ruddle, 2013; Leon *et al*., 2015). In fact, reefs with traditional systems of resources management in PICTs are healthier because the harvest of marine resources is better controlled (Hoffmann, 2002). When conservation measures are in line with traditional governance structures and values, local coastal communities are more likely to engage in and adopt conservation programs (Walter and Hamilton, 2014).

The interdependences between corals, non-climate and climate drivers point to the critical importance of an ecosystem-based approach to fisheries management throughout the Pacific (Welch 2016). The use of climate-informed, community-based ecosystem approaches to fisheries management (CEAFM) (SPC 2010, Heenan *et al*. 2015) is essential to maintain the role of key functional groups on reefs. CEAFM approaches should be based on primary fisheries management (Cochrane *et al*. 2011) intended to protect reef habitats and keep the harvest of reef fish and invertebrates within sustainable bounds.

Any intervention in PICTs should therefore pay attention to people's development aspirations, potential social, economic and environmental benefits, local dynamics of village governance, social rules and protocols, and traditional forms of knowledge that can inform sustainable solutions (Remling and Veitayaki, 2016). It is important for policy makers to understand the cultural influences that have helped shape current social norms and decision-making processes, and the ways in which adaptations to climate change can be developed and sustained (Nunn, 2009). It is extremely important that in the future PICT governments should take on ownership of the climate-change adaptation process to a greater degree than they do at present (Nunn, 2009).

The Pacific offers several examples of local initiatives that have been successful in improving coral communities, but it is still unclear how to bring together top-down global-scale climate change mitigation and bottom-up local initiatives to maximise the perceived benefits of improving the condition of coral ecosystems in the Pacific region. A clear lesson from the literature is that tenure systems and associated political systems differ substantially across PICTs (Aswani *et al*., 2017). As a result, one cannot simply extrapolate adaptation measures and strategies similarly across the Pacific. Local environmental, social and governance contexts must be considered when rolling out adaptation programmes in the Pacific.

It is also important that climate change must be addressed in terms of current pressing challenges to livelihoods, future risks and how to address these (Remling and Veitayaki, 2016; Veitayaki and Holland, *in press*). Building capacity is essential to improve local understanding about the complexities involved in climate change and adaptation, as well as to help communities better prepare for the future. Such capacity should be built around practical discussions on receding shorelines and processes to rehabilitate coastal habitats and protect local forests, water catchment areas and food sources. Coastal communities in PICTs understand well that only a healthy environment can support their basic needs for food and clean water in the long term, and have drawn connections to broader environmental changes such as climate change (Remling and Veitayaki, 2016; Veitayaki, *in press*).

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References

Adam, T.C., Brooks, A.J., Holbrook, S.J., Schmitt, R.J., Washburn, L., Bernardi, G. (2014) How will coral reef fish communities respond to climate-driven disturbances? Insight from landscape-scale perturbations. *Oecologia* 176, 285-296.

Adjeroud, M., Michonneau, F., Edmunds, P.J., Chancerelle, Y., de Loma, T.L., Penin, L., Thibaut, L., Vidal-Dupiol, J., Salvat, B., Galzin, R. (2009) Recurrent disturbances, recovery trajectories, and resilience of coral assemblages on a South Central Pacific reef. *Coral Reefs* 28, 775-780.

Al-Moghrabi, S.M. (2001) Unusual black band disease (BBD) outbreak in the northern tip of the Gulf of Aqaba (Jordan). *Coral Reefs* 19, 330-331.

Albert, S., Saunders, M.I., Roelfsema, C.M., Leon, J.X., Johnstone, E., Mackenzie, J.R., Hoegh-Guldberg, O., Grinham, A.R., Phinn, S.R., Duke, N.C., Mumby, P.J., Kovacs, E., Woodroffe, C.D. (2017) Winners and losers as mangrove, coral and seagrass ecosystems respond to sea-level rise in Solomon Islands. *Environ Res Lett* 12.

Albright, R., Mason, B. (2013) Projected near-future levels of temperature and pCO2 reduce coral fertilization success. *Plos One* 8, e56468.

Allen, A.S., Seymour, A.C., Rittschof, D. (2017) Chemoreception drives plastic consumption in a hard coral. *Mar Pollut Bull* 124, 198-205.

Allen, G.R. (2008) Conservation hotspots of biodiversity and endemism for Indo-Pacific coral reef fishes. *Aquat Conserv* 18, 541-556.

Anthony, K., Bay, L.K., Costanza, R., Firn, J., Gunn, J., Harrison, P., Heyward, A., Lundgren, P., Mead, D., Moore, T. (2017) New interventions are needed to save coral reefs. *Nature Ecology & Evolution* 1, 1420-1422.

Aronson, R.B., Precht, W.F. (2016) Physical and Biological Drivers of Coral-Reef Dynamics. *Coral Reefs World* 6, 261-275.

Aswani, S., Albert, S., Love, M. (2017) One size does not fit all: Critical insights for effective community-based resource management in Melanesia. *Mar Policy* 81, 381-391.

Aswani, S., Ruddle, K. (2013) Design of Realistic Hybrid Marine Resource Management Programs in Oceania. *Pac Sci* 67, 461-476.

Atkinson, S.C., Jupiter, S.D., Adams, V.M., Ingram, J.C., Narayan, S., Klein, C.J., Possingham, H.P. (2016) Prioritising Mangrove Ecosystem Services Results in Spatially Variable Management Priorities. *Plos One* 11.

Ayala, H. (2005) Vaka Moana–a road map for the South Pacific economy, in: Hooper, A. (Ed.) *Culture and sustainable development in the Pacific.* ANU E Press, Canberra, pp. 190-222.

Barros, V., Field, C. (2014) *Climate Change 2014 Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Preface.* Climate Change 2014: Impacts, Adaptation, and Vulnerability, Pt A: Global and Sectoral Aspects, Ix-Xi.

Barshis, D.J., Ladner, J.T., Oliver, T.A., Seneca, F.O., Traylor-Knowles, N., Palumbi, S.R. (2013) Genomic basis for coral resilience to climate change. *P Natl Acad Sci USA* 110, 1387-1392.

Bates, N.R., Astor, Y.M., Church, M.J., Currie, K., Dore, J.E., Gonzalez-Davila, M., Lorenzoni, L., Muller-Karger, F., Olafsson, J., Santana-Casiano, J.M. (2014) A Time-Series View of Changing Surface Ocean Chemistry Due to Ocean Uptake of Anthropogenic CO2 and Ocean Acidification. *Oceanography* 27, 126-141.

Beck, J.W., Recy, J., Taylor, F., Edwards, R.L., Cabioch, G. (1997) Abrupt changes in early Holocene tropical sea surface temperature derived from coral records. *Nature* 385, 705-707.

Bell, J.D., Cisneros-Montemayor, A., Hanich, Q., Johnson, J.E., Lehodey, P., Moore, B.R., Pratchett, M.S., Reygondeau, G., Senina, I., Virdin, J., Wabnitz, C.C.C. (2017) Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands. *Mar Policy*.

Bell, J.D., Ganachaud, A., Gehrke, P.C., Griffiths, S.P., Hobday, A.J., Hoegh-Guldberg, O., Johnson, J.E., Le Borgne, R., Lehodey, P., Lough, J.M., Matear, R.J., Pickering, T.D., Pratchett, M.S., Sen Gupta, A., Senina, I., Waycott, M. (2013) Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nat Clim Change* 3, 591-599.

Bell, J.D., Johnson, J.E., Hobday, A.J. (2011) *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change.* Secretariat of the Pacific Community, Noumea, New Caledonia.

Bellwood, D.R., Hughes, T.P., Nyström, M. (2004) Confronting the coral reef crisis. *Nature* 429, 827-833.

Berkelmans, R., van Oppen, M.J.H. (2006) The role of zooxanthellae in the thermal tolerance of corals: a 'nugget of hope' for coral reefs in an era of climate change. *P Roy Soc B-Biol Sci* 273, 2305-2312.

Berthe, C., Chancerelle, Y., Lecchini, D., Hedouin, L. (2016) *First Report of a Dramatic Rapid Loss of Living Coral on the North Coast of Western Samoa.* Vie Milieu 66, 155-157.

Bonesso, J.L., Leggat, W., Ainsworth, T.D. (2017) Exposure to elevated sea-surface temperatures below the bleaching threshold impairs coral recovery and regeneration following injury. *Peerj* 5.

Bridge, T.C.L., Hughes, T.P., Guinotte, J.M., Bongaerts, P. (2013) COMMENTARY: Call to protect all coral reefs. *Nat Clim Change* 3, 528-530.

Brown, C.J., Jupiter, S.D., Albert, S., Klein, C.J., Mangubhai, S., Maina, J.M., Mumby, P., Olley, J., Stewart-Koster, B., Tulloch, V., Wenger, A. (2017a) Tracing the influence of land-use change on water quality and coral reefs using a Bayesian model. *Sci Rep-Uk* 7.

Brown, C.J., Jupiter, S.D., Lin, H.Y., Albert, S., Klein, C., Maina, J.M., Tulloch, V.J.D., Wenger, A.S., Mumby, P.J. (2017b) Habitat change mediates the response of coral reef fish populations to terrestrial run-off. *Mar Ecol Prog Ser* 576, 55-68.

Bruckner, A.W., Coward, G., Bimson, K., Rattanawongwan, T. (2017) Predation by feeding aggregations of Drupella spp. inhibits the recovery of reefs damaged by a mass bleaching event. *Coral Reefs* 36, 1181-1187.

Bruno, J.F., Petes, L.E., Harvell, C.D., Hettinger, A. (2003) Nutrient enrichment can increase the severity of coral diseases. *Ecol Lett* 6, 1056-1061.

Bruno, J.F., Selig, E.R. (2007) Regional Decline of Coral Cover in the Indo-Pacific: Timing, Extent, and Subregional Comparisons. *Plos One* 2.

Butler, J.R.A., Skewes, T., Mitchell, D., Pontio, M., Hills, T. (2014) Stakeholder perceptions of ecosystem service declines in Milne Bay, Papua New Guinea: Is human population a more critical driver than climate change? *Mar Policy* 46, 1-13.

Camoin, G.F., Webster, J.M. (2015) Coral reef response to Quaternary sea-level and environmental changes: State of the science. *Sedimentology* 62, 401-428.

Carballo, J.L., Bautista, E., Nava, H., Cruz-Barraza, J.A., Chavez, J.A. (2013) Boring sponges, an increasing threat for coral reefs affected by bleaching events. *Ecol Evol* 3, 872-886.

Carilli, J., Donner, S.D., Hartmann, A.C. (2012) Historical Temperature Variability Affects Coral Response to Heat Stress. *Plos One* 7.

Carricart-Ganivet, J.P. (2004) Sea surface temperature and the growth of the West Atlantic reef-building coral Montastraea annularis. *J Exp Mar Biol Ecol* 302, 249-260.

Chan, N.C.S., Connolly, S.R. (2013) Sensitivity of coral calcification to ocean acidification: a meta-analysis. *Global Change Biol* 19, 282-290.

Chaves-Fonnegra, A., Riegl, B., Zea, S., Lopez, J.V., Brandt, M., Smith, T., Gilliam, D.S. (2017) Bleaching events regulate shifts from coral to excavating sponges in algae-dominated reefs. *Global Change Biol.*

Chazottes, V., Hutchings, P., Osorno, A. (2017) Impact of an experimental eutrophication on the processes of bioerosion on the reef: One Tree Island, Great Barrier Reef, Australia. *Mar Pollut Bull* 118, 125-130.

Cheal, A.J., Coleman, G., Delean, S., Miller, I., Osborne, K., Sweatman, H. (2002) Responses of coral and fish assemblages to a severe but short-lived tropical cyclone on the Great Barrier Reef, Australia. *Coral Reefs* 21, 131-142.

Cinner, J.E., McClanahan, T.R. (2006) Socioeconomic factors that lead to overfishing in small-scale coral reef fisheries of Papua New Guinea. *Environ Conserv* 33, 73-80.

Cloern, J.E. (2001) Our evolving conceptual model of the coastal eutrophication problem. *Mar Ecol Prog Ser* 210, 223-253.

Clua, E., Legendre, P. (2008) Shifting dominance among Scarid species on reefs representing a gradient of fishing pressure. *Aquat Living Resour* 21, 339-348.

Coelho, V.R., Fenner, D., Caruso, C., Bayles, B.R., Huang, Y., Birkeland, C. (2017) Shading as a mitigation tool for coral bleaching in three common Indo-Pacific species. *J Exp Mar Biol Ecol* 497, 152-163.

Comeau, S., Carpenter, R.C., Nojiri, Y., Putnam, H.M., Sakai, K., Edmunds, P.J. (2014) Pacific-wide contrast highlights resistance of reef calcifiers to ocean acidification. *Proc Biol Sci* 281, 20141339-20141339.

Connell, J.H. (1978) Diversity in tropical rain forests and coral reefs. *Science* 199, 1302-1310.

Connell, J.H. (1997) Disturbance and recovery of coral assemblages. *Coral Reefs* 16, S101-S113.

Cooper, T.F., De 'Ath, G., Fabricius, K.E., Lough, J.M. (2008) Declining coral calcification in massive Porites in two nearshore regions of the northern Great Barrier Reef. *Global Change Biol* 14, 529-538.

Craig, P., Birkeland, C., Belliveau, S. (2001) High temperatures tolerated by a diverse assemblage of shallow-water corals in American Samoa. *Coral Reefs* 20, 185-189.

Cumming, R.L., Toscano, M.A., Lovell, E.R., Carlson, B.A., Dulvy, N.K., Hughes, A., Koven, J.F., Quinn, N.J., Sykes, H.R., Taylor, O.J.S., Vaughn, D. (2000) Mass bleaching in the Fiji Islands, in: Moosa, M.K., Soemodihardjo, S., Soegiarto, A., Rominihtarto, K., Nontji, A., Soekarmo, Surharsono (Eds.), *Proceedings of the ninth international coral reef symposium*, Bali. 23-39 Oct. 2000, pp. 1161-1169.

D'Angelo, C., Smith, E.G., Oswald, F., Burt, J., Tchernov, D., Wiedenmann, J. (2012) Locally accelerated growth is part of the innate immune response and repair mechanisms in reef-building corals as detected by green fluorescent protein (GFP)-like pigments. *Coral Reefs* 31, 1045-1056.

Dadhich, A.P., Nadaoka, K. (2012) Analysis of Terrestrial Discharge from Agricultural Watersheds and Its Impact on Nearshore and Offshore Reefs in Fiji. *J Coastal Res* 28, 1225-1235.

Dandan, S.S., Falter, J.L., Lowe, R.J., McCulloch, M.T. (2015) Resilience of coral calcification to extreme temperature variations in the Kimberley region, northwest Australia. *Coral Reefs* 34, 1151-1163.

Darling, E.S., McClanahan, T.R., Cote, I.M. (2013) Life histories predict coral community disassembly under multiple stressors. *Glob Chang Biol* 19, 1930-1940.

Davies, J.M., Dunne, R.P., Brown, B.E. (1997) Coral bleaching and elevated sea-water temperature in Milne Bay Province, Papua New Guinea, 1996. *Mar Freshwater Res* 48, 513-516.

De'ath, G., Fabricius, K. (2010) Water quality as a regional driver of coral biodiversity and macroalgae on the Great Barrier Reef. *Ecol Appl* 20, 840-850.

De'ath, G., Fabricius, K.E., Sweatman, H., Puotinen, M. (2012) The 27-year decline of coral cover on the Great Barrier Reef and its causes. *P Natl Acad Sci USA* 109, 17995-17999.

De'ath, G., Lough, J.M., Fabricius, K.E. (2009) Declining Coral Calcification on the Great Barrier Reef. *Science* 323, 116-119.

Dean, R.G., Houston, J.R. (2013) Recent sea level trends and accelerations: Comparison of tide gauge and satellite results. *Coastal Engineering* 75, 4-9.

DeCarlo, T.M., Cohen, A.L., Barkley, H.C., Cobban, Q., Young, C., Shamberger, K.E., Brainard, R.E., Golbuu, Y. (2015) Coral macrobioerosion is accelerated by ocean acidification and nutrients. *Geology* 43, 7-10.

Dey, M.M., Gosh, K., Valmonte-Santos, R., Rosegrant, M.W., Chen, O.L. (2016) Economic impact of climate change and climate change adaptation strategies for fisheries sector in Fiji. *Mar Policy* 67, 164-170.

Diaz, R.J., Rosenberg, R. (2008) Spreading dead zones and consequences for marine ecosystems. *Science* 321, 926-929.

Done, T., Turak, E., Wakeford, M., DeVantier, L., McDonald, A., Fisk, D. (2007) Decadal changes in turbid-water coral communities at Pandora Reef: loss of resilience or too soon to tell? *Coral Reefs* 26, 789-805.

Done, T.J. (1992) Phase-Shifts in Coral-Reef Communities and Their Ecological Significance. *Hydrobiologia* 247, 121-132.

Done, T.J. (1996) *Expert advice on coral reef impacts Lihir Island,* Papua New Guinea, pp. 1-11.

Dore, J.E., Lukas, R., Sadler, D.W., Church, M.J., Karl, D.M. (2009) Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *P Natl Acad Sci USA* 106, 12235-12240.

Doropoulos, C., Hyndes, G.A., Abecasis, D., Verges, A. (2013) Herbivores strongly influence algal recruitment in both coral- and algal-dominated coral reef habitats. *Mar Ecol Prog Ser* 486, 153-164.

Dubinsky, Z., Stambler, N. (1996) Marine pollution and coral reefs. *Global Change Biol* 2, 511-526.

Dutra, L.X.C., Haworth, R.J. (2008) Human disturbance, natural resilience and management futures: the coral reefs of Todos os Santos Bay, Bahia, Brazil. *Journal of Sustainable Development* 1, 13-30.

Duvat, V.K.E., Pillet, V. (2017) Shoreline changes in reef islands of the Central Pacific: Takapoto Atoll, Northern Tuamotu, French Polynesia. *Geomorphology* 282, 96-118.

Edgar, G.J., Stuart-Smith, R.D., Willis, T.J., Kininmonth, S., Baker, S.C., Banks, S., Barrett, N.S., Becerro, M.A., Bernard, A.T.F., Berkhout, J., Buxton, C.D., Campbell, S.J., Cooper, A.T., Davey, M., Edgar, S.C., Forsterra, G., Galvan, D.E., Irigoyen, A.J., Kushner, D.J., Moura, R., Parnell, P.E., Shears, N.T., Soler, G., Strain, E.M.A., Thomson, R.J. (2014) Global conservation outcomes depend on marine protected areas with five key features. *Nature* 506, 216-+.

Elsner, J.B., Kossin, J.P., Jagger, T.H. (2008) The increasing intensity of the strongest tropical cyclones. *Nature* 455, 92-95.

Engelhardt, R.A. (2005) Culturally and ecologically sustainable tourism development through local community management, in: Hooper, A. (Ed.), *Culture and sustainable development in the Pacific*. ANU E Press, Canberra, p. 174.

Enochs, I.C., Manzello, D.P., Donham, E.M., Kolodziej, G., Okano, R., Johnston, L., Young, C., Iguel, J., Edwards, C.B., Fox, M.D., Valentino, L., Johnson, S., Benavente, D., Clark, S.J., Carlton, R., Burton, T., Eynaud, Y., Price, N.N. (2015) Shift from coral to macroalgae dominance on a volcanically acidified reef. *Nat Clim Change* 5, 1083-+.

Enochs, I.C., Manzello, D.P., Kolodziej, G., Noonan, S.H.C., Valentino, L., Fabricius, K.E. (2016) Enhanced macroboring and depressed calcification drive net dissolution at high-CO2 coral reefs. *P Roy Soc B-Biol Sci* 283.

Erftemeijer, P.L.A., Riegl, B., Hoeksema, B.W., Todd, P.A. (2012) Environmental impacts of dredging and other sediment disturbances on corals: A review. *Mar Pollut Bull* 64, 1737-1765.

Evenhuis, C., Lenton, A., Cantin, N.E., Lough, J.M. (2015) Modelling coral calcification accounting for the impacts of coral bleaching and ocean acidification. *Biogeosciences* 12, 2607-2630.

Fabricius, K.E., Kluibenschedl, A., Harrington, L., Noonan, S., De'ath, G. (2015) In situ changes of tropical crustose coralline algae along carbon dioxide gradients. *Sci Rep-Uk* 5.

Fabricius, K.E., Langdon, C., Uthicke, S., Humphrey, C., Noonan, S., De'ath, G., Okazaki, R., Muehllehner, N., Glas, M.S., Lough, J.M. (2011) Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nat Clim Change* 1, 165-169.

Fabricius, K.E., Noonan, S.H.C., Abrego, D., Harrington, L., De'ath, G. (2017) Low recruitment due to altered settlement substrata as primary constraint for coral communities under ocean acidification. *P Roy Soc B-Biol Sci* 284.

Fabry, V.J., Seibel, B.A., Feely, R.A., Orr, J.C. (2008) Impacts of ocean acidification on marine fauna and ecosystem processes. *Ices J Mar Sci* 65, 414-432.

Fisher, R., O'Leary, R.A., Low-Choy, S., Mengersen, K., Knowlton, N., Brainard, R.E., Caley, M.J. (2015) Species Richness on Coral Reefs and the Pursuit of Convergent Global Estimates. *Curr Biol* 25, 500-505.

Flynn, A. (2006) C*oral Reef Monitoring* 2006, p. 91.

Fowler, D., Coyle, M., Skiba, U., Sutton, M.A., Cape, J.N., Reis, S., Sheppard, L.J., Jenkins, A., Grizzetti, B., Galloway, J.N., Vitousek, P., Leach, A., Bouwman, A.F., Butterbach-Bahl, K., Dentener, F., Stevenson, D., Amann, M., Voss, M. (2013) The global nitrogen cycle in the twenty-first century. *Philos T R Soc B* 368.

Freeman, L.A., Kleypas, J.A., Miller, A.J. (2013) Coral reef habitat response to climate change scenarios. *Plos One* 8, e82404.

Furby, K.A., Apprill, A., Cervino, J.M., Ossolinski, J.E., Hughen, K.A. (2014) Incidence of lesions on Fungiidae corals in the eastern Red Sea is related to water temperature and coastal pollution. *Mar Environ Res* 98, 29-38.

Gardner, S.G., Raina, J.B., Nitschke, M.R., Nielsen, D.A., Stat, M., Motti, C.A., Ralph, P.J., Petrou, K. (2017) A multi-trait systems approach reveals a response cascade to bleaching in corals. *Bmc Biol* 15.

Gardner, T.A., Cote, I.M., Gill, J.A., Grant, A., Watkinson, A.R. (2005) Hurricanes and Caribbean coral reefs: Impacts, recovery patterns, and role in long-term decline. *Ecology* 86, 174-184.

Gattuso, J.P., Magnan, A., Bille, R., Cheung, W.W.L., Howes, E.L., Joos, F., Allemand, D., Bopp, L., Cooley, S.R., Eakin, C.M., Hoegh-Guldberg, O., Kelly, R.P., Portner, H.O., Rogers, A.D., Baxter, J.M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U.R., Treyer, S., Turley, C. (2015) Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science* 349.

Gillett, R., Cartwright, I. (2010) *The Future of Pacific Island Fisheries, Honiara*, p. 110.

Glynn, P.W. (1983) Extensive Bleaching and Death of Reef Corals on the Pacific Coast of Panama. *Environ Conserv* 10, 149-154.

Golbuu, Y., Gouezo, M., Kurihara, H., Rehm, L., Wolanski, E. (2016) Long-term isolation and local adaptation in Palau's Nikko Bay help corals thrive in acidic waters. *Coral Reefs* 35, 909-918.

Goreau, T., McClanahan, T., Hayes, R., Strong, A. (2000) Conservation of coral reefs after the 1998 global bleaching event. *Conserv Biol* 14, 5-15.

Guannel, G., Arkema, K., Ruggiero, P., Verutes, G. (2016) The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience. *Plos One* 11, e0158094.

Guillemot, N., Chabanet, P., Le Pape, O. (2010) Cyclone effects on coral reef habitats in New Caledonia (South Pacific). *Coral Reefs* 29, 445-453.

Guinotte, J.M., Buddemeier, R.W., Kleypas, J.A. (2003) Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. *Coral Reefs* 22, 551-558.

Haapkyla, J., Unsworth, R.K.F., Flavell, M., Bourne, D.G., Schaffelke, B., Willis, B.L. (2011) Seasonal Rainfall and Runoff Promote Coral Disease on an Inshore Reef. *Plos One* 6.

Hall, C.M. (2001) Trends in ocean and coastal tourism: the end of the last frontier? *Ocean Coast Manage* 44, 601-618.

Hall, N.M., Berry, K.L.E., Rintoul, L., Hoogenboom, M.O. (2015) Microplastic ingestion by scleractinian corals. *Mar Biol* 162, 725-732.

Halpern, B.S., Selkoe, K.A., White, C., Albert, S., Aswani, S., Lauer, M. (2013) Marine protected areas and resilience to sedimentation in the Solomon Islands. *Coral Reefs* 32, 61-69.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R. (2008) A global map of human impact on marine ecosystems. *Science* 319, 948-952.

Hassenruck, C., Hofmann, L.C., Bischof, K., Ramette, A. (2015) Seagrass biofilm communities at a naturally CO2-rich vent. *Env Microbiol Rep* 7, 516-525.

Haynes, D., Johnson, J.E. (2000) Organochlorine, heavy metal and polyaromatic hydrocarbon pollutant concentrations in the Great Barrier Reef (Australia) environment: a review. *Mar Pollut Bull* 41, 267-278.

Haywood, M.D.E., Dennis, D., Thomson, D.P., Pillans, R.D. (2016) Mine waste disposal leads to lower coral cover, reduced species richness and a predominance of simple coral growth forms on a fringing coral reef in Papua New Guinea. *Mar Environ Res* 115, 36-48.

Hoadley, K.D., Pettay, D.T., Grottoli, A.G., Cai, W.-J., Melman, T.F., Schoepf, V., Hu, X., Li, Q., Xu, H., Wang, Y., Matsui, Y., Baumann, J.H., Warner, M.E. (2015) Physiological response to elevated temperature and pCO_2 varies across four Pacific coral species: Understanding the unique host+symbiont response. *Sci Rep-Uk* 5, 18371.

Hoegh-Guldberg, O. (1999) Climate change, coral bleaching and the future of the world's coral reefs. *Mar Freshwater Res* 50, 839-866.

Hoegh-Guldberg, O., Andréfouët, S., Fabricius, K.E., Diaz-Pulido, G., Lough, J.M., Marshall, P.A., Pratchett, M.S. (2011) Vulnerability of coral reefs in the tropical Pacific to climate change, in: Bell, J.D., Johnson, J.E., Hobday, A.J. (Eds.), *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change.* Secretariat of the Pacific Community, Noumea, New Caledonia, pp. 251–296.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A., Hatziolos, M.E. (2007) Coral reefs under rapid climate change and ocean acidification. *Science* 318, 1737-1742.

Hoegh-Guldberg, O., Poloczanska, E.S., Skirving, W., Dove, S. (2017) Coral Reef Ecosystems under Climate Change and Ocean Acidification. *Frontiers in Marine Science* 4.

Hoffmann, T.C. (2002) Coral reef health and effects of socio-economic factors in Fiji and Cook Islands. *Mar Pollut Bull* 44, 1281-1293.

Holland, E., Nuttall, P., Newell, A., Prasad, B., Veitayaki, J., Bola, A., Kaitu'u, J. (2014) Connecting the dots: policy connections between Pacific Island shipping and global CO_2 and pollutant emission reduction. *Carbon Manag* 5, 93-105.

Holland, G., Bruyere, C.L. (2014) Recent intense hurricane response to global climate change. *Clim Dynam* 42, 617-627.

Howell, E.A., Bograd, S.J., Morishige, C., Seki, M.P., Polovina, J.J. (2012) On North Pacific circulation and associated marine debris concentration. *Mar Pollut Bull* 65, 16-22.

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B., Kleypas, J., Lough, J.M., Marshall, P., Nystrom, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B., Roughgarden, J. (2003) Climate change, human impacts, and the resilience of coral reefs. *Science* 301, 929-933.

Hughes, T.P., Barnes, M.L., Bellwood, D.R., Cinner, J.E., Cumming, G.S., Jackson, J.B.C., Kleypas, J., van de Leemput, I.A., Lough, J.M., Morrison, T.H., Palumbi, S.R., van Nes, E.H., Scheffer, M. (2017a) Coral reefs in the Anthropocene. *Nature* 546, 82-90.

Hughes, T.P., Kerry, J.T., Alvarez-Noriega, M., Alvarez-Romero, J.G., Anderson, K.D., Baird, A.H., Babcock, R.C., Beger, M., Bellwood, D.R., Berkelmans, R., Bridge, T.C., Butler, I.R., Byrne, M., Cantin, N.E., Comeau, S., Connolly, S.R., Cumming, G.S., Dalton, S.J., Diaz-Pulido, G., Eakin, C.M., Figueira, W.F., Gilmour, J.P., Harrison, H.B., Heron, S.F., Hoey, A.S., Hobbs, J.P.A., Hoogenboom, M.O., Kennedy, E.V., Kuo, C.Y., Lough, J.M., Lowe, R.J., Liu, G., Cculloch, M.T.M., Malcolm, H.A., Mcwilliam, M.J., Pandolfi, J.M., Pears, R.J., Pratchett, M.S., Schoepf, V., Simpson, T., Skirving, W.J., Sommer, B., Torda, G., Wachenfeld, D.R., Willis, B.L., Wilson, S.K. (2017b) Global warming and recurrent mass bleaching of corals. *Nature* 543, 373-+.

Hughes, T.P., Rodrigues, M.J., Bellwood, D.R., Ceccarelli, D., Hoegh-Guldberg, O., McCook, L., Moltschaniwskyj, N., Pratchett, M.S., Steneck, R.S., Willis, B. (2007) Phase shifts, herbivory, and the resilience of coral reefs to climate change. *Curr Bio*l 17, 360-365.

IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, in: Team, C.W., Pachauri, R.K., Meyer, L.A. (Eds.). IPCC, Geneva, Switzerland, p. 151.

Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A., Hughes, T.P., Kidwell, S., Lange, C.B., Lenihan, H.S., Pandolfi, J.M., Peterson, C.H., Steneck, R.S., Tegner, M.J., Warner, R.R. (2001) Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293, 629-638.

Jevrejeva, S., Grinsted, A., Moore, J.C. (2009) Anthropogenic forcing dominates sea level rise since 1850. *Geophys Res Lett* 36.

Johnson, J., Bell, J., De Young, C. (2013) *Priority Adaptations to Climate Change for Pacific Habitats, Fisheries and Aquaculture: Reducing Risks and Capitalizing on Opportunities.* FAO Fisheries and Aquaculture Proceedings No. 28, Rome.

Johnson, J., Welch, D., Fraser, A. (2016a) *Climate Change Impacts in North Efate, Vanuatu.* Vanuatu RESCCUE project, Noumea, New Caledonia.

Johnson, J.E., Bell, J.D., Allain, V., Hanich, Q., Lehodey, P., Moore, B., Nicol, S., Pickering, T. (2017) The Pacific Islands: Fisheries and Aquaculture and Climate Change, in: Philips, B., Ramirez, M. (Eds.), I*mplications of climate change for fisheries & aquaculture: a global analysis.* Wiley Pubs, New York, USA.

Johnson, J.E., Bell, J.D., Sen Gupta, A. (2016b) *Pacific Islands ocean acidification vulnerability assessment.* SPREP, Apia, Samoa.

Johnson, J.E., Brodie, J., Waterhouse, J. (2017) *Wastewater Pollution and Coral Reefs: Science-to-Policy Brief,* in: United Nations Environment Program (Ed.), Report to the United Nations Environment Assembly of the United Nations Environment Programme. UNEP, p. 74.

Kamya, P.Z., Byrne, M., Graba-Landry, A., Dworjanyn, S.A. (2016) Near-future ocean acidification enhances the feeding rate and development of the herbivorous juveniles of the crown-of-thorns starfish, Acanthaster planci. *Coral Reefs* 35, 1241-1251.

Kamya, P.Z., Byrne, M., Mos, B., Hall, L., Dworjanyn, S.A. (2017) Indirect effects of ocean acidification drive feeding and growth of juvenile crown-of-thorns starfish, *Acanthaster planci*. *P Roy Soc B-Biol Sci* 284.

Karnauskas, K.B., Cohen, A.L. (2012) Equatorial refuge amid tropical warming. *Nat Clim Change* 2, 530-534.

Keith, S.A., Maynard, J.A., Edwards, A.J., Guest, J.R., Bauman, A.G., van Hooidonk, R., Heron, S.F., Berumen, M.L., Bouwmeester, J., Piromvaragorn, S., Rahbek, C., Baird, A.H. (2016) Coral mass spawning predicted by rapid seasonal rise in ocean temperature. *Proc Biol Sci* 283, 20160011-20160019.

Kench, P.S., Ford, M.R., Owen, S.D. (2018) Patterns of island change and persistence offer alternate adaptation pathways for atoll nations. *Nat Commun* 9.

Kininmonth, S., Lemm, S., Malone, C., Hatley, T. (2014) Spatial vulnerability assessment of anchor damage within the Great Barrier Reef World Heritage Area, Australia. *Ocean Coast Manage* 100, 20-31.

Kleypas, J.A., Castruccio, F.S., Curchitser, E.N., McLeod, E. (2015) The impact of ENSO on coral heat stress in the western equatorial Pacific. *Glob Chang Biol* 21, 2525-2539.

Kleypas, J.A., McManus, J.W., Meñez, L.A.B., 1999. Environmental Limits to Coral Reef Development: Where Do We Draw the Line? *Am Zool* 39, 146-159.

Kroeker, K.J., Kordas, R.L., Crim, R.N., Singh, G.G. (2010) Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecol Lett* 13, 1419-1434.

Kuffner, I.B., Paul, V.J. (2004) Effects of the benthic cyanobacterium Lyngbya majuscula on larval recruitment of the reef corals Acropora surculosa and Pocillopora damicornis. *Coral Reefs* 23, 455-458.

Kuta, K.G., Richardson, L.L. (2002) Ecological aspects of black band disease of corals: relationships between disease incidence and environmental factors. *Coral Reefs* 21, 393-398.

Lal, R.L. (2016) *Coral settlement, survivability, and diversity in a heavily stressed urban reef environment in the Fiji Islands*, MSC Thesis. The University of the South Pacific, Fiji.

Lam, E.K.Y., Chui, A.P.Y., Kwok, C.K., Ip, A.H.P., Chan, S.W., Leung, H.N., Yeung, L.C., Ang, P.O. (2015) High levels of inorganic nutrients affect fertilization kinetics, early development and settlement of the scleractinian coral *Platygyra acuta*. *Coral Reefs* 34, 837-848.

Lamb, J.B., Willis, B.L., Fiorenza, E.A., Couch, C.S., Howard, R., Rader, D.N., True, J.D., Kelly, L.A., Ahmad, A., Jompa, J., Harvell, C.D. (2018) Plastic waste associated with disease on coral reefs. *Science* 359, 460-462.

Langlais, C.E., Lenton, A., Heron, S.F., Evenhuis, C., Sen Gupta, A., Brown, J.N., Kuchinke, M. (2017) Coral bleaching pathways under the control of regional temperature variability. *Nat Clim Change* 7, 839-+.

Le Nohaic, M., Ross, C.L., Cornwall, C.E., Comeau, S., Lowe, R., McCulloch, M.T., Schoepf, V. (2017) Marine heatwave causes unprecedented regional mass bleaching of thermally resistant corals in northwestern Australia. *Sci Rep-Uk* 7.

Lenton, A., McInnes, K.L., O'Grady, J.G. (2015) Marine Projections of Warming and Ocean Acidification in the Australasian Region. *Aust Meteorol Ocean* 65, S1-S28.

Leon, J.X., Hardcastle, J., James, R., Albert, S., Kereseka, J., Woodroffe, C.D. (2015) Supporting Local and Traditional Knowledge with Science for Adaptation to Climate Change: Lessons Learned from Participatory Three-Dimensional Modeling in BoeBoe, Solomon Islands. *Coast Manage* 43, 424-438.

Levin, L.A., Liu, K.K., Emeis, K.C., Breitburg, D.L., Cloern, J., Deutsch, C., Giani, M., Goffart, A., Hofmann, E.E., Lachkar, Z., Limburg, K., Liu, S.M., Montes, E., Naqvi, W., Ragueneau, O., Rabouille, C., Sarkar, S.K., Swaney, D.P., Wassman, P., Wishner, K.F. (2015) Comparative biogeochemistry-ecosystem-human interactions on dynamic continental margins. *J Marine Syst* 141, 3-17.

Lough, J.M. (2012) Small change, big difference: Sea surface temperature distributions for tropical coral reef ecosystems, 1950-2011. *J Geophys Res-Oceans* 117, n/a-n/a.

Lovell, E., Sykes, H., Deiye, M., Wantiez, L., Carrigue, C., Virly, S., Samuelu, J., Solofa, A., Poulasi, T., Pakoa, K., Sabetian, A., Afzal, D., Hughes, A., Sulu, R. (2004) *Status of coral reefs in the South West Pacific: Fiji, Nauru, New Caledonia, Samoa, Solomon*

Islands, Tuvalu and Vanuatu, in: Wilkinson, C. (Ed.), Status GCRMN, Townsville.

Lovell, E.R., Sykes, H.R. (2004) Fiji, in: Sulu, R. (Ed.), *Status of coral reefs in the Southwest Pacific: 2004.* IPS Publications, University of the South Pacific, Suva, pp. 1-82.

Maata, M., Singh, S. (2008) Heavy metal pollution in Suva harbour sediments, Fiji. *Environmental Chemistry Letters* 6, 113-118.

Maes, C., Blanke, B. (2015) Tracking the origins of plastic debris across the Coral Sea: A case study from the Ouvéa Island, New Caledonia. *Mar Pollut Bull* 97, 160-168.

Mangubhai, S. (2016) *Impact of Tropical Cyclone Winston on Coral Reefs in the Vatu-i-Ra Seascape,* Report No. 01/16, Suva, Fiji, p. 27.

Martinez, E., Maamaatuaiahutapu, K., Taillandier, V. (2009) Floating marine debris surface drift: Convergence and accumulation toward the South Pacific subtropical gyre. *Mar Pollut Bull* 58, 1347-1355.

Matthews, E., Veitayaki, J., Bidesi, V.R., 1998. Fijian villagers adapt to changes in local fisheries. *Ocean Coast Manage* 38, 207-224.

Maynard, J., van Hooidonk, R., Eakin, C.M., Puotinen, M., Garren, M., Williams, G., Heron, S.F., Lamb, J., Weil, E., Willis, B., Harvell, C.D. (2015a) Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence. *Nat Clim Change* 5, 688-+.

Maynard, J.A., McKagan, S., Raymundo, L., Johnson, S., Ahmadia, G.N., Johnston, L., Houk, P., Williams, G.J., Kendall, M., Heron, S.F., van Hooidonk, R., Mcleod, E., Tracey, D., Planes, S. (2015b) Assessing relative resilience potential of coral reefs to inform management. *Biol Conserv* 192, 109-119.

Mayor, A. (1924) Structure and ecology of Samoan reefs. Carnegie Institute, Washington Publication 340. *Department Of Marine Biology* 19, 27-36.

McCauley, D.J., DeSalles, P.A., Young, H.S., Dunbar, R.B., Dirzo, R., Mills, M.M., Micheli, F. (2012) From wing to wing: the persistence of long ecological interaction chains in less-disturbed ecosystems. *Sci Rep-Uk* 2.

McCook, L.J. (1999) Macroalgae, nutrients and phase shifts on coral reefs: scientific issues and management consequences for the Great Barrier Reef. *Coral Reefs* 18, 357-367.

McCook, L.J., Ayling, T., Cappo, M., Choat, J.H., Evans, R.D., De Freitas, D.M., Heupel, M., Hughes, T.P., Jones, G.P., Mapstone, B., Marsh, H., Mills, M., Molloy, F.J., Pitcher, C.R., Pressey, R.L., Russ, G.R., Sutton, S., Sweatman, H., Tobin, R., Wachenfeld, D.R., Williamson, D.H. (2010) Adaptive management of the Great Barrier Reef: A globally significant demonstration of the benefits of networks of marine reserves. *P Natl Acad Sci USA* 107, 18278-18285.

McGowan, H., Theobald, A. (2017) ENSO Weather and Coral Bleaching on the Great Barrier Reef, Australia. *Geophys Res Lett* 44, 10601-10607.

McManus, J.W., Polsenberg, J.F. (2004) Coral-algal phase shifts on coral reefs: ecological and environmental aspects. *Progress in Oceanography* 60, 263-279.

Meissner, K.J., Lippmann, T., Sen Gupta, A. (2012) Large-scale stress factors affecting coral reefs: open ocean sea surface temperature and surface seawater aragonite saturation over the next 400 years. *Coral Reefs* 31, 309-319.

Moberg, F., Folke, C. (1999) Ecological goods and services of coral reef ecosystem. *Ecological Economics* 29, 215-233.

Morris, C., Mackay, K., Leong, J.A., Garrgue, C., Kere, N., Manele, B., Poulasi, T., Raubani, J., Sapatu, M., Sarramegna, S., Sykes, H., Bartlett, C., Virly, S., Wantiez, L. (2008) Status of the coral reefs in the South West Pacific: Fiji, New Caledonia, Samoa, Solomon Islands, Tuvalu and Vanuatu, in: Wilkinson, C. (Ed.), *Status of coral reefs of the world: 2008.* Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia, pp. 177-188.

Morris, C.W. (2009) *South-West Pacific Status of coral reefs report, 2007.* CRISP, Suva, p. 209.

Morrison, R.J., 1999. The regional approach to management of marine pollution in the South Pacific. *Ocean Coast Manage* 42, 503-521.

Morrison, R.J., Denton, G.R.W., Tamata, U.B., Grignon, J. (2013) Anthropogenic biogeochemical impacts on coral reefs in the Pacific Islands-An overview. *Deep-Sea Res Pt Ii* 96, 5-12.

Movono, A., Dahles, H., Becken, S. (2018) Fijian culture and the environment: a focus on the ecological and social interconnectedness of tourism development. *J Sustain Tour* 26, 451-469.

Mumby, P.J. (2009) Phase shifts and the stability of macroalgal communities on Caribbean coral reefs. *Coral Reefs* 28, 761-773.

Mundy, C. (1996) *A quantitative survey of the corals of American Samoa.* Report to the Department of Marine and Wildlife Resources Government of American Samoa, Pago Pago, American Samoa.

Naidu, S., Aalbersberg, W.G.L., Brodie, J.E., Fuavao, V.A., Maata, M., Naqasima, M., Whippy, P., Morrison, R.J. (1991) *Water quality studies on selected South Pacific lagoons.* UNEP Regional Seas Reports and Studies No. 136, UNEP and SPREP Reports and Studies No. 49. UNEP and SPREP, Suva.

Nakamura, M., Higa, Y., Kumagai, N., Okaji, K. (2016) Using Long-Term Removal Data to Manage a Crown-of-Thorns Starfish Population. *Diversity* 8, 24.

Negri, A.P., Heyward, A.J. (2001) Inhibition of coral fertilisation and larval metamorphosis by tributyltin and copper. *Mar Environ Res* 51, 17-27.

Newell, A., Nuttall, P., Prasad, B., Veitayaki, J. (2017) Turning the Tide: the need for sustainable sea transport in the Pacific. *Mar Policy* 75, 249-259.

Newman, M., Wittenberg, A.T., Cheng, L., Compo, G.P., Smith, C.A. (2018) he extreme 2015/16 El Nino, in the context of historical climate variability and change. In: "Explaining extreme events of 2016 from a climate perspective". *Bulletin of the American Meteorological Society* 99, 21-26.

Nott, J., Walsh, K. (2015) *FactCheck: is global warming intensifying cyclones in the Pacific?* The Conversation Media Group Ltd.

Nunn, P.D. (1990) Recent coastline changes and their implications for future changes in the Cook Islands, Fiji, Kiribati, Solomon Islands, Tonga, Tuvalu, Vanuatu and Western Samoa, in: Pernetta, J.C., Hughes, P.J. (Eds.), *Implications of expected climate changes in the South Pacific Region: an overview.* UNEP Regional Seas Reports and Studies No. 128. UNEP Regional Seas Reports and Studies, Apia.

Nunn, P.D. (2009) Responding to the challenges of climate change in the Pacific Islands: management and technological imperatives. *Clim Res* 40, 211-231.

Nurse, L.A., McLean, R.F., Agard, J., Briguglio, L.P., Duvat-Magnan, V., Pelesikoti, N., Tompkins, E., A.Webb (2014) Small Islands, in: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., L.L. White (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 16133-11654.

Nuttal, P., Newell, A., Biman, P., Veitayaki, J., Holland, E. (2014) A review of sustainable sea-transport for Oceania: Providing context for renewable energy shipping for the Pacific. *Mar Policy* 43, 283-287.

Nuttall, P., Veitayaki, J. (2015) Oceania is vast, Canoe is centre, Village is anchor, Continent is margin, in: Smith, H.D., De Vivero, J.L.S., Agardy, T.S. (Eds.), *Routledge Handbook of Ocean Resources and Management.* Routledge, London, pp. 560-575.

Obura, D., Mangubhai, S. (2011) Coral mortality associated with thermal fluctuations in the Phoenix Islands, 2002-2005. *Coral Reefs* 30, 607-619.

Oliver, J.K., Berkelmans, R., Eakin, C.M. (2009) Coral bleaching in space and time, in: van Open, M.J.H., Lough, J.M. (Eds.), *Coral Bleaching: patterns, processes, causes and consequences.* Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 21-39.

Oliver, T.A., Palumbi, S.R. (2011) Many corals host thermally resistant symbionts in high-temperature habitat. *Coral Reefs* 30, 241-250.

Pandolfi, J.M., Connolly, S.R., Marshall, D.J., Cohen, A.L. (2011) Projecting Coral Reef Futures Under Global Warming and Ocean Acidification. *Science* 333, 418-422.

Paxton, C.W., Baria, M.V.B., Weis, V.M., Harii, S. (2016) Effect of elevated temperature on fecundity and reproductive timing in the coral Acropora digitifera. *Zygote* 24, 511-516.

Perry, C.T., Alvarez-Filip, L., Graham, N.A.J., Mumby, P.J., Wilson, S.K., Kench, P.S., Manzello, D.P., Morgan, K.M., Slangen, A.B.A., Thomson, D.P., Januchowski-Hartley, F., Smithers, S.G., Steneck, R.R., Carlton, R., Edinger, E.E., Enochs, I.C., Estrada-Saldívar, N., Haywood, M.D.E., Kolodziej, G., Murphy, G.N., Pérez-Cervantes, E., Suchley, A., Valentino, L., Boenish, R., Wilson, M., Macdonald, C. (*in press)* Loss of coral reef growth capacity to track sea-level rse under climate change. *Nature.*

Pichel, W.G., Churnside, J.H., Veenstra, T.S., Foley, D.G., Friedman, K.S., Brainard, R.E., Nicoll, J.B., Zheng, Q., Clemente-Colon, P. (2007) Marine debris collects within the North Pacific Subtropical Convergence Zone. *Mar Pollut Bull* 54, 1207-1211.

Pinto, R., Patrício, J., Neto, J.M., Salas, F., Marques, J.C. (2010) Assessing estuarine quality under the ecosystem services scope: Ecological and socioeconomic aspects. *Ecological Complexity* 7, 389-402.

Rasher, D.B., Engel, S., Bonito, V., Fraser, G.J., Montoya, J.P., Hay, M.E. (2012) Effects of herbivory, nutrients, and reef protection on algal proliferation and coral growth on a tropical reef. *Oecologia* 169, 187-198.

Redding, J.E., Myers-Miller, R.L., Baker, D.M., Fogel, M., Raymundo, L.J., Kim, K. (2013) Link between sewage-derived nitrogen pollution and coral disease severity in Guam. *Mar Pollut Bull* 73, 57-63.

Reenberg, A., Birch-Thomsen, T., Mertz, O., Fog, B., Christiansen, S. (2008) Adaptation of Human Coping Strategies in a Small Island Society in the SW Pacific-50 Years of Change in the Coupled Human-Environment System on Bellona, Solomon Islands. *Hum Ecol* 36, 807-819.

Reichert, J., Schellenberg, J., Schubert, P., Wilke, T. (2018) Responses of reef building corals to microplastic exposure. *Environmental Pollution.* 237, 955-960.

Reisinger, A., Kitching, R.L., Chiew, F., Hughes, L., Newton, P.C.D., Schuster, S.S., Tait, A., P. Whetton (2014) Australasia, in: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., L.L.White (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1371-1438.

Remling, E., Veitayaki, J. (2016) Community-based action in Fiji's Gau Island: a model for the Pacific? *International Journal of Climate Change Strategies and Management* 8, 375-398.

Restrepo, J.D., Park, E., Aquino, S., Latrubesse, E.M. (2016) Coral reefs chronically exposed to river sediment plumes in the southwestern Caribbean: Rosario Islands, Colombia. *Science of the Total Environment* 553, 316-329.

Reuters (2017) *Fiji to move more than 40 villages inland as seas rise,* The Sydney Morning Herald. Fairfax Media, Sydney.

Richardson, K., Haynes, D., Talouli, A., Donoghue, M. (2017) Marine pollution originating from purse seine and longline fishing vessel operations in the Western and Central Pacific Ocean, 2003-2015. *Ambio* 46, 190-200.

Riegl, B., Glynn, P.W., Wieters, E., Purkis, S., d'Angelo, C., Wiedenmann, J. (2015) Water column productivity and temperature predict coral reef regeneration across the Indo-Pacific. *Sci Rep-Uk* 5, 8273.

Rodgers, K.u.S., Cox, E.F. (2003) The effects of trampling on Hawaiian corals along a gradient of human use. *Biol Conserv* 112, 383-389.

Rogers, C.S. (1990) Responses of Coral Reefs and Reef Organisms to Sedimentation. *Mar Ecol Prog Ser* 62, 185-202.

Rotmann, S. (2001) *Coral bleaching event on Lihir Island, February-March, 2001*.

Ruiz-Moreno, D., Willis, B.L., Page, A.C., Weil, E., Croquer, A., Vargas-Angel, B., Jordan-Garza, A.G., Jordan-Dahlgren, E., Raymundo, L., Harvell, C.D. (2012) Global coral disease prevalence associated with sea temperature anomalies and local factors. *Dis Aquat Organ* 100, 249-261.

Sajjad, F., Noreen, U., Zaman, K. (2014) Climate change and air pollution jointly creating nightmare for tourism industry. *Environmental Science and Pollution Research* 21, 12403-12418.

Salvat, B., Allemand, D.S.r., 7-12. (2009) *Scientific Review: Acidification and coral reefs*. CRIOBE, CNRS, Centre Scientifique de Monaco, New Caledonia, p. 32.

Samuelu, J.A.-L., Sapatu, M. (2009) Samoa, in: Morris, C.W. (Ed.), *South-West Pacific Status of coral reefs report, 2007.* CRISP, Suva.

Sandin, S.A., Smith, J.E., DeMartini, E.E., Dinsdale, E.A., Donner, S.D., Friedlander, A.M., Konotchick, T., Malay, M., Maragos, J.E., Obura, D., Pantos, O., Paulay, G., Richie, M., Rohwer, F., Schroeder, R.E., Walsh, S., Jackson, J.B.C., Knowlton, N., Sala, E. (2008) Baselines and Degradation of Coral Reefs in the Northern Line Islands. *Plos One 3*.

Sato, Y., Civiello, M., Bell, S.C., Willis, B.L., Bourne, D.G. (2016) Integrated approach to understanding the onset and pathogenesis of black band disease in corals. *Environ Microbiol* 18, 752-765.

Shantz, A.A., Burkepile, D.E., 2014. Context-dependent effects of nutrient loading on the coral-algal mutualism. *Ecology* 95, 1995-2005.

Sheridan, C., Grosjean, P., Leblud, J., Palmer, C.V., Kushmaro, A., Eeckhaut, I. (2014) Sedimentation rapidly induces an immune response and depletes energy stores in a hard coral. *Coral Reefs* 33, 1067-1076.

Singh, S. (2018) *Contribution of Symbiodinium clades to Pocillopora's response to thermal stress in Fiji and French Polynesia,* MSC Thesis. The University of the South Pacific, Suva.

Singh, S., Aalbersberg, W.G.L., Morrison, R.J. (2009) Nutrient Pollution in Laucala Bay, Fiji Islands. *Water Air and Soil Pollution* 204, 363-372.

Smith, L.D., Negri, A.P., Philipp, E., Webster, N.S., Heyward, A.J. (2003) The effects of antifoulant-paint-contaminated sediments on coral recruits and branchlets. *Mar Biol* 143, 651-657.

South, G.R., Skelton, P.A., Veitayaki, J., Resture, A., Carpenter, C., Pratt, C., Lawedrau, A. (2004) The Global International Waters Assessment for the Pacific Islands: Aspects of transboundary, water shortage, and coastal fisheries issues. *Ambio* 33, 98-106.

Sparks, K.M., Foo, S.A., Uthicke, S., Byrne, M., Lamare, M. (2017) Paternal identity influences response of Acanthaster planci embryos to ocean acidification and warming. *Coral Reefs* 36, 325-338.

Stuart-Smith, R.D., Edgar, G.J., Barrett, N.S., Kininmonth, S.J., Bates, A.E. (2015) Thermal biases and vulnerability to warming in the world's marine fauna. *Nature* 528, 88-92.

Stuhldreier, I., Bastian, P., Schonig, E., Wild, C. (2015) Effects of simulated eutrophication and overfishing on algae and invertebrate settlement in a coral reef of Koh Phangan, Gulf of Thailand. *Mar Pollut Bull* 92, 35-44.

Sulu, R. (2004) *Status of coral reefs in the Southwest Pacific: 2004*. IPS Publications, University of the South Pacific, Suva, p. 252.

Sykes, H., Morris, C.W. (2009) Status of coral reefs in the Fiji Islands, 2007 in: Morris, C.W. (Ed.), *South-West Pacific Status of coral reefs report, 2007*. CRISP, Suva, pp. 1-52.

Szmant, A.M., Gassman, N.J. (1990) The effects of prolonged ?bleaching? on the tissue biomass and reproduction of the reef coral *Montastrea annularis*. *Coral Reefs* 8, 217-224.

Terry, J.P. (2007) *Tropical Cyclones: Climatology and Impacts in the South Pacific*. Springer, New York.

The Locally-Managed Marine Area (LMMA) Network (2014) *Traditional Practices, Suva*.

Thomas, L., Palumbi, S.R. (2017) The genomics of recovery from coral bleaching. *Proc Biol Sci* 284.

Tilmant, J.T. (1987) Impacts of Recreational Activities on Coral Reefs, in: Salvat, B. (Ed.), *Human Impacts on Coral Reefs: Facts and Recommendations*. Antenne Museum E.P.H.E., French Polynesia.

United Nations Environment Programme (2017) *Towards a Pollution-Free Planet Background Report.* United Nations Environment Programme, Nairobi, Kenya.

Uthicke, S., Logan, M., Liddy, M., Francis, D., Hardy, N., Lamare, M. (2015) Climate change as an unexpected co-factor promoting coral eating seastar (Acanthaster planci) outbreaks. *Sci Rep-Uk* 5.

Valmonte-Santos, R., Rosegrant, M.W., Dey, M.M. (2016) Fisheries sector under climate change in the coral triangle countries of Pacific Islands: Current status and policy issues. *Mar Policy* 67, 148-155.

van Dam, J., W., Negri, A.P., Uthicke, S., Mueller, J.F., 2011. Chemical pollution on coral reefs: exposure and ecological effects, in: Sanchez-Bayo, F., van den Brink, P.J., Mann, R.M. (Eds.), *Ecological impact of toxic chemicals.* Bentham Science Publishers Ltd, pp. 187-211.

van Hooidonk, R., Maynard, J., Tamelander, J., Gove, J., Ahmadia, G., Raymundo, L., Williams, G., Heron, S.F., Planes, S. (2016) Local-scale projections of coral reef futures and implications of the Paris Agreement. *Sci Rep-Uk* 6.

van Hooidonk, R., Maynard, J.A., Manzello, D., Planes, S. (2014) Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. *Global Change Biol* 20, 103-112.

van Oppen, M.J.H., Oliver, J.K., Putnam, H.M., Gates, R.D. (2015) Building coral reef resilience through assisted evolution. *P Natl Acad Sci USA* 112, 2307-2313.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K. (2011) The representative concentration pathways: an overview. *Climatic Change* 109, 5-31.

van Woesik, R., Golbuu, Y., Roff, G. (2015) Keep up or drown: adjustment of western Pacific coral reefs to sea-level rise in the 21st century. *Roy Soc Open Sci* 2.

Vanhatalo, J., Hosack, G.R., Sweatman, H. (2017) Spatiotemporal modelling of crown-of-thorns starfish outbreaks on the Great Barrier Reef to inform control strategies. *J Appl Ecol* 54, 188-197.

Veitayaki, J. (1995) *Fisheries development in Fiji: The quest for sustainability*. Institute of Pacific Studies and the Ocean Resources Management Programme, Suva.

Veitayaki, J. (2010) Pacific Islands drowning in their waste: waste management issues that threaten sustainability, *Proceedings of International Seminar on Islands and Oceans 2010* Ocean Policy Research Foundation, Tokyo.

Veitayaki, J. (2014) Vakarau ni se Siga Toka (prepare while there is time): Lomani Gau response to Climate Change, in: Qalo, R. (Ed.), *Pacific Voices Local Government and Climate Change.* PACE-SD and Commonwealth Local Government Pacific Forum, Suva, pp. 85-101.

Veitayaki, J. (*in press) Ocean in Us: security of life in the world's largest ocean*. University of Hawaii Press, Hawaii.

Veitayaki, J., Holland, E. (*in press)* Lessons from Lomani Gau Project, Fiji: a local community in the world's largest ocean, in: Crook, T., Rudiak-Gould, P. (Eds.), *Appropriating Climate Change: Pacific Reception of a Scientific Prophecy*.

Veitayaki, J., Ledua, E. (2016) Policy options for coastal and tuna fisheries in the Pacific Islands: sustaining resources on the same side of the same coin, in: Fache, E., Pauwels, S. (Eds.), *Fisheries in the Pacific Islands the challenges of governance and sustainability.* Pacific-Credo Publications, Marseille, France, pp. 255-287.

Veitayaki, J., South, G.R. (1997) Coastal fisheries in the tropical South Pacific: A question of sustainability, in: Sidik, B.J., Yussof, F.M., Zaki, M.S.M., Petr, T. (Eds.), *Fisheries and the environment* *beyond 2000.* Universiti Putra Malaysia, Serdang, Malaysia.

Veitayaki, J., Waqalevu, V., Varea, R., Rollings, N. (2017) Mangrove in the Small Island Developing States in the Pacific: An Overview of a highly important and seriously threatened species, in: Das Gupta, R., Shaw, R. (Eds.), *Participatory Mangrove Management in a Changing Climate Perspectives from the Asia-Pacific.* Springer, Tokyo, pp. 303-328.

Voss, J.D., Richardson, L.L. (2006) Nutrient enrichment enhances black band disease progression in corals. *Coral Reefs* 25, 569-576.

Walter, R.K., Hamilton, R.J. (2014) A cultural landscape approach to community-based conservation in Solomon Islands. *Ecol Soc* 19.

Waycott, M., McKenzie, L., Mellors, J., Ellison, J., Sheaves, M., Collier, C. *et al*. (2011) Vulnerability of mangrove, seagrass and intertidal sand and mud flat habitats in the tropical Pacific to climate change, in: Bell, J.D., Johnson, J.E., Hobday, A.J. (Eds.), *Vulnerability of tropical Pacific fisheries and aquaculture to climate change.* Secretariat of the Pacific Community, Noumea, New Caledonia.

Wicks, L.C., Gardner, J.P.A., Davy, S.K. (2012) Host tolerance, not symbiont tolerance, determines the distribution of coral species in relation to their environment at a Central Pacific atoll. *Coral Reefs* 31, 389-398.

Wiedenmann, J., D'Angelo, C., Smith, E.G., Hunt, A.N., Legiret, F.E., Postle, A.D., Achterberg, E.P. (2013) Nutrient enrichment can increase the susceptibility of reef corals to bleaching. *Nat Clim Change* 3, 160-164.

Wild, C., Hoegh-Guldberg, O., Naumann, M.S., Colombo-Pallotta, M.F., Ateweberhan, M., Fitt, W.K., Iglesias-Prieto, R., Palmer, C., Bythell, J.C., Ortiz, J.C., Loya, Y., van Woesik, R. (2011) Climate change impedes scleractinian corals as primary reef ecosystem engineers. *Mar Freshwater Res* 62, 205-215.

Wilkinson, C. (2004) Status of Coral Reefs of the World: 2004. *Global Coral Reef Monitoring Network and Australian Institute of Marine Science*, Perth, Australia.

Wilkinson, C. (2008) *Status of coral reefs of the world: 2008.* Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia, p. 296.

Williams, I.D., Baum, J.K., Heenan, A., Hanson, K.M., Nadon, M.O., Brainard, R.E. (2015) Human, Oceanographic and Habitat Drivers of Central and Western Pacific Coral Reef Fish Assemblages. *Plos One* 10.

Wolanski, E., Andutta, F., Deleersnijder, E., Li, Y., Thomas, C.J. (2017) The Gulf of Carpentaria heated Torres Strait and the Northern Great Barrier Reef during the 2016 mass coral bleaching event. *Estuar Coast Shelf S* 194, 172-181.

Woodroffe, C.D., Brooke, B.P., Linklater, M., Kennedy, D.M., Jones, B.G., Buchanan, C., Mleczko, R., Hua, Q.A., Zhao, J.X. (2010) Response of coral reefs to climate change: Expansion and demise of the southernmost Pacific coral reef. *Geophys Res Lett* 37, L15602.

Woodroffe, C.D., Webster, J.M. (2014) Coral reefs and sea-level change. *Mar Geol* 352, 248-267.

Wooldridge, S.A., Heron, S.F., Brodie, J.E., Done, T.J., Masiri, I., Hinrichs, S. (2017) Excess seawater nutrients, enlarged algal symbiont densities and bleaching sensitive reef locations: 2. A regional-scale predictive model for the Great Barrier Reef, Australia. *Mar Pollut Bull* 114, 343-354.

Zann, L.P. (1994) The status of coral reefs in South Western Pacific Islands. *Mar Pollut Bull* 29, 52-61.

Zeller, D., Harper, S., Zylich, K., Pauly, D. (2015) Synthesis of underreported small-scale fisheries catch in Pacific island waters. *Coral Reefs* 34, 25-39.