Ecosystem-based adaptation in marine ecosystems of tropical Oceania in response to climate change

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Tropical Oceania, including Melanesia, Polynesia, Micronesia and northern Australia, is one of the most biodiverse regions of the world. Climate change impacts have already occurred in the region and will become one of the greatest threats to biodiversity and people. Climate projections indicate that sea levels will rise in many places but not uniformly. Islands will warm and annual rainfall will increase and exhibit strong decadal variations. Increases in global atmospheric CO_2 concentration are causing ocean acidification, compromising the ability of organisms such as corals to maintain their calcium carbonate skeletons. We discuss these climate threats and their implications for the biodiversity of several ecosystems (coral reefs, seagrass and mangroves) in the region. We highlight current adaptation approaches designed to address these threats, including efforts to integrate ecosystem and community-based approaches. Finally, we identify guiding principles for developing effective ecosystem-based adaptation strategies. Despite broad differences in governance and social systems within the region, particularly between Australia and the rest of the Pacific, threats and planning objectives are similar. Ensuring community awareness and participation are essential everywhere. The science underpinning ecosystem-based adaptation strategies is in its infancy but there is great opportunity for communicating approaches and lessons learnt between developing and developed nations in tropical Oceania.

INTRODUCTION

TROPICAL Oceania is a region in the central Pacific Ocean that includes Melanesia, Polynesia, Micronesia and northern Australia. It is ecologically, culturally and socially diverse (Kingsford *et al.* 2009) and includes the majority of the world's small "island" countries and territories, ranging from low-lying coral atolls to high volcanic islands. A good example of the diversity of the region is the country of Papua New Guinea, with a population of ~6.7 million, over 850 indigenous languages, and harbouring 5-9% of the world's total biodiversity (Mittermeier *et al.* 1998; Myers *et al.* 2000). Tropical Oceania is additionally characterized by high levels of rural poverty and high dependence on marine and coastal resources for livelihoods and food security (Bell *et al.* 2009; Hoegh-Guldberg *et al.* 2009).

Marine and coastal environments across tropical Oceania are facing increasing threats due to burgeoning human populations and economic development. For example, humans have already caused the extinction of >1200 bird species on oceanic islands in the Pacific (Blackburn *et al.* 2004). Impacts of anthropogenic climate change are evident (Hoegh-Guldberg *et al.* 2009; Kingsford *et al.* 2009), and it is likely to become one of the greatest threats to biodiversity and human communities (IPCC 2007). In addition to climate change, coastal ecosystems in the region face human impacts such as pollution, sedimentation, overfishing, and coastal development (Burke *et al.* 2011). With the exception of Australia, tropical Oceania nations are among the most vulnerable to climate change and environmental stress given poverty, growing populations, poorly developed infrastructure, and few resources to cope with climatic perturbations (Mimura 1999; Diffenbaugh *et al.* 2007). Therefore, to successfully protect the human and biological communities, conservation planning efforts will need to address climate change, poverty alleviation and other human impacts.

The aim of this paper is threefold. First, we summarize the threat of climate change for tropical Oceania (Table 1), and the impacts on coastal and marine ecosystems (coral reefs, seagrass and mangroves). Then we discuss adaptation approaches designed to reduce these threats and the integration of ecosystem-based adaptation into these approaches to support biodiversity and human communities in the region. Finally, we develop some guiding principles around ecosystem-based adaptation by

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Table 1. Climate change variables and their impacts and consequences for tropical Oceania.

Climate change variables	Local impacts
Climate drivers	• The ocean and atmosphere determine the climate of islands, any small islands in the Pacific have quite different atmospheric circulation patterns compared to larger neighbouring landmasses. The climate of small islands in the Pacific is also affected by trade winds, paired Hadley cells and Walker circulation, seasonally varying convergence zones such as the South Pacific Convergence Zone (SPCZ), semi-permanent sub-tropcial high-pressure belts, and zonal westerlies to the south (Mimura *et al.* 2007). Interannual climate variability is strongly nfluenced by El Niño-Southern Oscillation (ENSO), while the Interdecadal Pacific Oscillation (IPO) is the dominant mode of variability over decadal timescales. Factors affecting local scale climate variability include differences between windward and leeward sides of an island, or high montane versus low islands.
Atmospheric and ocean warming	• Climate models indicate warming across the region by 2100,~2–4°C for Australia and New Zealand and ~1–3°C for the South Pacific (Christensen *et al.* 2007). Many models suggest stronger warming in the central equatorial Pacific and weaker warming to the south (Christensen *et al.* 2007). Recent studies suggest annual and seasonal ocean surface and air temperatures have increased by 0.6–1.0°C since 1910 throughout much of the South Pacific, south-west of the SPCZ (Mimura *et al.* 2007). Trends are not linear — decadel increases of 0.3–0.5°C in annual temperatures have been observed only since the 1970s, preceded by cooling after the 1940s to the north-east of the SPCZ (Folland *et al.* 2003). The upper Pacific Ocean has been warming and freshening with the warming footprint associated with the thick mode waters of the Antarctic Circumpolar Current (IPCC 2007), and observations of changes in temperature have been linked to indices such as the Pacific Decadal Oscillation, Southern Annular Mode and ENSO, making it difficult to attribute change to a natural or climate signal. New models show that the rate of warming, that is the median rate of change since 1960, has been three times greater on land (0.22°C) than the oceans (0.07°C), however, the velocity of climate change (geographic shifts of temperature isoclines over time) and shifts in the seasonal timing of temperature within the global ocean are comparable to terrestrial systems, despite slower oceanic warming (Burrows *et al.* 2011). Oceanic warming patterns have deviated regionally within Oceania which may in turn drive more complex shifts in biodiversity rather than linear poleward migration and phenological shifts in annual lifecycles.
Sea-level rise	• Sea-level rise (SLR) is difficult to quantify for Oceania due to the short temporal extent of time-series data for the region and large observed variations in sea-level rise in due to ocean circulation changes associated with ENSO events. TOPEX/Poseidon satellite altimeter data shows that between 1993 and 2003, a reduction in sea level of ~3mm yr^{1} occurred in Queensland, Australia. Longer-term *in situ* data from 1955–2003 shows a rise of 0.4 mm yr^{-1} for Queensland and Northern Territories, demonstrating the inherent problems assessing changes in this region. From 1993 to 2001, data show large rates of sea-level rise over the western Pacific and sea-level falls in the eastern Pacific (Church *et al.* 2006). Few time-series of SLR that date back to 1950 or earlier exist for the Pacific Islands, however, there is close agreement from data recorded at the Tuvalu atolls, which shows a mean rise in sea level of 2.0 ± 1.7 mm yr- (Church et al. 2006). Analyses of long-term sea-level records (>25 years) around Pacific show an average mean relative sea-level rise of 0.77 mm/yr (Mitchell et al. 2001); longer-term records (>50 yrs) suggest an average rate of SLR of 1.6 mm/yr, (Bindoff *et al.* 2007). The maximum rate of SLR in the central and eastern Pacific was between 2.0–2.5 mm/yr, peaking at over 3 mm/yr (Church *et al.* 2004). SLR will not uniformly affect islands of Oceania given the diversity of tectonic processes often within a relatively small geographic area (e.g., Nunn and Peltier 2001).
Ocean acidification (OA)	• Global atmospheric CO_2 concentration has increased from about 280 parts per million (ppm) in 1880 to 387 ppm in 2009 (ESRL/NOAA 2009), due primarily to fossil fuel emissions. Half of the CO_2 released by human activities has remained in the atmospheric; 30% has been absorbed into the oceans (Sabine *et al.* 2004). Surface ocean pH is 0.1 unit lower than pre-industrial values and pH is projected to decrease another 0.3–0.4 units by 2100 (i.e., a 100–150% increase in concentration of hydrogen ions; Orr *et al.* 2005). Increased atmospheric CO_2 uptake by the oceans alters seawater chemistry changing pH, biogeochemical cycling and chemical speciation, resulting in under-saturation states and dissolution of calcium carbonate (aragonite and cacite). Shoaling of the aragonite saturation horizon has been observed in all ocean basins, with a change between 40–100m for the Pacific north of 20°N (Sabine *et al.* 2002). At present, there are no quantitative estimates for the central and south Pacific region. Carbonate ion concentration is projected to decrease; when water is undersaturated with respect to calcium carbonate, marine organisms can no longer form their shells/skeletons (Raven *et al.* 2005).

Table 1. *continued.*

Climate change variables	Local impacts
	OA has been identified as a major climate-related threat to low latitude coastal marine systems, including coral reefs and their associated communities (Kleypas *et al.* 1999; Hughes *et al.* 2003; Munday *et al.* 2009a), and its impact is predicted to worsen during the 21st century (Guinotte *et al.* 2003). Lower temperatures make CO_2 more soluble creating a likely gradient of OA across tropical Oceania. Over the next century, the extent and rates of change may be unprecedented in millions of years (Caldeira and Wickett 2003; Pelejero *et al.* 2010).
Changes in precipitation	• A 3% increase in annual precipitation is projected by 2100 over the southern Pacific when averaged across a number of models (Christensen *et al.* 2007). Individual model projections for the southern Pacific range from -4+11% and over half the models show increases between 3 and 6% (Christensen *et al.* 2007). The tendency for precipitation increase in the Pacific is strongest in the region of the ICTZ (Christensen *et al.* 2007).
Changes in storms/cyclones	• ENSO fluctuations have a strong impact on patterns of tropical cyclone occurrence in the southern Pacific, and uncertainty regarding future ENSO behaviour contributes to uncertainty with respect to tropical cyclone behaviour (Walsh 2004). Recent studies of tropical cyclone behaviour in the Australian region suggest there is no clear picture regarding regional changes in frequency and movement, but increases in intensity are indicated (Christensen *et al.* 2007). During an El Niño event, the incidence of tropical storms typically decreases in the far-western Pacific and the Australian regions, but increases in the central and eastern Pacific, and vice versa (Mimura *et al.* 2007). Projections suggest that in the tropical South Pacific, small islands to the east of the dateline are likely to receive a higher number of tropical storms during an El Niño event compared with a La Niña event and vice versa (Brazdil *et al.* 2002). Webster *et al.* (2005) found more than a doubling in the number of category 4 and 5 storms in the South-West Pacific from the period 1975–1989 to the period 1990–2004.

comparing examples of its application in different parts of tropical Oceania. We hope these principles will help guide future implementation of ecosystem-based adaptation.

Vulnerability of coastal and marine biodiversity to climate change

Tropical coastal and marine ecosystems such as mangrove forests, coral reefs, and seagrasses are particularly vulnerable to climate change impacts including atmospheric and/or ocean warming, sea-level rise, changes in rainfall activity patterns, changes in storms and cyclones, and increases in ocean acidification. We describe how tropical ecosystems are currently, or projected to be, affected by such changes. Other coastal and marine habitats in the region are impacted by climate change (e.g., carbonate sediments, calcareous algal reefs), but fall outside the scope of this review.

Mangrove forests

Increasing atmospheric temperatures affect mangrove species' distribution and composition, alter growth rate and metabolism, and possibly change mangrove phenology, including timing of flowering and fruiting (Field 1995; Ellison 2000). Mangrove productivity is determined by two temperature-sensitive processes: photosynthetic carbon gain and respiration (Lovelock *et al.* 2009). Photosynthesis in tropical mangroves is limited by warm midday leaf temperatures (Cheeseman *et al.* 1997; Ellison 2000; Lovelock *et al.* 2009). By contrast, photosynthesis and reproduction are limited by cooler temperatures at high latitudes (Duke 1990). Expansion of mangrove species to high latitudes may be expected with warming and increasing productivity, particularly near southern distribution limits (Ellison 2000; Lovelock *et al.* 2009).

Sea-level rise (SLR) is the greatest climate change threat facing mangrove (Field 1995; McLeod and Salm 2008). Geological records indicate that previous sea-level fluctuations have created survival crises and opportunities for mangrove communities (Field 1995; McLeod and Salm 2008). SLR may kill mangroves due to erosion and inundation (Ellison 2000), but mangroves can adapt if SLR occurs slowly (Ellison and Stoddart 1991). Mangroves may either migrate landward as new habitat becomes available through erosion and inundation of coastal areas, or increase growth upward where sediment accretion rates compensate for the rate of SLR (Wolanski and Chappell 1996; Gilman *et al.* 2008). Often, migration is not possible due to natural (e.g., steep slopes and cliffs) or artificial barriers (e.g., sea walls, infrastructure, and roads). Reductions in mangrove area or local extinctions may occur if mangroves are not able to keep pace with SLR (Lovelock 2011; Trail 2011). Mangroves most at risk from SLR have low sedimentary influx or limited capacity for landward migration (e.g., on low-lying carbonate islands or near settlements) (Ellison 2000; McLeod *et al.* 2008). SLR is likely to result in major losses of mangroves in tropical

Oceania, with predictions that by 2100, Papua New Guinea will lose 34% and Solomon Islands 68% of their mangroves (McLeod *et al.* 2010a). An earlier study estimated that nearly 13% of the total mangrove area (~524,000 ha) in 16 Pacific Islands countries and territories would be lost (Gilman *et al.* 2006), based on IPCC's upper estimate of global SLR (0.88 m by 2100; Church *et al.* 2001).

Mangroves are also sensitive to changes in rainfall intensity, frequency of dry periods, increased inundation and alteration of the water table (Field 1995; Ellison 2000). Decreasing rainfall delivers less water to groundwater and increases salinity (Gilman *et al.* 2008). Declining groundwater and increasing salinity affects mangrove productivity, altering community composition toward dominance by salt-tolerant species, and ultimately reducing the diversity of mangrove ecosystems (Field 1995; Gilman *et al.* 2008). Where precipitation increases, mangrove growth rates and productivity might increase, leading to invasion of salt marsh or wetland vegetation (Field 1995; Duke *et al.* 1998; Gilman *et al.* 2008). The reverse is true during periods of drought, whereby the proportion of salt pans within estuaries may expand as mangroves contract (Bucher and Saenger 1994).

Increases in intensity and/or frequency of storms may result in mangrove defoliation and tree mortality (Gilman *et al.* 2008). The associated storm surge, strong currents, and waves that accompany storms can increase mechanical damage and bioerosion of mangroves (Woodroffe and Grime 1999; Cahoon *et al.* 2003). Impacts of storm damage, including soil erosion, soil deposition, peat collapse, and soil compression (Cahoon *et al.* 2003), may alter mangrove sediment elevation and hydrological regimes. Such changes in elevation and hydrology can limit recovery of mangroves (i.e., seedling recruitment), following storm events (Cahoon *et al.* 2003; Gilman *et al.* 2008).

Mangroves are not likely to bevulnerable to ocean acidification, given the majority of their branches and leaves are permanently above high tide levels. However, productivity may be enhanced by increasing atmospheric CO_2 levels but any potential gain is dependent on interactions with other factors (Lovelock *et al.* 2009; although see Ball *et al.* 1997). For example, growth rates of *Rhizophora apiculata* and *R. stylosa*, treated with elevated CO_2, did not increase when limited by salinity, but increased with humidity limitation (Ball *et al.* 1997).

Seagrass

For seagrass communities, warming ocean temperatures are likely to result in distribution shifts, changes in patterns of sexual reproduction, altered growth rates, metabolism, and changes in their carbon balance (Short and Neckles 1999). The macro- and micro-algal epiphytes on seagrasses, and their grazer communities, are an important part of seagrass ecosystems, contributing to productivity and nutrient cycling (Bologna and Heck 1999; Moncrieff and Sullivan 2001). Seagrass ecosystems are structured by nutrient loads as well as temperature, and alteration of these factors shifts balance among different components of the ecosystem (Zaldivar et al 2009). Elevated sea temperature could potentially increase the growth of competitive algae and epiphytes, which can overgrow seagrass and reduce the available sunlight needed for survival (Björk *et al.* 2008). However, the presence of grazers, such as molluscs and fish that may be vulnerable to exploitation, can control epiphyte growth and may buffer environmental stresses (Moksnes et al 2008; Blake and Duffy 2010). Due to different thermal thresholds of seagrass species, increased temperatures are likely to favour species which prefer warmer temperatures or those with higher thermal stress tolerances (Björk *et al.* 2008). For example, warm temperatures have caused large-scale diebacks of *Amphibolis antarctica* and *Zostera* spp. in southern Australia (Seddon *et al.* 2000).

Seagrass are also vulnerable to SLR, limiting growth due to an increase in water column depth, changes in tidal variation, altered currents, changes in turbidity and decreased light availability (Short and Neckles 1999). Seagrass may colonize landward, as saltwater intrusion occurs in estuaries and rivers (Short and Neckles 1999), but will be threatened where this cannot occur or where altered currents change the deposition of the sandy substrate for growth. Seagrass on isolated submerged banks may also die-off, as water depth increases and migration is impossible. Deep water seagrass beds with low-levels light will be particularly vulnerable.

Increases in rainfall and/or storms and resultant land-based discharge of sediment can smother seagrass beds (Björk *et al.* 2008) and prolonged turbidity can shade-out and cause large scale die-off of seagrass (MRAG 2010). For example, in 1992 in Hervey Bay, Australia, two major floods and a cyclone killed 1000 m^2 of seagrass beds, over three weeks (Preen *et al.* 1995). In deep waters or light-limited systems, any increased turbidity may exceed photosynthetic capabilities of seagrass, affecting their survival.

Increases in the levels of dissolved CO_2 in seawater may result in increased photosynthesis and growth of seagrass (Björk *et al.* 2008). However, experimental evidence for increasing seagrass productivity in response to elevated CO_2 levels is inconclusive. Under CO_2 enrichment, a short-term experiment demonstrated faster growth rates of *Zostera marina* (Thom 1996). In contrast, a long-term experiment showed there was no effect on its productivity (biomass-specific growth rates), but it did significantly increase reproductive output, below-ground biomass and vegetative proliferation of new shoots in light-repleted treatments-suggesting increasing atmospheric and ocean surface CO_2 result in increaeses in area-specific productivity of seagrass meadows (Palacios and Zimmerman 2007). Increases in CO_2 may also stimulate epiphytic algal growth, shading seagrass leaves and slowing growth. Further, increases in photosynthesis and growth are likely to be counteracted by SLR, reduced light availability, and decreased survival (Short and Neckles 1999).

Coral Reefs

Coral reef are particularly vulnerable to increasing sea temperatures as they can induce bleaching events. Bleaching can be triggered by small increases in sea temperature of 1-3°C, above average annual temperatures (Hoegh-Guldberg 1999). When corals bleach, polyps expel their symbiotic algae that provide energy and nutrients (Glynn 1991; Weis 2008). If bleaching is prolonged or severe, corals may die. Over the past three decades, there has been climate-induced mass bleaching in most coral regions of the world (Baker *et al.* 2008). Coral reefs across Micronesia and western Polynesia are particularly vulnerable to bleaching (MRAG 2010). The frequency and magnitude of devastating bleaching events has increased since the late 1970s, largely associated with ENSO events (Coles 2008). Over the past decade, coral bleaching has regularly occurred in Polynesia (Tahiti, Cook Islands, and Tonga), Micronesia (Palau), parts of Melanesia (Papua New Guinea and the Solomon Islands), and the Great Barrier Reef in Australia (Berkelmans *et al.* 2004; Wilkinson 2008; Anthony and Marshall 2009).

Climate projections indicate that thermal thresholds for corals will be exceeded across the Pacific more frequently than reefs can tolerate by around 2030 (Nicholls *et al.* 2007; Barnett 2008). The resultant bleaching and mortality, which in the past has been confined to ENSO events, could occur annually (Donner *et al.* 2009). Coarse-scale modelling for the Pacific region indicates that by the second half of the century, much of the equatorial regions of Micronesia and Polynesia and around the Solomon Islands will be beyond the thermal tolerance of corals (Guinotte *et al.* 2003; McLeod *et al.* 2010b). Such changes would seriously affect biodiversity and coastal communities that rely on reefs for their food and livelihoods, reducing income from reef-related tourism and fisheries, and reducing coastal protection provided by reefs.

Changes in rainfall might also affect coral reefs through increased frequency and severity of flooding events. The reduced salinity, increased terrestrial sediment and enriched nutrients in river runoff, particularly from cleared and cultivated catchments, may directly and indirectly impact corals and other reef organisms. For example, sticky flocs, which form when sediments aggregate together in nutrient-rich waters, smother coral recruits and juvenile colonies adjacent to land, compromising recovery from other disturbance (Fabricius 2005).

Increases in storm frequency and intensity are likely to affect coral reefs in tropical Oceania. Extreme waves and currents associated with cyclones can break corals, cause sediment plumes, and remove the entire coral reef framework in some locations (Fabricius and De'ath 2008). A recent coral reef assessment in the southwest Pacific indicated that cyclones were one of the greatest threats to reefs, with cyclone damage reported on reefs in New Caledonia, Samoa, Solomon Islands, and Vanuatu. For example, Cyclone Erica in 2003 destroyed 10–80% of live coral cover on New Caledonia and Cyclone Heta damaged 13% of reefs in Samoa (Wilkinson 2008). Major damage was caused to coral reefs on the Great Barrier Reef by Tropical Cyclones Larry and Yasi in 2011, severely damaging 300 km of the Great Barrier Reef (GBRMPA 2011). If cyclone intensity increases by half a category, a 50-60% greater cyclone-related loss in coral cover may result, compared to present-day rates, assuming full recovery between events (Fabricius and De'ath 2008). Increases in disturbance frequency and intensity would increase the proportion of reefs with low coral cover and structural complexity (Fabricius and De'ath 2008).

SLR may not directly affect most reefs, because its projected rate and magnitude are within the potential accretion rates of most corals (Smith and Buddemeier 1992). However, reefs on rapidly subsiding margins may be compromised if vertical accretion cannot keep pace with SLR coupled with subsidence rates. This phenomenon has occurred in the geologic past as reefs that formed during low sea level stands "drowned" following rapid SLR associated with major deglaciations (Webster *et al.* 2004a,b). The Gulf of Carpentaria, northern Australia, contains a newly reported coral reef province (Harris *et al.*, 2004; 2008). These reefs are submerged relict reefs, formed when sea levels were much lower and the climate cooler, but growth rates were unable to keep up with contemporary rising sea levels. The Gulf of Carpentaria may act as a climate change refuge, providing a source of propagules for coral species dispersing eastward and southward towards the Great Barrier Reef to fill niches potentially vacated by coral species less tolerant of warmer temperatures (Harris et al 2004; 2008). SLR may additionally adversely affect reefs due to increased sedimentation from shoreline erosion.

Reduction in calcium carbonate shell formation and impairment of physiological functioning in response to lower seawater pH levels reduce survival in biogenic reef forming species such as corals and associated fauna (Kleypas *et al.* 1999; Hoegh-Guldberg *et al.* 2007; Munday *et al.* 2010). Undersaturation may act in synergy with changing temperatures over similar spatio-temporal scales, producing ecological "winners and losers" (Doney *et al.* 2009). Ocean acidification may widely disrupt marine ecosystems and services they provide, including fisheries (Cooley *et al.* 2009). Increasing ocean acidity also lowers the thermal bleaching threshold of corals (Anthony *et al.* 2008). Consequences on reef systems are twofold. First, reductions in carbonate accumulation and growth will weaken reef structure (Guinotte *et al.* 2003; Kinch *et al.* 2010), and also affect the protection, shelter, settlement substrate, nursery and/or feeding grounds of reef species (Leadley *et al.* 2010). Second, the consequences of these impacts will gradually reduce the ability of coral reefs to maintain their structure against forces that cause breakage and erosion, compounding "drowning" of reefs by rapid SLR (Pulglise and Kelty 2007).

A recent reduction in coral growth rates has raised concerns that ocean acidification is already impacting corals (Bak *et al.* 2009). Analysis of cores from 328 massive corals on 69 reefs on the Great Barrier Reef showed 14.2% decline in calcification and 13.3% decline in linear growth since 1990, attributed to a combination of stressors such as increasing temperature and declining aragonite saturation state of seawater (De'ath *et al.* 2009). Ocean acidification can also affect the physiology of water-breathing animals with long-term effects on metabolic functions (Portner 2004). Such processes are expected to affect long-term growth and reproduction, harmful at population and species levels. Experimental studies using coral reef fish from eastern Australian have found potentially profound effects on chemosensory cue detection and predator-avoidance behaviour on settlement-stage larvae (Dixson *et al.* 2010; Munday *et al.* 2009 a,b). Ocean acidification could also reduce recruitment success of reef fish and threaten population sustainability (Munday *et al.* 2010).

Planning for anthropogenic climate change

The vulnerability of a species to anthropogenic climate change is determined by its exposure (i.e. region of high climatic change), its sensitivity to climate change (defined by intrinsic biological traits), and its adaptive capacity (see Fig. 1; IPCC 2001; Allen Consulting Group 2005). For ecosystems, vulnerability is determined by the complex interactions and synergies between the component species, proximate ecological and evolutionary processes, and their relative susceptibility to climate change (Mackey *et al.* 2008; Watson *et al.* 2011). Given uncertainties associated with climate change projections at fine scales and the associated ecological response, identifying adaptation strategies that involve all these three factors (exposure, sensitivity and adaptive capacity) is seldom possible (Mimura *et al.* 2007; Leadley *et al.* 2010).

Reducing exposure and sensitivity in ecosystems

Mitigation is the only practical way to limit exposure of ecosystems to climate change. Stabilising global temperatures at ~present-day levels (2005; 0.6°C above pre-industrial) requires near-zero emissions (from any source) within a decade (Matthews and Caldeira 2008). Limiting climate change to 2°C warming from pre-industrial times would probably limit biological damage although due to feedbacks in the earth's system the effects of previous emissions will still cause warming of the global climate throughout much of the 21st Century (O'Neill and Oppenheimer 2002; IPCC 2007). Ocean acidification is also irreversible this century, as it will take thousands of years for ocean chemistry to re-equilibrate to pre-industrial conditions (Raven *et al.* 2005). Most nations

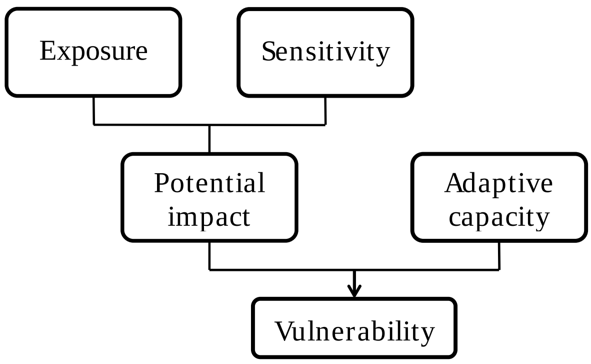

Fig. 1. Components of vulnerability. Adapted from IPCC (2001); Allen Consulting Group (2005).

within Oceania do not emit high levels of carbon and so there is little they can do directly to mitigate CO_2 emissions, except for Australia, and to a far lesser extent, Papua New Guinea and Solomon Islands. Oceania countries need to influence international political processes.

Reducing or eliminating non-climate stresses that contribute to degradation may reduce the sensitivity of species and ecosystems to direct climate change impacts (Mackey *et al.* 2008). Ecosystems in good condition are more likely to withstand disturbance (including those caused by climate change) than those that are highly degraded (Mumby *et al.* 2006; Babcock *et al.* 2010; Mumby and Harborne 2010; but see Cote and Darling 2010). A range of non-climate stresses pose immediate and acute threats to ecosystem health across the region. Commercial fishing pressure is a significant cause of degradation to both target species and associated ecosystems, but it is difficult to disentangle impacts of climate change and fishing (Genner *et al.* 2010). Holistic coastal zone management can help mitigate some of these threats by planning for sustainable coastal development, appropriate waste and marine pollution management, and best practices for resource and catchment management (Done and Reichelt 1998; Fabbri 1998; Cicin-Sain and Belfiore 2006).

One of the best examples of implementing integrated coastal zone management is in the Great Barrier Reef Marine Park, Australia, and adjacent catchments where strategies focus on reducing all human-pressures in the coastal zone. This is achieved by minimizing the fragmentation of coastal habitats during development, ensuring habitats that are lost are compensated by habitats protected elsewhere, and ensuring that coastal development allows buffer zones to enable landward migration of

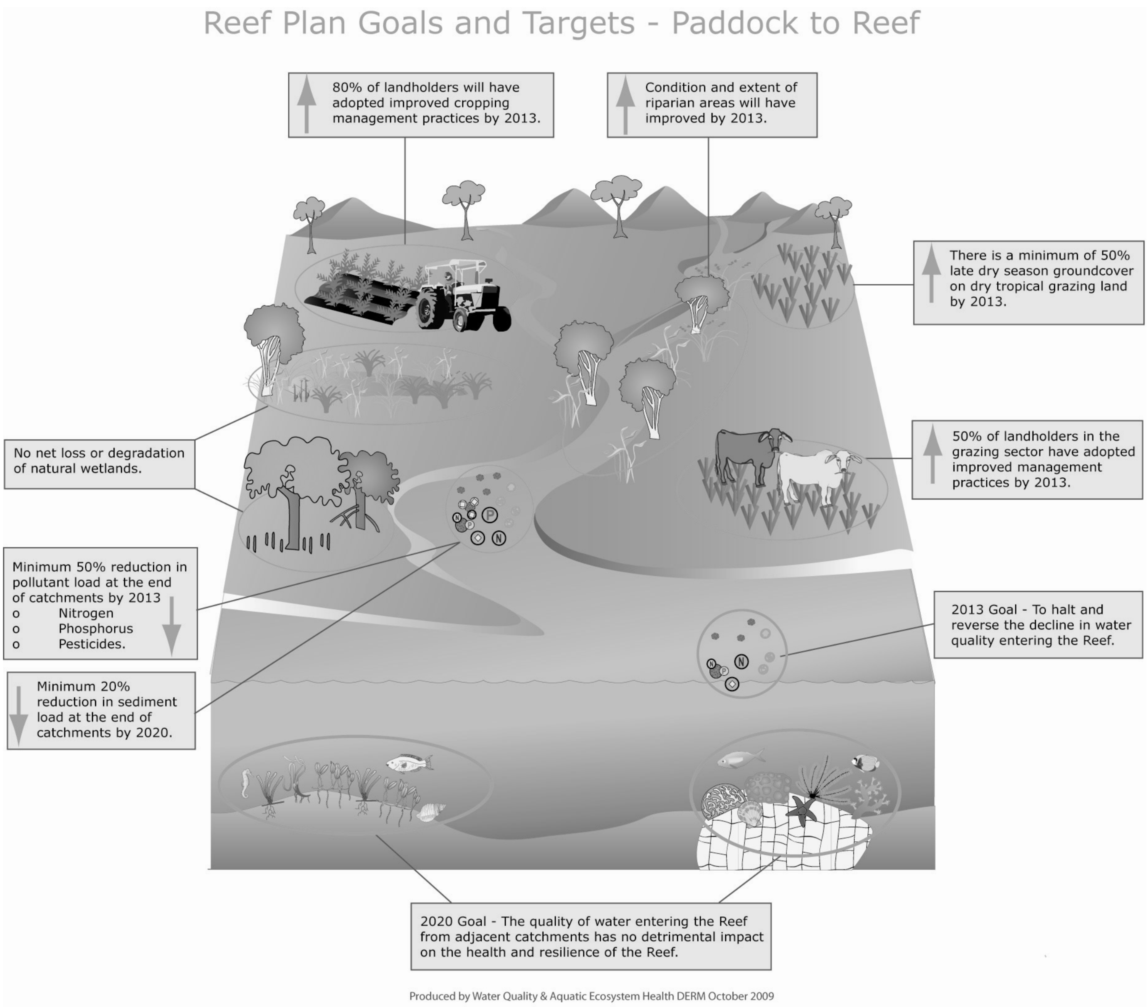

Fig. 2. Integrated coastal zone planning and climate adaptation planning in the Great Barrier Reef, Australia, extensive community participation is incorporated into planning but decision-making is more top down and science-based than in other regions in Oceania. Planning is based on identifying key natural resource assets and setting clear resource condition targets (© The State of Queensland [Department of the Premier and Cabinet) 2009]).

coastal habitats in response to SLR (Fig. 2). Fishing impacts are reduced through by-catch reduction devices, control on effort and closures (Fernandes *et al.* 2005). Another good example is Babeldaob Island, Republic of Palau in the tropical Pacific, where land-use planning and environmental impact assessment are controlling development of infrastructure (e.g., roads and housing) and there is establishment of marine and terrestrial protected areas (Clarke and Jupiter 2010a).

Increasing adaptive capacity of species and ecosystems

The capacity of species to adapt to climate-induced environmental changes depends on genetic or phenotypic plasticity, ability to move or retreat to refugia, or change timing of lifecycle events (Mackey *et al.* 2008). Any strategy that protects large intact coastal populations of species or habitats will help species to use their intrinsic capabilities to overcome climate change, or allow them to move to suitable areas. The protection of ecosystems resilient to past degradation or climate events could increase the adaptive capacity of a system. These areas are adapted genetically, phenotypically or behaviourally to change, and can serve as refuges and corridors between suitable habitat, facilitating repopulation by recruits and enhancing the recovery of adjacent areas damaged by climate change impacts (Puglise and Kelty 2007; McLeod *et al.* 2009).

A planning technique that has been used to help increase the adaptive capacity of species and ecosystems is the creation of buffer zones. For example, establishing buffer zones bordering the seaward and landward margins of protected mangrove areas supports future migration in response to SLR. Landward zones are important for mangroves experiencing SLR to enable landward expansion, whereas seaward buffer zones are important in areas where land is moving seaward (McLeod and Salm 2008). Such buffer zones may also support seagrass ecosystem resilience if they limit soil, nutrient, and pollutant run-off (Björk *et al.* 2008).

Ecosystem-Based Adaptation (EBA)

Ecosystem-Based Adaptation (EBA) strategies integrate biodiversity conservation and the protection of "services" ecosystems provided to humans (e.g., freshwater, timber, fish, coastal protection) (Colls *et al.* 2009; Vignola *et al.* 2009). EBA approaches can help reduce vulnerability of humans and ecosystems to anthropogenic climate change through the promotion of sustainable management, conservation, and restoration activities. In tropical Oceania, implementing EBA requires effective governance regimes and policy instruments and must be economically efficient. We highlight some guiding principles for developing effective EBA strategies relevant for tropical Oceania, based on the literature and existing projects in the region. We focus specifically on examples where strengthening local awareness, participation, governance and policy frameworks has increased adaptive capacity to respond to climate disturbance.

Community awareness

In tropical Oceania, many people depend upon coastal and marine ecosystems and their associated goods and services (Hoegh-Guldberg *et al.* 2009). Significant changes to these ecosystems adversely affect households and incomes of resource users and residents. Furthermore, coastal people in the region adapt to changes in climate including, climate variability, climate-related hazards and associated extreme events (e.g., floods, sea-level variation, high waves, cyclones, coastal inundation, and erosion) (Nicholls *et al.* 2007). For example, Pacific islanders have diversified crop varieties, stored food surpluses, controlled consumption, and co-operated between communities to maintain food security throughout unpredictable climate events (Campbell 2006). Building these traditional approaches into the first step of adaptation planning is essential through engaging communities and boosting awareness.

Current local perceptions and interpretations of climate variability are diverse among communities and social groups, complicated by language barriers to communicating climate impacts and adaptation strategies. For example, there is no equivalent expression in Fijian for "resilience" and the Fijian term "*draki*" means both climate and weather. General and unbiased background information on global climate change needs to be framed in the Pacific context before any group discussion with communities to boost understanding. Using this approach in Fiji, the Wildlife Conservation Society has successfully engaged local communities across the Vatu-i-Ra seascape in focal group interviews to identify climate hazards of greatest threats to local resources, using the Community-Based Risk Screening — Adaptation and Livelihoods (CRiSTAL) tool (Tables 2 and 3, IISD 2009). Participants then consider the sustainability of current strategies for coping with climate hazards and, if they are inadequate, use facilitated group brainstorms activities to develop alternatives (Table 2). These include income and food diversification, infrastructure development, and resource management actions.

Raising awareness does not simply mean identifying possible activities for local people, as shortsighted "solutions" may produce mal-adaptive actions and undermine local adaptive

Table 2. Climate hazards identified by Fiji community members of the Vatu-i-Ra seascape, during focal group interviews: resources impacted: current coping strategies; self-assessment of sustainability of current strategies; alternative coping strategies proposed during the interviews; and percentage of interviews in which issues were discussed as a measure of regional threat (source Fiji Wildlife Conservation Society).

Hazard	Resources Impacted	Current Coping Strategies	Sustainability	Alternative Strategies	%
Cyclone	Crops (taro, cassava, kava, copra, fruit trees)	Cut leaves (of cassava and kava only) prior to cyclone	Yes, although may affect harvest volume as sometimes tubers and roots rot or become hardened	Diversify crops to spread risk; Plant crops that grow low to the ground (e.g. sweet potato) during cyclone season	36%
	Housing infrastructure	Monitor warnings via radio. Secure houses. Repair damage after cyclone.	Majority believe reactionary approach is sustainable, however this may change if cyclone frequency and intensity increases and causes more damage	Strengthen houses and secure drinking water sources. Rebuild damaged houses in less vulnerable locations	36%
Floods/ Soil Erosion/ Sedimentation	Crops (taro, cassava, kava, copra, fruit trees)	Relocate plantations on high ground. Avoid planting during wet season. Use chemical fertilizer to improve soil fertility.	Chemical fertilizer not sustainable, as expensive and can have ecosystem and health effects. Other strategies more sustainable.	Diversify crops to spread risk. Request faster growing varieties. Restore riverbank and upland vegetation. Do not completely clearcut plantations.	82%
	Livestock	Move livestock to high ground	Yes, however need adequate early warning systems to move livestock	Move piggeries away from rivers	36%
	Transportation infrastructure and market access	Rebuild bridges with support from Public Works Department	No, due to resource limitations of Public Works Department	Work with Public Works Department to invest in maintaining and strengthening existing transport infrastructure (roads, bridges) to reduce damage	27%
Floods/ Soil Erosion/ Sedimentation cont.	Freshwater and marine subsistence/ commercial species	None	N/A	Establish protected areas along watercourses and downstream. Restore riverbank vegetation	55%
	Clan boundaries	None	N/A	Have Native Lands and Fisheries Commission remark official boundaries to avoid conflict. Restore upland and riverbank vegetation.	27%
Drought	Water availability	Ration water. Bathe in streams.	No, because may result in poor hygiene and health.	Protect and revegetate water catchments. Apply for small grants to invest in water tanks, pumps and piping.	9%
	Education (schools shut when not enough water)	None	N/A	Apply for small grants to invest in water tanks, pumps and piping.	9%
	Crops	None	N/A	Request drought tolerant strains from Ministry of Agriculture	9%
Storm surge/ Sea level rise	Coastal infrastructure	Rebuild houses away from coast	No, because many coastal villages have little available land for building new dwellings	Plant mangroves. Build stone seawalls.	27%
	Coconut trees	Replant trees	Maybe, as coconut trees take ~5-6 years to mature	Request to Ministry of Agriculture for commercially viable trees that stabilize coastlines	27%

Table 3. Examples of tools to support the development and implementation climate change adaptation strategies throughout tropical Queensland.

Resource	Description	Access
Adapting to a Changing Climate Outreach Toolkit	The Micronesia Conservation Trust and The Nature Conservancy on behalf of the Micronesia Challenge supported development of an outreach toolkit for community based climate change adaptation. The toolkit consists of large flipcharts, booklets, facilitator guide, and video and is intended to motivate and engage communities to take actions to address climate change impacts.	http://www.cakex.org/virtual-library/3440
Adapting to Climate Variability and Change: A Guidance Manual for Development Planning	USAID developed guidance to assist missions and other partners to screen for vulnerability of development projects to climate change and to identify adaptation options.	http://pdf.usaid.gov/pdf_docs/PNADJ990.pdf
Adaptation Database for Planning Tool (ADAPT)	An online database that guides users through ICLEI's 5 Milestones for Climate Adaptation planning framework. ADAPT walks users through the process of assessing vulnerabilities, setting resiliency goals, and developing plans that integrate into existing hazard and comprehensive planning efforts.	http://www.icleiusa.org
Climate Vulnerability and Capacity Analysis (CVCA) Handbook	The methodology presented in the CVCA Handbook is geared toward assessing vulnerability and adaptive capacity at the community level and prioritizes local knowledge in the data gathering and analysis process. The Handbook builds on Care's Community Based Adaptation framework, and can be used to design appropriate interventions to support adaptation.	http://iklim.cob.gov.tr/iklim/Files/eKutuphane/Climate%20Vulnerability%20and%20Capacity%20%20Analysis%20Handbook.pdf
CRiSTAL (Community-based Risk Screening Tool – Adaptation and Livelihoods)	CriSTAL enables local decision makers to assess the impact a project may have on the resources of a community, and modify projects to reduce vulnerability and enhance adaptive capacity by incorporating adaptation methods.	http://www.cristaltool.org
Indicators to assess community-level climate change vulnerability: An addendum to SocMon and SEM-Pasifika regional socioeconomic monitoring guidelines	This addendum was developed to provide a minimum set of socioeconomic indicators related to climate change to support a socioeconomic assessment of any site vulnerable to climate change impacts. This document is being added to regional socioeconomic monitoring guidelines produced by the Global Socioeconomic Monitoring Initiative for Coastal Management.	http://www.socmon.org/
NOAA CSC Coastal Inundation Toolkit	This toolkit provides guidance on how to prepare, estimate and map inundation for a given area. It includes basic information about coastal inundation, identification of exposure and potential impacts, mapping inundation to assess potential impacts, assessing community's risks, vulnerability, and resilience, and communicating risk strategies to initiate change.	http://www.csc.noaa.gov/digitalcoast/inundation/
SimCLIM	SimCLIM is a software system that integrates models and data for purposes of assessing the impacts of, and adaptations to, climate variability and change, including extreme events.	http://www.climsystems.com/simclim/index.php

capacity (Roncoli 2006). For example, building protective seawalls is now common practice in some of the islands off northern Papua New Guinea (Fig. 3, J. Watson *unpublished data*). Despite efforts of local communities, these seawalls have failed to stop the flooding of islands as sea-level has risen too quickly. Plus, as reef limestone was used to build the seawalls, they have led to the destruction of biodiverse coral reefs and their supporting food security services such as. In addition, successful application of tools such as CRiSTAL and various other approaches (Table 2) in one location does not mean that the processes are directly transferrable to other cultural contexts. Lessons from Vanuatu show that generic methodologies and tools to engage communities are often limited in stimulating active community participation, learning and decision-making (Warwick 2009). Successful outcomes in Vanuatu started with informal discussions within small groups and evolved into deep conversations about adaptation approaches.

Stakeholder participation

Engagement of local communities in policy, incorporation of traditional and local knowledge, and the design of adaptation responses that recognize the diversity of local contexts and aspirations are essential for successful local adaptation strategies (Reid *et al.* 2009; Vignola *et al.* 2009). This is true in both developed and developing nations in the tropical Pacific to produce "ownership" of adaptation approaches for effective implementation.

For example, planning in much of tropical Oceania occurs through small-scale, bottom-up processes directly engaging local communities, including participatory approaches that successfully support spatial planning. Three dimensional modelling has worked in Fiji, Papua New Guinea, Solomon Islands and Australia (Rambaldi 2006). Using basic 2D contour maps, participants develop 3D models of their area by stacking sheets of cardboard to build elevation contours. These models are overlaid with maps of resources and human stressors to raise awareness of the connection between land-based activities and associated impacts on the marine environment. The Lauru Land Conference of Tribal Communities, the Choiseul Provincial Government, and The Nature Conservancy recently applied this tool to community-based climate change adaptation planning in BoeBoe, a community in Choiseul province, Solomon Islands (Fig 4). The tool promoted full community participation and ownership of an accessible, geo-referenced relief-model of the BoeBoe customary lands and near-shore coastal

Fig. 3. Building protective sea walls from blasting coral reef is now a common practice in some of the islands off northern Papua New Guinea. This is a good example of a maladaptive action that undermines local communities' adaptive captive (J. Watson *unpublished data*, Photo: J. Watson).

Fig. 4. In Choiseul, Solomon Islands, a community based bottom-up participatory process is occurring for spatial planning. Here a 3D model is developed by the community to help planning, including ecosystem-based adaptation (Photo: Javier Leon).

areas, providing a "ridge to reef" view of local geography, with important ecosystems and their services easily identified and discussed. The tool is also cost-effective (~US$0.04 per hectare, 1:10,000 scale model) empowering community-based planning and decision-making (Hardcastle *et al.* 2004). Advantageously, the model remains in the community whenever needed but, use is restricted to small groups.

Contrasting other Tropical Pacific nations, governments in Australia develop a top-down, large-scale planning process, working mainly with interest groups. The *Paddock-to-Reef* integrated monitoring, modelling and reporting programme in Queensland, Australia (Fig. 2) aims to ensure that the quality of water entering the Great Barrier Reef from adjacent catchments has no longer-term detrimental impacts (Queensland Government 2009). The government used a collaborative approach to develop the programme with different tiers of government, industry, regional natural resource management bodies and research organizations. The programme links monitoring and modelling across a range of attributes and scales. Engagement in the Australian context is equally important, as individual stakeholder groups (e.g., peak bodies for fishing, farming, industry or conservation) are well funded, well organized, and politically engaged. Once legislation is enacted and programmes promulgated, various levels of Government (local, state and national) are relatively well resourced with appropriate governance structures.

The effectiveness of top-down versus bottom-up planning will depend on how well it is matched with governance infrastructure and resources, as well as support for the management actions (Mills *et al.* 2010). Within tropical Oceania, there may be scope to scale-up local level management actions to deal more effectively and holistically with large-scale impacts from climate change. For example, in Fiji, stakeholders have come together to discuss how community-based marine management can feed into zoning options within provincial-level integrated coastal management plans, whose development is underway (S. Jupiter, pers. comm.). Similarly, there may be scope to scale-down top-down regional plans where appropriate. For example, in Australia, the government could work closer with particular local farming communities to reduce the amount of nutrients used on crops, to reduce high nutrient run-off to coral reefs.

Community-based management

EBA should be complemented with building and strengthening community-based management. Many coastal communities in the tropical Pacific have customary land, island and coastal tenure, supported by traditional governance arrangements. Top-down adaptation approaches from formal government initiatives probably fail beyond pilot project and demonstration activities (Reid *et al.* 2009; Mataki *et al.* 2007). Implementation of EBA can thus be strengthened by developing new hybrid management institutions that can work with traditional leaders and government to share responsibility for planning, implementation and enforcement (Reti 1993; Clarke and Jupiter 2010b).

In many nations of Oceania, traditional authority over resource use and management rests with the village and district chiefs (Clarke and Jupiter 2010b). Chiefs manage a wide range of community issues (e.g., customary protocol, conflict resolution, and youth education) and may not have sufficient time or resources to address climate change. In response, many communities have developed local resource management groups with responsibilities for assessing environmental impacts and making recommendations for management implementation. For example, in the Republic of Marshall Islands, atoll communities have formed Natural Resource Management Committees, following national guidance on conservation planning, named "Reimaanlok", or "Way Forward" (Baker *et al.* 2010). The Namdrik Atoll Natural Resource Management and Development Plan 2010 to 2015 is supported by a resource management committee of local government leaders, community representatives, and traditional leaders (Iroji) of Namdrik. This serves as the key liaison and co-ordination point with the national Government and its nominated co-ordination group, the Coastal and Marine Action Committee. Since 2009, this committee has incorporated EBA approaches into the "Reimaanlok", and tested their implementation on several atolls. The Coastal and Marine Action Committee partnership includes non-governmental organizations, such as the Marshall Islands Conservation Society, and the Women United of the Marshall Islands, connecting research and education through the College of the Marshall Islands. The inclusive make-up of the Coastal and Marine Action Committee and the strengthening of local management institutions bridges community needs with relevant Government sectors and national development programmes, and actively engages national and international partners.

Even larger, well-resourced countries such as Australia rely on local groups, such as the Natural Resource Management bodies, to bridge the gap between governments and regional communities. Their structure comprises different levels of governments (local, state and national) and key stakeholders within the Natural Resource Management region with a combination of bottom-up and top-down planning processes (Campbell 2008). These bodies are tasked with developing an integrated plan with local communities and identifying key natural resource assets, setting and prioritizing resource condition targets, and outlining necessary management actions for targets. Climate change adaptation based on EBA is being incorporated into Natural Resource Management plans across Australia.

Policy and management frameworks

EBA should be considered within national development plans and programmes, and biodiversity conservation and natural resource management sectors need to advance adaptation strategies (Colls *et al.* 2009). Integrating these approaches is a key focus in Oceania. Pacific Island countries and territories have generally implemented stand-alone adaptation policies (e.g., National Adaptation Program of Action), but are starting to integrate adaptation into development proposals and planning (King 2010). Despite this recent progress, many existing and emerging policies do not address lesser-known persistent or emerging problems compounded by predicted climate change impacts. These include the need for environmental impact assessments for development approval and integration of climate adaptation into sectoral plans and Disaster Risk Reduction policies. Transformative policies addressing drivers of environmental degradation (i.e., demographic change and consumptions patterns) will be required if countries are to adequately respond to and reduce non-climatic threats to ecosystems (UNEP 2007).

Protected areas are an important management tool for EBA. The trend for protected area programmes in tropical Oceania is for establishment of locally-managed marine areas (LMMAs), implemented and managed mostly by communities and local Governments in the region (Fig. 4). Incorporating EBA into protected area planning will help consideration of climate change in the design and management of protected areas. In the Solomon Islands province of Choiseul (locally named Lauru), LMMAs and terrestrial protected areas are formally established and networked as part of a protected area planning process. The design of a network of protected areas is based on EBA principles and community participation in the identification of protected areas (Game *et al.* 2011).

Limitations

Most of tropical Oceania is subject to climate change impacts caused by the rest of the world. Unless the rest of the world acts, the future of most of tropical Oceania are at severe risk regardless of human settlements in the success of an EBA plan (or any adaptation strategy). It will almost be impossible to avoid the most catastrophic ecological climate change impacts if greenhouses gases continue to be released (Colls *et al.* 2009).

Even under current climate conditions, adaptation options of tropical marine ecosystems are limited. For example, adaptation options for mangroves are limited by obstacles to migration such as lack of sediment to keep up with sea level rise. Isolated mangrove or seagrass communities in remote areas may also have limited adaptation options. For coral reef ecosystems, limited adaptation options may emerge in coming decades for many species when tipping points for physiological thresholds are reached. Even healthy and resilient ecosystems are unable to protect human communities from all climate hazards, and some engineering options will need to be compared to EBA approaches to determine relative costs and benefits. EBA may not always be possible due to proximity of human settlements and development where high levels of human degradation limit EBA adaptation options. EBA initiatives may also be limited by lack of funding, land-use conflicts, community opposition, and/or knowledge gaps (i.e., lack of information about costs and benefits of EBA approaches; Colls *et al.* 2009).

CONCLUSION

This paper summarizes the current knowledge of regional climate change projections and impacts on three major ecosystems across tropical Oceania. The impacts of climate change will likely be severe and widespread, but not all places will be impacted equally and not all impacts will be negative. While activities that mitigate climate change is the only way to limit exposure to climate change, reducing non-climate stresses that contribute to ecosystem degradation reduce the vulnerability of species and ecosystem to direct climate change impacts. Integrating EBA into adaptation planning and action has great potential and we have provided demonstration case studies. To implement ecosystem based adaptation, governments, communities and stakeholders must accept that the challenge climate change presents is real and work together to identify the most feasible actions that benefit people and biodiversity. While some climate change adaptation actions are the same or similar to existing conservation actions, the magnitude of the challenge will likely require communities, researchers, conservation practitioners, and decision makers to develop new and innovative strategies that address multiple stresses and interactive feedbacks. We are beginning to implement climate adaptation approaches in tropical Oceania and throughout the world. The challenge ahead is to test and refine these approaches to ensure that they are sufficient to sustain coastal communities and ecosystems in the region.

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