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Effects of Climate Change on Mangroves Relevant to the Pacific Islands

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EXECUTIVE SUMMARY
Pacific island mangroves include the world's centre of mangrove biodiversity in Papua New Guinea, and extend east through all countries and territories as far as the Marshall Islands and Samoa. Mangroves provide many values to local communities, however immense worldwide losses have occurred in the past century owing to human coastal development, including around urban centres in the Pacific islands. There is limited published information on the current health and status of Pacific island mangroves. Mangrove seaward edge retreat attributed to relative sea level rise has been shown by spatial analysis between 1961-2003 in American Samoa, long-term mangrove zone retreat landward has been shown from the tectonically subsiding coastlines of SW Papua and Tikina Wai, Fiji, and Micronesian mangrove substrates are not keeping up with relative sea level rise, all indicating future mangrove loss with accelerated rates. Future effects of climate change on Pacific island mangroves could include mangrove mortality during unusually dry periods, and devastating impacts from the higher rates of sea level rise that are projected. There is agreement and consensus that potential impacts of projected sea level rise will be high on mangroves of the Pacific islands, and priority adaptation actions include promotion of mangrove substrate accretion and mangrove monitoring.

Introduction

Mangroves are a taxonomically diverse group of tropical tree species, which have developed adaptations to inter-tidal habitats including salt control strategies, aerial roots, seed germination before release, and waxy leaves to conserve fresh water. There are approximately 70 species of true mangroves across the tropics (Polidoro *et al.,* 2014), with their global centre of diversity in Papua New Guinea (PNG) in the Western Pacific. Mangroves grow in shore-parallel zones of different species, from mean sea level to high tide levels, each zone with different percentages of tidal inundation. While mangroves are a biogenic community primarily of trees alongside specially adapted fauna, the word also refers to the wetland habitat in which they occur, of low energy, low gradient tropical coastlines falling between mean and high tide levels (Figure 1).

Pacific mangrove distributions

Mangrove areas in the Pacific island countries and territories (PICTs) have recently been assessed to cover a total area of 6,237.55 km^2, representing 4.52% of the total mangrove forests in the world (Bhattarai & Giri, 2011). Mangroves are most extensive on the high islands, such as in PNG, Solomon Islands, Fiji and New Caledonia (Table 1), which have fluvial

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Figure 1. Seaward edge of mangroves at Nooto Ramsar site, Kiribati. The seaward edge is at mean tide level. *Rhizophora stylosa* with aerial prop roots is one of the most widespread species in the Pacific islands, here growing on a carbonate sand substrate (Photo: J. Ellison).

catchments that deliver sediment to the coast, developing estuaries with more extensive intertidal areas. Of Pacific island mangrove areas, 97% are in these 4 PICTs (Bhattarai & Giri, 2011), with PNG being the eight most mangrove-rich country in the world, with 3.5% of the world mangrove area (Giri *et al*., 2011). Areas of mangroves have been reported differently in other publications (eg. Ellison, 2009), reviewing sources which are dated and use a variety of methods of assessment. This review features the Bhattarai & Giri (2011) data, as they use standard techniques across all PICTs, while Hamilton & Casey (2016) only assess six Pacific island PICTs.

Mangrove species numbers and richness are highest in the west Pacific (Table 1), and decrease towards the east, as far as the Marshall Islands in the north and Samoa in the south, with an introduced outlier in French Polynesia. The complement of species is different in each PICT, causing unique varieties in community structures in each island group. Different species numbers relative to Table 1 which are reported in other publications are largely caused by differences in the definitions of a “true” relative to an “associate” mangrove species. Some PICTs with smaller mangrove areas may have the highest proportion of mangroves relative to dry land, and all mangroves have immense values for Pacific island peoples.

Mangrove values and uses

Mangroves provide a wide range of values for coastal people (Ellison, 2009, Spalding *et al*., 2010), such as fish, crabs, timber and fuelwood (Figure 2). Fish are a cornerstone of food security in the Pacific island region, providing 50–90% of protein for coastal communities (Bell *et al*., 2017). Recent mapping evaluation from Fiji (Atkinson *et al*., 2016) shows valuable contribution of mangrove ecosystems to coastal protection (particularly to infrastructure and populated areas), fisheries (particularly where runoff is not polluted), carbon storage and sequestration, and biodiversity (such as tourism benefits). Many mangrove areas showed co-benefits of several values. For Lami Town in Fiji (200 households), mangrove ecosystem services of storm protection and indirect services were valued at F$158,920 over a one-year timeframe (Rao *et al*., 2013).

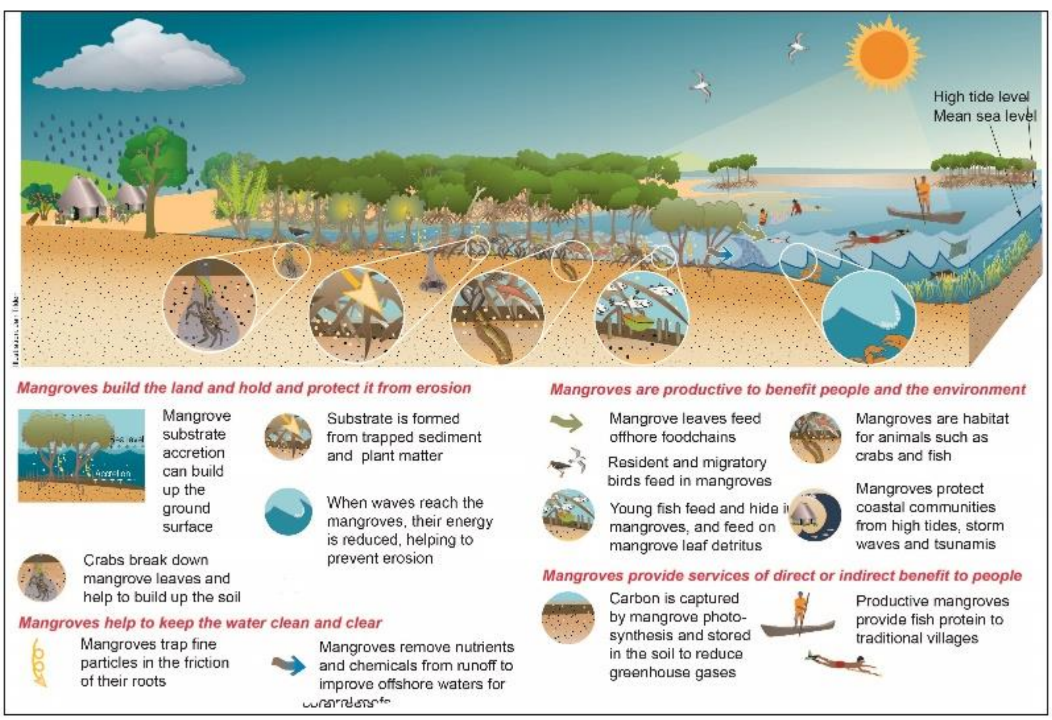


Figure 2. Mangrove species zonation, and values of the ecosystem to people (Illustrator: Jan Tilden).

Table 1. Mangroves of the PICTs listed from west to east. Sources: Mangrove areas (Bhattarai & Giri, 2011), mangrove species (Waycott *et al*., 2011). Geomorphic setting of the major mangrove areas (Neall & Trewick, 2008; Campbell, 2009).

Country or territory	Mangrove geomorphic setting	Total land area (km^2)	Species (hybrid)	Mangrove area (km^2)	Mangrove % of land
Palau	Volcanic and raised limestone	494	14(1)	56.664	11.47
Guam	Volcanic, and raised limestone	541	12	0.342	0.06
Northern Mariana Islands	Volcanic	478	3	0.2808	0.06
PNG	Continental	462,243	31(2)	4801.21	1.04
Federated States of Micronesia	Volcanic	700	15(1)	99.0045	14.14
New Caledonia	Continental	19,100	15(3)	250.985	1.31
Solomon Islands	Volcanic	27,556	17(2)	470.996	1.71
Vanuatu	Volcanic	11,880	14(3)	13.7817	0.12
Nauru	Raised limestone	21	2	0.036	0.17
Marshall Islands	Atolls	112	5	0.0234	0.02
Tuvalu	Atolls	26	2	0.0909	0.35
Fiji	Continental	18,272	7(1)	525.03	2.87
Wallis and Futuna	Volcanic	255	2	0.1386	0.05
Kiribati	Atolls	690	4	0.1791	0.03
Samoa	Volcanic	2935	3	3.7215	0.13
American Samoa	Volcanic	197	3	0.8991	0.46
Tonga	Raised limestone	699	7	7.7886	1.11
Tokelau	Atolls	10	0	0	0.00
Niue	Raised limestone	259	1	0	0.00
Cook Islands	Volcanic	240	0	0	0.00
French Polynesia	Volcanic	3521	1	0.0012	0.00

Established mangroves promote vertical accretion through peat formation (Lee *et al*., 2014), which contributes natural adaptation to sea-level rise, as well as carbon sequestration from the organic matter in the sediment (Bouillon *et al*., 2009). In the Pacific, net long-term mangrove substrate accretion of 1.1-2.0 mm/year was shown from the high island of Viti Levu, Fiji, and 0.7 mm/year from the low island of Tongatapu, Tonga (Ellison & Stoddart, 1991; Ellison & Strickland, 2015). Mangrove-sediment carbon stores are approximately five times larger than those found in temperate, boreal and tropical terrestrial forests (Bouillon, 2011; Donato *et al*., 2011), and are thought to bury carbon at rates up to 50 times higher than those in tropical rainforests (Bouillon, 2011). For example, the Commonwealth's Vanuatu Blue Carbon Report showed that coastal ecosystems are significantly better at trapping and storing carbon relative to terrestrial forests (mangroves averaging 1500-2250 t CO_2 eq/ha) (Laken, 2014). In the Rewa delta, Fiji, the 8,600 ha of mangroves contain c. 1,700 tonnes of carbon dioxide equivalents per hectare, which using conservative values for verified carbon credits, are equivalent to F$8,500- $25,000/ha (Heider, 2013).

What is Already Happening?

Direct human impacts

Despite the values that mangroves provide, the worldwide mangrove area has reduced by more than half over what it was just over a century ago, owing to direct human impacts (Spalding *et al*., 2010, Giri *et al*., 2011). The largest losses are from conversion of mangrove areas to urban and industrial facilities, aquaculture and agriculture (Spalding *et al*., 2010). Mangrove area worldwide reduced from over 200,000 km^2 early last century to 188,000 km^2 in 1980, to 137,760 km^2 in 2000 (Giri *et al*., 2011) with rising rates of loss after 1980, though with some slowing of rates of loss 2000-2012 (Hamilton & Casey, 2016). Asia has the highest losses, largely due to human impacts (Long *et al*., 2014, Polidoro *et al*., 2014). In the Pacific islands, mangrove loss results from infill for coastal infrastructure and rubbish dumps, particularly close to urban centres such as Nuku'alofa, Lautoka, Port Vila, Honiara and Apia (Veitayaki *et al*., 2017). Mangrove losses and gains of deltaic mangroves in PNG deltas have occurred due to geomorphological processes (Shearman, 2010; Shearman *et al*., 2013), with net losses from the 1970s to 2000s.

Climate change impacts

Mangroves are also sensitive to climate change impacts, associated with the Anthropocene enhanced greenhouse effect and ocean warming. Potential impacts of climate change on mangroves in the Pacific islands region have been reviewed earlier (Ellison, 2000, 2001; Gehrke *et al*., 2007; Ellison & Fiu, 2010; Walcott *et al*., 2011), and this paper focuses on the more recent climate change projections and relevant mangrove research.

Atmospheric CO_2 increase and warming temperatures

Temperatures have increased at a rate between 0.1°C and 0.2°C per decade throughout the Pacific Islands during the 20th century (Christenson *et al*., 2013); a warming of both the ocean surface and land temperatures of about 1°C (IPCC, 2013). Atmospheric CO_2 concentrations have increased at about 2 ppmv/ year over the last decade, at increased rates relative to previous decades (IPCC, 2013). Increased CO_2 enhances the growth of mangrove trees (Wong *et al*., 2013), being a reactant in photosynthesis, and increases in temperature will likely have positive benefits to mangroves (Ellison & Cannicci, 2016), however no research has been carried out in the Pacific islands.

Precipitation changes

Precipitation amounts and seasonality across the Pacific islands region show intra-regional trends generally of highest rainfall in the Equatorial west Pacific, and increased seasonality and reduced totals with increased latitude (Ellison, 2009). Variation is caused by El Niño events (ENSO), when rainfall decreases in western regions and increases in the central Pacific, and during strong El Niño events (e.g., 1982/1983, 1997/1998), massive droughts and food shortages can occur (Christenson *et al*., 2013).

As exemplified by comparing the windward and leeward coasts of Pacific high islands, wetter coasts have taller, more productive and more diverse mangroves, and drier coasts have lower canopy height and lower diversity of mangroves. On Viti Levu, Fiji, Fiu *et al*. (2010) showed the wet windward mangroves at Verata to be dominated by the more freshwater tolerant *Bruguiera gymnorrhiza*, while the dry leeward coast mangroves at Tikina Wai were dominated by salt tolerant *Rhizophora* species and hybrids of only stunted heights up to 4 m. As shown by average tree diameter data (Figure 3), Verata mangroves had up to 4x greater biomass relative to Tikina Wai, while Tikina Wai has extensive salt flat areas which are lacking in wetter mangroves This indicates the adaptive capacity of some mangrove species to drier conditions.

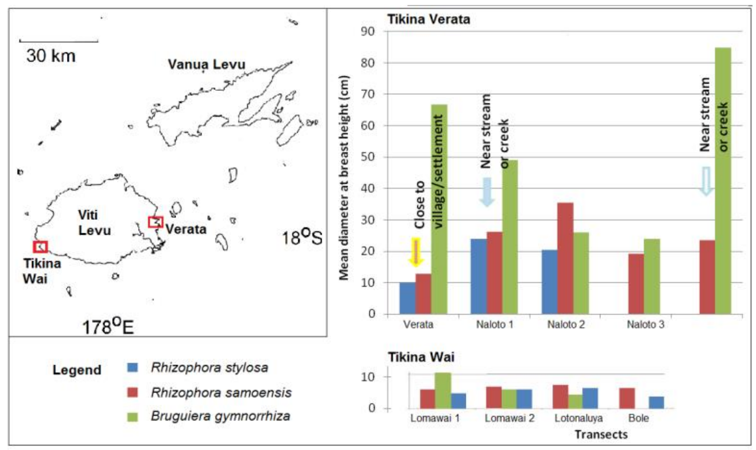


Figure 3. Mean diameter of mangroves at Tikina Wai (annual rainfall 1882 mm) and Verata (annual rainfall 2915 mm), on Viti Levu, Fiji (adapted from Fiu *et al*., 2010).

However, recent indications of the effects of extended low rainfall and moisture stress on mangroves are reported from 15-18°S in the Gulf of Carpentaria, where more than 74 km^2 of mangroves along 100 km of coastline died in late 2015- early 2016 (Duke *et al.*, 2017). Multiple species were affected (*Avicennia marina*, *Rhizophora stylosa* and *Ceriops tagal)*, dieback areas matching zonation contours, and extending down the profile from mostly higher elevation contour levels. In Iran, Mafi-Gholami *et al*. (2017) showed that drought occurrences correlated with spatial reduction of mangrove areas and canopy cover. Spatial analysis of three large mangrove areas of Fiji 1960s-2000s showed area gain and loss cycles such as with expansion of salt pans and reduction of mangroves, then recovery (Fiu *et al*., 2010), which may be related to ENSO droughts. Further research on these potential correlations would be helpful in understanding Pacific island mangrove responses to reduced rainfall.

Storms

During ENSO events, tropical cyclone numbers in the Pacific islands tend to increase and occur farther east than normal, while during La Niña, the western tropical

Pacific experiences above-average numbers of tropical cyclones (Christensen *et al*., 2013).

Several records exist of damage in mangroves following cyclones (Ellison, 2012a), usually resulting in a complete defoliation over the narrow area of cyclone paths, however few studies have focused on the ecological and physical effects of such severe storms on Pacific islands (Swarp, 1992; Kauffmann & Cole, 2010). Following a severe typhoon impacting mangroves of Yap, all trees suffered canopy damage, with significant proportions snapped or wind-thrown, however *Sonneratia* showed vigorous ability to re-sprout, and the majority of *Bruguiera* and *Rhizophora* were able to re-foliate (Kauffmann & Cole, 2010). Following severe Cyclone Winston in Fiji in 2016, mangroves were extensively damaged, and local people reported damage to fisheries and mud crab harvesting (Vandervord *et al*., 2016). Severe storm impacts directly on mangroves were recently assessed outside the region following Tropical Cyclone Yasi in 2011 impacting Hinchinbrook Island, Queensland (18^{o}S) (Ashbridge *et al*., 2015). Wind gusts were up to 290 km/ hour, wave heights >7 m, rainfall intensive, and the cyclone c. 700 km in diameter. Mangroves within the 200 km^2 area of Hinchinbrook Island were 17.2% damaged, with high winds and waves eroding sediment and destroying and uprooting trees.

Sea level rise

Eustatic sea level rise in the last few decades has largely resulted from ocean warming and thermal expansion (Church *et al*., 2013). The IPCC (2013) observed that sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (high confidence). Over the period from 1901-2010, global mean sea level rose by 0.19 m [0.17 to 0.21], however, there are few long-term tide gauges in the Pacific islands, so trends are uncertain.

While retreat of Pacific island shorelines is a high expectation with continued sea level rise (Wong *et al*., 2014), many studies have shown that these thresholds have not as yet been reached (Duvat *et al*., 2017). While the mangrove shorelines assessed are limited, spatial analysis of the mangrove lagoon shore of the Nooto Ramsar site of North Tarawa, Kiribati (Ellison *et al*., 2017), showed that the mangrove area expanded and prograded seawards 1998–2013, increasing by 17%, at a rate of 604 m^2/year (Figure 4B).

Retreat of mangroves from the seaward edge has also been shown in a few studies, which is a key sign of sea level rise impacts (Gilman *et al*., 2008), at locations where the local rate of relative sea level rise (RSLR) is greater than global averages. Mangrove seaward edge retreat at Tutuila, American Samoa has been shown by spatial analysis of shoreline change over four decades in three mangrove areas, with landward retreat of mangrove seaward margins of 25, 64, and 72 mm/year attributed to RSLR of 2 mm/year (Gilman *et al*., 2007) (Figure 4A). Other observations of retreat of mangroves owing to rising sea levels (Ellison, 1999; Ellison & Zouh, 2012; Ashbridge *et al*., 2015) do not include the Pacific islands.

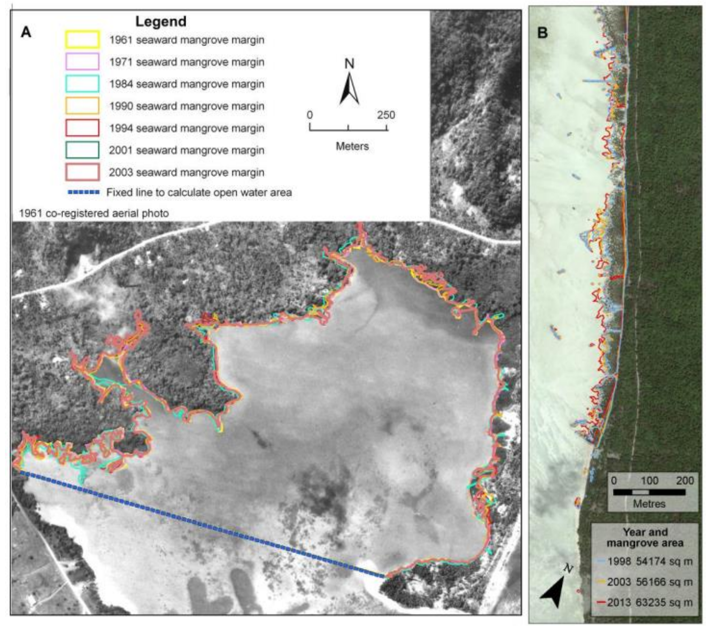


Figure 4. A Mangrove retreat 1961-2003 at Nu'uli, American Samoa with mean area loss of 483.85 m^2/ year (adapted from Gilman *et al*., 2007). **B** Mangrove advance 1998-2013 at Nooto, Kiribati, with mean area gain of 604 m^2/year (adapted from Ellison *et al*., 2017).

Long-term mangrove zone retreat landward has also been shown by palaeoecological analysis, such as the tectonically subsiding coastlines of SW Papua (Ellison, 2005) and Tikina Wai, Fiji (Ellison & Strickland, 2015). At Tikina Wai, western Viti Levu, RSLR over the last 1,000 years was shown to be 2.1 mm/year, with gradual retreat of seaward *Rhizophora* zones replacing landward *Bruguiera* zones over time (Ellison & Strickland, 2015), with substrate accretion was occurring at up to 2.0 mm/year. In studies where long-term RSLR exceeds net accretion rates, mangrove zones have retreated landwards (Ellison & Cannicci, 2016).

Mangrove accretion rates are recommended for monitoring intertidal surface-elevation trajectories in coastal wetlands (Webb *et al*., 2013; Cahoon, 2015; Lovelock *et al*. 2015). Analysis of mangrove surface elevation data from surface elevation tables and a sediment surface marker horizon showed that about 50% of study sites are not keeping up with RSLR, particularly low islands and subsiding locations (Alongi, 2015), with fringe mangroves more vulnerable than basin settings (Sasmito *et al*., 2015). In parts of Micronesia, mangrove sediments are not keeping pace with current rates of sea level rise (Krauss *et al*., 2003, 2010). At the majority of mangrove locations studied, including two in the Pacific islands (Lovelock *et al*., 2015), the current rates of sea level rise exceeded the soil surface elevation gain. Such studies, however, are limited in scope and geographic extent (Lee *et al*., 2014), and can have some potential limitations (Nolte *et al*., 2013).

What Could Happen?

Temperature increases

Annual average air and sea surface temperatures are projected to continue to increase for all tropical Pacific countries (Christensen *et al*., 2013). Negative impacts to mangroves from such temperature rises alone are not expected. Mangroves have a high degree of tolerance to heat stress relative to other plants, and these projected increases are below those known to cause detrimental effects (Gilman *et al*., 2008; Ellison & Cannicci, 2016).

Temperature rise may change mangrove species compositions and timing of flowering and fruiting, and expanding mangrove ranges to higher latitudes where range is limited by temperature (Gilman *et al*., 2008). There are recent reports of mangrove expansion to higher latitudes with increased winter temperatures (Osland *et al*., 2015; Saintilan *et al*., 2014; Armitage *et al*., 2015). This however is unlikely to manifest in the Pacific islands region, as the latitudes into which mangroves are expanding on continents are higher than those where land occurs in the region, and the region's oceanic distances are barriers to propagule transport. Long distance dispersal of mangroves is rare in reality (Yan *et al*., 2016).

Increased sea water temperatures, however, reduce coral reef productivity (Hoegh-Guldburg *et al*., 2007), providing an indirect vulnerability to mangroves from reduced sediment supply to mangroves on low islands, and increased exposure to wave action (Waycott *et al*., 2011).

Carbon dioxide increases

Continued increases in atmospheric CO_2 are very likely (IPCC, 2013), and expected to increase productivity of mangroves, provided salinity and humidity remain conducive to tree growth (Waycott *et al*., 2011). Mangrove responses to increasing atmospheric CO_2 will be complex (Alongi, 2015), benefitting some species, while others show little change or decline. Species patterns within estuaries on volcanic and continental islands (Table 1) may adjust based on the ability of each species in relation to increasing CO_2 levels to respond to changes over time and space in salinity, nutrient availability, and other drivers (Alongi, 2015). Increased allocation to below-ground biomass has been shown to occur with elevated CO_2, resulting in greater gains in soil surface elevation and stability under sea level rise (Langley *et al*., 2009).

An indirect impact of increased ocean acidity that results from elevated atmospheric CO_2 on mangrove systems could be reduction in the supply of carbonate sediment, essential for the resilience of atoll shorelines in particular (Ellison *et al*., 2017). Ocean acidification under RCP4.5 and RCP 6.0 will impact formation and maintenance of coral reefs (high confidence) (Carabine & Dupar, 2014).

Rainfall changes

Precipitation patterns in the region are 25% likely to not change, 25% likely to increase by 1-2% and 4% likely to increase by 4% (Christensen *et al*., 2013). Among the more dispersed Pacific Islands, the near-equatorial regions are likely to get wetter, and for Vanuatu, Tonga, Samoa, Niue, Fiji, a decrease in dry season rainfall may be accompanied by an increase in the wet season, indicating an intensified seasonal cycle (Christenson *et al*., 2013). However, these projections carry uncertainty even in the direction of change. There is high confidence that the ENSO very likely remains as the dominant mode of inter-annual variability, and due to increased moisture availability, the associated precipitation variability on regional scales likely will intensify (Christensen *et al*., 2013).

Reduced rainfall and humidity are expected to cause reduction in mangrove diversity, photosynthesis, productivity and growth rates along with substrate subsidence (Waycott *et al*., 2011). Depending on environmental conditions, mangroves can minimise water loss and maximise growth by using water more efficiently and reducing transpiration rates (Waycott *et al*., 2011). At locations with low rainfall and high evaporation, soil salinity in the upper intertidal gradient may be high, and during drought periods that are below average, extensive mortality has been shown to occur (Duke *et al*., 2017).

Rainfall patterns can affect reproductive success of mangroves, with three species of mangroves in Fiji shown to have greater reproductive success on the wetter west coast of Viti Levu relative to the leeward dry coast, and in normal years relative to drought years (Tyagi & Pillai 1996, Tyagi 2001). Reduced precipitation has been shown to negatively influence mangrove reproduction rates (Agraz Hernández *et al*., 2015), *Rhizophora mangle* showing reduced flowering and hypocotyl production during drier periods relative to normal. Overall, decreased precipitation is expected to result in notable reduction of mangrove area caused by the conversion of upper tidal zones to drier, hypersaline flats (Short *et al*., 2016). Reduced catchment rainfall and river flow on volcanic and continental islands (Table 1) may decrease the delivery of sediment to estuarine mangrove habitats, reducing accretion rates that allow mangroves to adapt to rising sea levels (Ellison, in press).

Cyclones and storms

Climate change projections have indicated an intensification of tropical and extra-tropical cyclones, combined with larger extreme waves and storm surges (IPCC, 2013). Strong, destructive winds and extreme tides can cause physical damage to mangroves and exacerbate coastal erosion, and may also increase physiological stressors including salinity and anoxia associated with more frequent and prolonged periods of flooding (Short *et al*., 2016).

While immediate damage from severe storms is high in mangroves, they can mostly recover from impacts by re-foliating, re-sprouting or regenerating (Kauffmann & Cole, 2010). Subsequent to severe damage from Cyclone Yasi in Queensland, mangrove regeneration occurred, but was hindered in areas that had suffered erosion or changes to the sediment substrate (Ashbridge *et al*., 2015). As a result of sediment movement during storm wave action or catchment runoff, mangroves can be killed by shallow sediment burial (Ellison, 1999). If the ground level is eroded to below the elevation that mangroves inhabit, then successful regrowth of seedlings will not occur.

Over time, recruitment of seedlings mostly occurs from adjacent undamaged areas, and the mangrove habitat becomes re-established. This natural adaptive capacity can be enhanced and accelerated by replanting programmes. Storms can however be a tipping point for mangrove areas under stress from other climate change effects.

Sea level rise

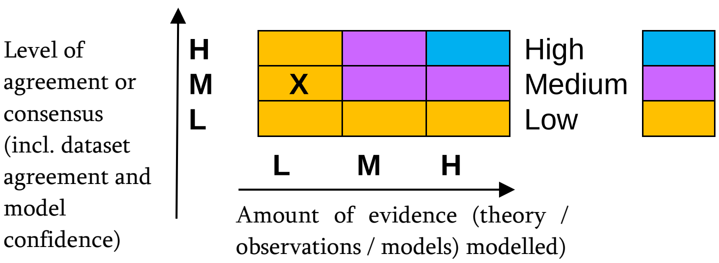
In the RCP4.5 scenario, sea level rise in the Pacific islands region is likely of 0.5-0.6 m by 2081-2100 relative to 1986-2005 sea levels (Nurse *et al*., 2014), and in the RCP8.5 scenario 0.74 [0.52-0.98] m (Church *et al*., 2013). RSLR will vary from these projections owing to the tectonic settings of different Pacific islands (Ellison & Strickland, 2015), and regional variability caused by the ENSO. The ENSO plays a strong role in the tropical western Pacific regional sea level, with lower than average sea level during El Niño events and higher than average sea level during La Niña events, by as much as plus or minus 200–300 mm (Carabine & Dupar, 2014). The large variability caused by El Niño and the shortness of many individual tide-gauge records contribute to the uncertainty of historical rates of sea-level rise (Church *et al*., 2006), and hence the tectonic deviations of local sea level trends relative to the IPCC sea level rise projections. The Pacific islands region is tectonically active, with some islands and coastlines subsiding and others uplifting (Nunn, 1998). With global sea level rise, subsiding coastlines such as western Viti Levu are more vulnerable to RSLR compared to uplifting coastlines (Ellison, 2015), such as the uplifting Amal area of Crab Bay, Vanuatu (Veitayaki *et al*., 2017).

Mangroves grow between mean sea-level and mean high water (Figure 2), and zonation across this profile of mangrove species is controlled by inundation frequency of tidal waters. With RSLR, these tidal conditions under which mangroves grow are altered, so the growth and survival of existing trees is affected. Increased sea level rates of rise have great potential impact on mangroves, however, where mangroves can continue to accumulate sediments at appropriate rates, the effects will be less severe. Mangrove inundation related mortality may be mitigated if mangrove substrates can "keep up" with rising sea level by accretion, which can be promoted by mangrove biogeomorphic processes of autogenic accumulation and mineral sediment trapping (Ellison, in press). However, mangroves with low tidal range and low sediment supply could be submerged as early as 2070, including northern Papua New Guinea and the Solomon Islands (Lovelock *et al*., 2015). The Pacific islands region is micro-tidal with tidal ranges mostly around 1 m, which will cause their mangroves to have greater vulnerability relative to macro-tidal mangroves (Ellison, 2012b; 2015).

Mangrove migration inland is possible, but in reality this involves mortality at current locations, and successful establishment of new trees from seedlings at higher elevations, if suitable habitats exist and are not blocked by human infrastructure such as coastal roads. Some literature using the term "inland migration" may underestimate the disruption and uncertainties in timeframes that these processes involve for trees, relative to people. Mangrove species of the landward margin are particularly vulnerable to sea-level rise if recruitment inland is blocked owing to coastal development or topography (Di Nitto *et al*., 2008), causing their habitat to be squeezed as more seaward mangroves recruit into the landward zone. Such species that occur at the landward edge, or upstream in tidal estuaries include *Nypa fruticans, Lumnitzera racemosa, Lumnitzera littorea, Sonneratia caseolaris, Sonneratia lanceolata,* and *Xylocarpus granatum* (Polidoro *et al*., 2014).

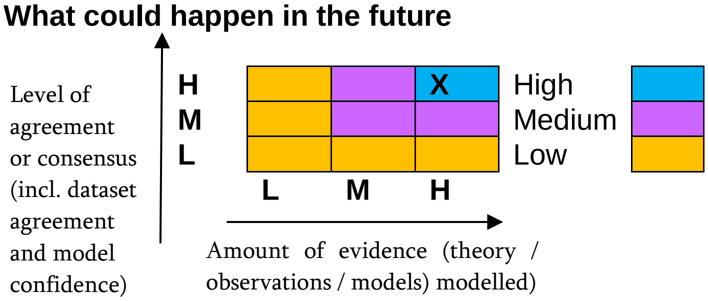
Confidence Assessment

What is already happening



There is limited published information on the current health and status of Pacific island mangroves. Mangrove seaward edge retreat attributed to relative sea level rise has been shown by spatial analysis 1961-2003 in American Samoa, long-term mangrove zone retreat landward has been shown from the tectonically subsiding coastlines of SW Papua and Tikina Wai, Fiji, and Micronesian mangrove substrates are not keeping up with relative sea level rise, all indicating future vulnerability with accelerated rates.

What could happen in the future



Assessments of potential future effects on Pacific island mangroves utilise long-term palaeoecological reconstructions, vulnerability assessments from Fiji, accretion rate measurements from Micronesia, and relevant evidence from outside of the region where a great deal more research is available. There is a high level of agreement and consensus from these, and the IPCC WG2 chapters, that the potential impacts of projected sea level rise will be high on mangroves. Impacts of other climate change effects are less certain.

Knowledge Gaps

The most critical components of a mangrove climate change vulnerability assessment are exposure components of relative sea level trends and sediment supply, and sensitivity components of forest health, recent spatial changes and net accretion rates (Ellison, 2015). All of these are huge gaps in knowledge for the majority of Pacific island mangroves.

Socio-economic Impacts

As many Pacific island communities are dependent on mangrove areas for provision of daily protein from fish and crabs, the potential impacts of mangrove loss are high. As shown in Figure 2, there are a range of other benefits that mangroves provide to people, hence mangrove loss will bring risks and hardship to Pacific island people.

Adaptation options

Adaptation options for identified climate change vulnerabilities in mangrove areas are provided in Ellison (2012b), as a result of trials in countries including Fiji. These are summarised in Table 2.

Table 2. Summary of mangrove adaptation priority actions to reduce climate change vulnerability, of which detailed guides are provided in Ellison (2012b).

	Improve local management	Reduce non-climate stressors	Improve legislation	Strategic protected areas	Rehabilitate and replant	Promote accretion	Plan for inland migration	Monitoring and evaluation	Reef/seagrass rehabilitation
Low tidal range				■		■	■	■	
Relative sea level rise is high						■	■	■	
Sedimentation supply rate is low						■		■	
Drier conditions projected					■			■	
Mangrove condition is poor	■	■		■	■		■	■	
Seaward edge retreating						■	■	■	
Mangrove area loss						■	■	■	
Elevations in mangroves						■	■	■	
Elevations above unavailable							■	■	
Sedimentation rates low						■		■	
Adjacent coral reef resilience low		■						■	■
Adjacent seagrass resilience low		■						■	■
Management capacity low	■							■	
Stakeholder involvement poor	■		■					■	
Protection legislation weak			■					■	

Promotion of mangrove substrate accretion is a priority to several vulnerabilities (Table 2) and will enable natural mangrove ecosystem-based adaptation to mitigate sea level rise. The following actions promote mangrove sedimentation:

- Reduction of non-climate stressors, such as human impacts, to improve health and condition of the existing mangrove forests
- Rehabilitation of degraded mangrove areas, particularly sections that are eroding, as dense seedlings enhance accretion
- Coastal zone planning to remove obstructions to sediment supply. This includes removal or redesign of coastal structures that interrupt longshore drift or enhance reflective wave action
- Influencing river dam design and operation to maintain fluvial sediment supply to mangrove areas
- Prohibition of sediment removal or dredging from areas that are a source of sediment to mangrove areas
- Reduction and control of boat wakes close to mangrove areas and margins
- Active enhancement of mangrove sediment accretion rates, by use of coastal structures, has been shown to be successful in mangrove restoration along an eroding coastline in Malaysia (Hashim *et al*., 2010; Tamin *et al*., 2011). There is potential for trials of such approaches for mangrove planting on Pacific island shorelines (Ellison *et al*., 2017).

Mangrove monitoring is an overall priority action, to assess ongoing condition and the results of adaptation actions. Regional protocols are given in Ellison *et al*. (2012).

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