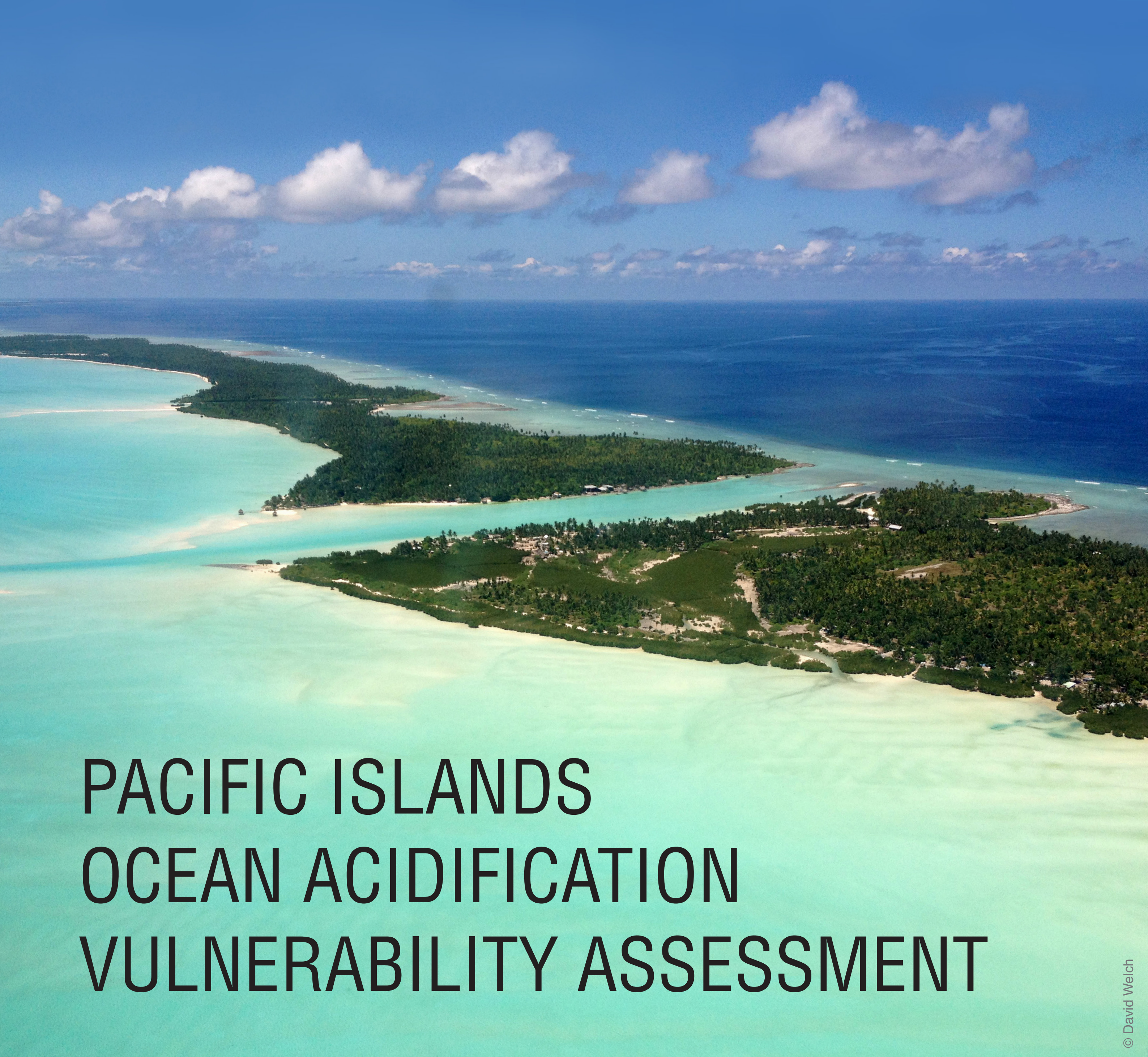

PACIFIC ISLANDS OCEAN ACIDIFICATION VULNERABILITY ASSESSMENT

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EXECUTIVE SUMMARY

The Pacific island region covers an area of more than 27 million km^2 and is dominated by ocean. The 22 Pacific island countries and territories are mostly small island states with significant geological, biological, and social diversity. Unsurprisingly, Pacific island people have a high dependence on their ocean resources for food security, livelihoods, and economic revenue, as well as cultural connections to marine environments and animals.

Throughout the tropical Pacific, fisheries and aquaculture make vital contributions to economic development, government revenue, food security, and livelihoods. Climate change, and ocean acidification, are expected to have profound effects on the status and distribution of coastal and oceanic habitats, the fish and invertebrates they support and, as a result, the productivity of fisheries and aquaculture.

Anthropogenic activities have caused a significant increase in greenhouse gas emissions into the Earth's atmosphere, with 24–33% of the excess carbon dioxide being absorbed by oceans globally, changing the chemical composition of seawater. Average ocean pH is now 8.1 and varies seasonally and spatially by 0.3 units. Increased emissions of greenhouse gases have decreased the pH of the tropical Pacific Ocean by 0.06 pH units since the beginning of the industrial era (in the early 19th Century), and the current rate of decrease is ~0.02 units per decade. Ultimately, the pH of the tropical Pacific Ocean is projected to decrease by a further 0.15 units from the historical 1986–2005 period by 2050.

Declining ocean pH will cause dramatic changes in aragonite (calcium carbonate) saturation, with implications for calcifying organisms, such as corals, some plankton, and shellfish. The best available modelling suggests that by 2050, only about 15% of coral reefs around the world will be in areas where aragonite levels are 'adequate' for sustainable coral growth. The Pacific island region will experience similar changes and, as a result, oceanic and coastal reef habitats are expected to be modified. Subsequent declines in fisheries productivity of some target species (e.g. reef fish and sea cucumbers) and impacts on calcareous aquaculture commodities (e.g. pearl oysters and marine ornamentals) are anticipated.

Some species associated with coral reefs will be affected by ocean acidification directly and indirectly through declines in the structural complexities of coral reef habitats. The direct effects of ocean acidification on tuna resources have yet to be determined, but the indirect effects are expected to be minor. However, the loss of calcareous organisms in oceanic food webs could have a significant effect on the transfer of anthropogenic carbon from the photic zone to the deep ocean. Aquaculture commodities in the tropical Pacific that are expected to be most vulnerable to ocean acidification are pearl oysters, shrimp, and marine ornamentals, whereas seaweed may benefit from increased levels of CO_2 in seawater in some locations depending on the influences of other environmental changes (e.g. increasing temperatures and rainfall).

There are significant implications of the combined effects of population growth and reef degradation due to ocean acidification and coral bleaching for reef-dependent communities in many Pacific island countries. The countries that were assessed as having reef-dependent communities with the highest relative vulnerability to ocean acidification impacts on reefs and their fisheries (for food security and livelihoods), aquaculture (for jobs), and tourism (for jobs and contribution to GDP) were (in order of most vulnerable) Solomon Islands, Kiribati, Papua New Guinea (PNG), Federated States of Micronesia (FSM), Tonga, and Tuvalu. The Pacific island countries and territories that had the lowest relative vulnerability to ocean acidification impacts on reefs and the goods and services they provide were Niue, the Commonwealth of the Northern Mariana Islands (CNMI), Tokelau, New Caledonia, and Guam. High ratios of reef to land area, dependence of household incomes on coastal fisheries, and limited education as a key component of low adaptive capacity all contribute to high vulnerability.

Based on preliminary tuna distribution modelling, Kiribati, Tuvalu, Tokelau, Cook Islands, and French Polynesia are likely to have future opportunities to negotiate increased access fees for distant water fishing nations. In contrast, the eastward shift in the distribution of skipjack tuna could pose some problems for tuna catches and processing in the western Pacific region.

The key implications of ocean acidification for governance and management centre around identifying the extent to which declines in fisheries and aquaculture productivity are likely to affect the regional and national plans and policies that Pacific island countries and territories have put in place to maximise the sustainable benefits for economic development, food security, and livelihoods. Efforts to reduce dependence on marine resources will present part of the solution as the impacts of ocean acidification manifest in the Pacific region and marine resources decline.

Pacific island nations that have rapidly growing, reef-dependent communities, which are vulnerable to declines in reef condition, demersal and invertebrate fisheries, and aquaculture, have limited ability to adapt, and will need targeted assistance to adapt as ocean acidification accelerates. For example, adaptation actions for food security will need to focus on (1) improving the management of the coastal zone and coastal fish stocks to reduce the gap to be filled between the fish needed for food security and sustainable fish harvests from coral reefs and (2) developing practical ways to fill the food gap with tuna. The lack of ocean acidification monitoring data in the region (along with the need for more comprehensive reef and fisheries data) is a significant issue that needs to be addressed through national and regional-scale policy and planning. Ultimately, if emissions keep rising over the 21st century the pH of the tropical Pacific Ocean is projected to decrease by a further 0.15 units from the historical 1986–2005 period by 2050.

OCEAN ACIDIFICATION PROJECTIONS FOR THE PACIFIC ISLAND REGION

INTRODUCTION

The tropical Pacific region encompasses 22 Pacific island countries and territories (PICTs) across more than 27million km^2 of the tropical and subtropical Pacific Ocean. From an oceanographic and fisheries management perspective, this region includes the area known as the Western and Central Pacific Ocean. Given this vast area, it comes as no surprise that the region has significant geological, biological, and social diversity. The region has historically been divided into three sub-regions in recognition of this diversity—Melanesia, Micronesia, and Polynesia—based on the physical nature of the islands, biogeography, ethnic origin and culture (Figure 1).

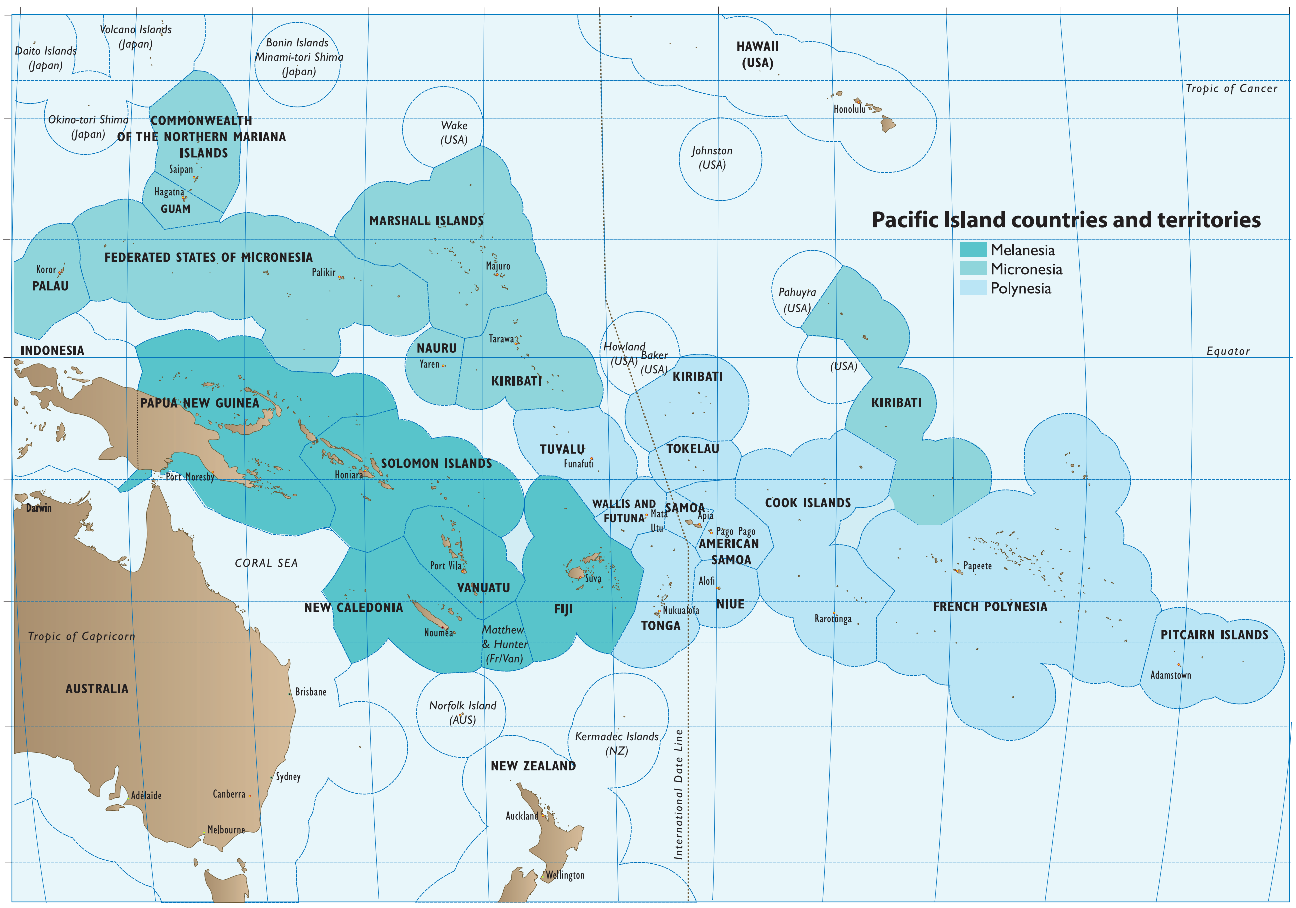


Figure 1. Map of the tropical Pacific island region (Source: Pacific Community).

Throughout the tropical Pacific, fisheries and aquaculture make vital contributions to economic development, government revenue, food security, and livelihoods (Bell et al. 2011a, 2013). Climate change, and specifically ocean acidification, are expected to have profound effects on the condition, abundance, and distribution of coastal and oceanic habitats, the fish and invertebrates they support and, as a result, the productivity of fisheries and aquaculture in the tropical Pacific. Ocean acidification are expected to become an increasingly significant driver of environmental change as the absorption of carbon dioxide (CO_2) by oceans accelerates and critical thresholds are passed. Pacific island people need to know whether future changes in ocean chemistry due to acidification are likely to irreversibly change their marine ecosystems and disrupt the plans being developed to optimise the economic and social benefits they receive from fisheries and aquaculture.

This report aims to address these questions by summarising the projected changes in ocean chemistry for the Pacific island region (from 130°E to 130°W and 25°N to 25°S) at regional and sub-regional scales, assessing the vulnerability of Pacific coastal and oceanic habitats and fisheries to ocean acidification using an established framework, and discussing the implications for Pacific island communities dependent on fisheries and aquaculture for food security and livelihoods. Lastly, the report provides insight into the implications for economic revenue, current governance, and management, along with some recommendations. The challenge for management and policy makers is to mainstream strategies that address the implications of ocean acidification on marine ecosystems, seafood supply, and livelihoods for dependent communities and economies.

1.2 SUMMARY OF CLIMATE CHANGE PROJECTIONS FOR THE TROPICAL PACIFIC

Global climate change is of particular concern to the tropical Pacific region due to the vast area of ocean, the dependence of Pacific Islanders on their marine resources, and the exposure of many small island nations to projected changes. Anthropogenic activities have caused a significant increase in greenhouse gas emissions into the Earth's atmosphere, with 24–33% of the excess CO_2 being absorbed by oceans globally (Le Quéré et al. 2009), changing the chemical composition of seawater (Sabine and Feely 2007).

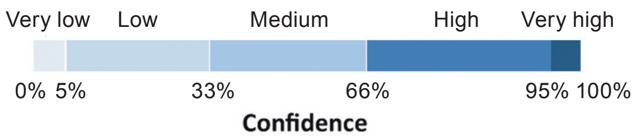
The acidity of the global oceans has been relatively stable for millions of years. Due to this stability, carbonate ions are naturally abundant, and the common pure minerals of calcium carbonate (aragonite and calcite) are formed in surface waters and do not dissolve. The pH of the ocean is related to the amount of carbon dioxide in the atmosphere (see Appendix A). Average ocean pH is now ~8.1 and varies seasonally and spatially by ~0.3 units due to changes in sea surface temperature and upwelling of deep waters rich in CO_2. Increased emissions of CO_2 have decreased the pH of the tropical Pacific Ocean by 0.06 pH units since the beginning of the industrial era (Raven et al. 2005). The current rate of decrease is ~0.02 units per decade, which roughly corresponds to an increase in surface hydrogen ion content of 30%, and is unprecedented in the past 300 million years. The increased acidity of seawater is reducing the saturation state of aragonite, the mineral that calcifying organisms, such as corals, certain plankton, and shellfish, use to build calcium carbonate skeletons.

Importantly, ocean acidification is only one of the environmental changes being driven by increasing greenhouse gas emissions. Some of the other properties of the tropical Pacific Ocean also projected to alter under climate change include sea surface temperature, sea level, nutrient supply, dissolved oxygen levels, and wider ocean circulation patterns (Table 1). These changes interact to impact on the marine ecosystems and organisms of the Pacific islands region, which will have implications for dependent communities and industries (Bell et al. 2011a, Bell and Taylor 2015).

TABLE 1. Summary of observed and projected changes to the main features of the tropical Pacific region. Observed changes are relative to the period 1950–1960. Projected changes are relative to 1980–1999. Estimates of confidence are provided for each projection (Source: Bell et al. 2011b).

Ocean feature	Observed changes	2035		2100	
		B1	A2	B1	A2
Currents	South Pacific gyre has strengthened	SEC decreases at the equator; EUC becomes shallower; SECC decreases and retracts westward in the upper 50 m			
Sea surface temperature		Projected to increase significantly over the entire region			
		+0.6 to +0.8°C	+0.7 to +0.8°C	+1.2 to +1.6°C	+2.2 to +2.7°C
Ocean temperature at 80 m	+0.6 to 1°C since 1950	+0.4 to +0.6°C		+1.0 to +1.3°C	+1.6 to +2.8°C
Warm Pool	Warmer and fresher	Extends eastward; water warms and becomes fresher, and area of warmest waters increases			
Equatorial upwelling	Decreased	Integral transport 9°S–9°N remains unchanged			
Eddy activity	No measurable changes	Probable variations in regions where major oceanic currents change			
Nutrient supply	Decreased slightly in two locations	Decrease due to increased stratification and shallower mixed layer, with a possible decrease of up to 20% under A2 by 2100			
Dissolved oxygen	Expansion of low-oxygen waters	Possible decrease due to lower oxygen intake at high latitudes			
		Possible increase near the equator due to decreased remineralisation			
Ocean acidification		Aragonite saturation (Ω) projected to continue to decrease significantly			
	➢ Ω decreased from 4.3 to 3.9	n/a	Ω ~ 3.3	Ω ~ 3.0	Ω ~ 2.4
	➢ Ω horizon rises from 600 to 560 m	n/a	~ 456 m	n/a	~ 262 m
	➢ pH decreased from 8.14 to 8.08	n/a	~ 7.98	n/a	~ 7.81
Waves	Increased in far west Pacific; no data elsewhere	Slight increase (up to 10 cm) in swell wave height; patterns depend on ENSO and tropical cyclones			
Sea level	+6 cm since 1960	Projected to rise significantly			
		*	+8 cm	+18 to +38 cm	+23 to +51 cm
		**	+20 to +30 cm	+70 to +110 cm	+90 to +140 cm
Island effects	Not observed	Probable; undocumented			

* Projections from the IPCC-AR4, not including any contribution due to dynamical changes of ice sheets; ** projections from recent empirical models (Section 3.3.8.2); SEC = South Equatorial Current; EUC = Equatorial Undercurrent; SECC = South Equatorial Counter Current; ENSO = El Niño-Southern Oscillation; n/a = estimate not available.



1.3 OCEAN ACIDIFICATION PROJECTIONS

Future changes in ocean pH and aragonite saturation will largely depend on the atmospheric concentration of CO_2. These values are also affected, to a smaller extent, by changes in water temperature and salinity. A number of state-of-the-art climate models are now available as part of CMIP5[1] (Taylor et al. 2012) that include the effects of ocean chemistry (older models only reproduce physical changes to the climate system) and can be used to project future chemical changes. The following analysis uses a new multi-model dataset of ocean chemical properties developed by Lenton et al. (in press).

Based on the RCP8.5 'business-as-usual' scenario[2] that assumes a continuation of the rapid increase in global CO_2 emissions, tropical Pacific pH is projected to decrease by a further 0.15 units from the historical 1986–2005 period into the 2040–2060 period (averaged between 15°S to 15°N and 120°E to 280°E). Moreover, dramatic changes in aragonite saturation are also projected to occur (Figure 2). Saturation levels greater than 4 are considered optimal for coral calcification, while levels less than 3.5 are considered very low for a healthy reef system to continue reef-building (Langdon and Atkinson 2005). Saturation levels less than 3 are considered extremely marginal for growth of corals, with no major reef systems currently found at locations with these levels. Model projections suggest that by mid-century, the entire tropical Pacific region will have shifted to sub-optimal conditions, with aragonite saturation levels between 3 and 3.5. This represents a drop of approximately 0.6 in the tropical region, corresponding to a decline in coral calcification rate of about 10% (Chan and Connolly 2013).

1 Coupled Model Inter-comparison Project (version 5) represents a number of climate change experiments using multiple climate models from different scientific groups.

2 RCP85 'business-as-usual' scenario assumes that atmospheric CO_2 concentration rises from present day values of ~400 ppm to ~540 ppm in 2050.

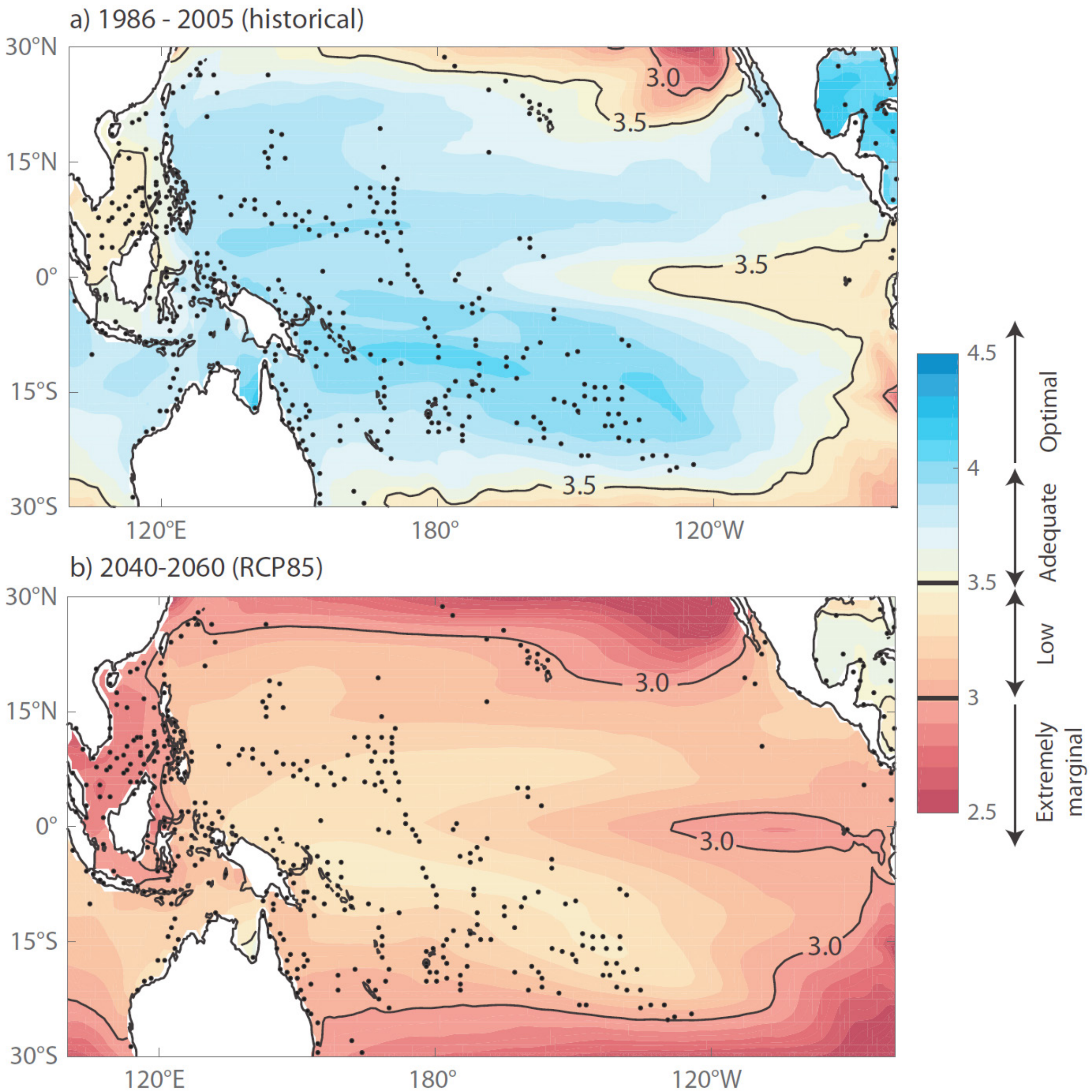


FIGURE 2. Aragonite saturation state for the periods (a) 1986–2005 (based on a multi-model median from the CMIP5 historical simulations) and (b) 2040–2060 (based on RCP8.5 simulations). Contour lines of 3 and 3.5 are superimposed. Black dots indicate location of coral reefs (Multi-model data source: Lenton et al. [in press]).

VULNERABILITY OF TROPICAL PACIFIC HABITATS AND FISHERIES TO PROJECTED OCEAN ACIDIFICATION

This vulnerability assessment is based on the highest 'business-as-usual' (RCP8.5) emissions scenario from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR5 2014) for a future timeframe centred around 2050 (2040–2060), relative to a 1986–2005 baseline. Global greenhouse gas emissions are currently on a trajectory that approximately matches that of RCP8.5.

This vulnerability assessment also applied a widely accepted framework adopted by the IPCC and several other initiatives aimed at assessing vulnerability to climate change (Schneider et al. 2007) and refined for application as a semi-quantitative method to marine ecosystems and communities (Bell et al. 2011a, Welch and Johnson 2013). The framework assesses vulnerability as a function of exposure, sensitivity, and adaptive capacity (Figure 3).

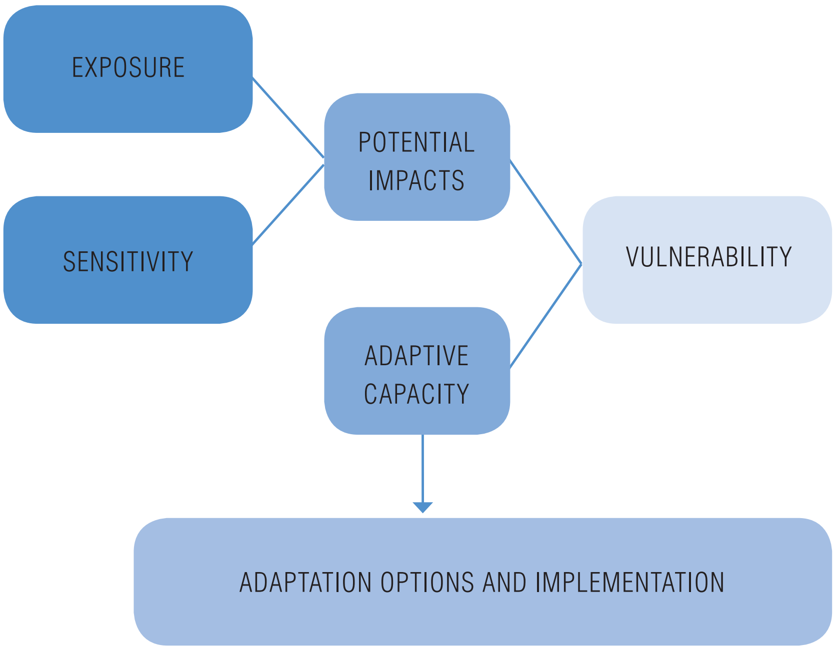


FIGURE 3. Vulnerability assessment framework used for ocean acidification in the tropical Pacific

Some important factors that were considered when conducting the assessment include (1) spatial variation in ocean acidification because not all parts of the tropical Pacific Ocean will be exposed equally to changes in biogeochemistry, (2) the different sensitivities of marine species to ocean acidification, and (3) the resilience of dependent Pacific island communities to cope with the socio-economic consequences of ocean acidification.

2.1 CORAL REEFS AND COASTAL FISHERIES

The tropical Pacific Ocean contains more than 25% of coral reefs in the world—nearly 66,000 km²—with some PICTs having very large areas of reef under their jurisdiction, areas that are often larger than their land area. For example, 12 PICTs have at least twice as much reef as land, and some of these have vastly more reef area (Table 2). These large areas of coral reef provide important goods and services to the people of the Pacific island region, including essential habitats for coastal fisheries and coastal protection. For many of these Pacific island communities, coral reefs provide important sources of protein and income that they could not obtain elsewhere. The high annual fish consumption per capita reflects this reliance on reefs for food, as well as a source of livelihoods for households (Table 2).

TABLE 2. Indicators of PICT dependence on coral reefs: land area and reef area (PICTs with twice as much reef highlighted in green), annual national fish consumption, and household income from coastal fisheries (data source: Bell et al. 2011b). n/a: data not available

PICT	Reef area (km²)	Land area (km²)	National fish consumption (kg/person)	1st or 2nd income from coastal fishing (%)
American Samoa	368	197	63	n/a
Cook Islands	667	240	35*	20.1
Federated States of Micronesia (FSM)	15,074	700	69*	52.5
Fiji	10,000	18,272	21*	93.3
French Polynesia	15,126	3,521	70*	26.7
Guam	238	541	27	n/a
Kiribati	4,320	810	62	58.1
Marshall Islands (RMI)	13,930	112	39	53.6
Nauru	7	21	56	22.0
Niue	56	259	79	10.1
CNMI	250	478	n/a	n/a
New Caledonia	35,925	19,000	26*	46.2
PNG	22,200	462,243	13#	85.8
Palau	2,496	494	33*	25.9
Pitcairn Islands	48	5	148	n/a
Samoa	466	2,935	87*	50.8
Solomon Islands	8,535	27,556	33	61.0
Tokelau	204	10	200	n/a
Tonga	5,811	699	20*	46.2
Tuvalu	3,175	26	110*	48.4
Vanuatu	1,244	11,880	20	61.1
Wallis & Futuna	932	255	74	44.3

* PICTs where the rural fish consumption per person is higher than the national average.

\# Fish consumption in coastal PNG is 53 kg/person/year, significantly higher than national average.

From a global perspective, the Pacific region has experienced relatively low pressure on coastal resources; however, almost 50% of coral island reefs are currently considered threatened, with about 20% rated as highly or very highly threatened (World Resource Institute 2012). Overfishing and runoff from land-based sources are the predominant threats. Coastal development is also a major pressure in some urbanised areas. For example, the remote atoll reefs in French Polynesia, the FSM, and the Marshall Islands have some of the lowest overall threat ratings, but localised threats are high in these PICTs around the more developed islands (World Resource Institute 2012). Ocean acidification is expected to exacerbate pressures already threatening these important ecosystems.

Projections that the tropical Pacific Ocean will become more acidic mean that less aragonite will be available for corals to build their skeletons (see Section 1.3). The consequences of this change for coral reefs are slower coral growth and compromised reef structures. The present-day aragonite saturation level is close to the point where calcareous organisms may already be experiencing a weakening in their skeletons and shells. In this state, reef systems will be far more susceptible to other pressures, including coral disease and bleaching, which are also projected to increase in frequency due to climate change and are a more imminent threat to reefs (Meissner et al. 2012, van Hooidonk et al. 2014). These changes are also likely to reduce the fitness of calcareous organisms and their resistance to predation.

The best available modelling suggests that by 2030, about 50% of the world's reefs will still be in areas where aragonite levels are 'adequate' for coral growth, that is, where aragonite saturation state is 3.5 or higher. By 2050, however, only about 15% of reefs will be in areas where aragonite levels are 'adequate' for sustainable coral growth (World Resource Institute 2012). In the tropical Pacific Ocean, the area with suitable chemistry for coral growth will decrease in proportion to the global average of 15%, with much of the region having 'low' or marginal aragonite saturation for calcification, 'adequate' areas located in the central Pacific, and with the far eastern region at or below an aragonite saturation state of 3 by 2050 (Figure 2).

Reef-building corals require specific environmental conditions, e.g. temperature, salinity, and light, to survive, and ocean chemistry is particularly important for calcification rates and growth. Due to the importance of carbonate ions for reef calcification (Hoegh-Guldberg et al. 2007, Doney et al. 2009), reductions in aragonite saturation will decrease the calcification rate of reef-building corals and other calcifying organisms (e.g. molluscs and crustaceans).

As well as declining calcification rates, reduced carbonate ion concentrations are likely to increase the rate of biological erosion (via reduced density of coral skeletons and increased dissolution), allowing the activities of external bio-eroders (e.g. fish and sea urchins) as well as internal bio-eroders (e.g. worms and sponges) to dominate (Hoegh-Guldberg et al. 2011) (Figure 4). Tipping the balance between reef calcification in favour of erosion will result in a progressive loss of reef structure and integrity. The precise relationship between reef calcification and erosion depends on a number of factors, such as water quality, location, and latitude (Hoegh-Guldberg et al. 2011). While ocean acidification is expected to be detrimental to calcifying organisms, greater CO_2 concentrations may result in increased productivity of seagrasses, mangroves, macroalgae, and non-calcifying seaweed, although particular life stages of these organisms may be sensitive to more acidic conditions (Cheung et al. 2015), (section 2.2).

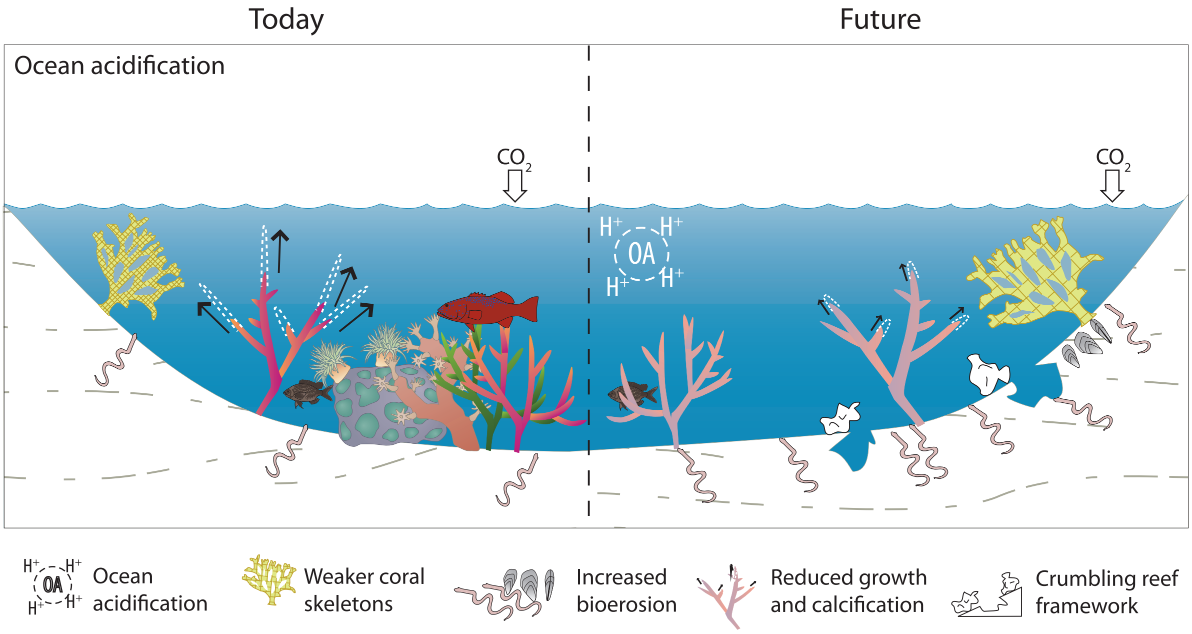


FIGURE 4. Effects of projected ocean acidification (ocean acidification) on coral reefs. Reduced calcification of reef-building corals and calcareous algae as ocean pH declines is expected to change the balance of reef processes from net construction to net erosion, leading to loss of corals and reef frameworks (Source: Hoegh-Guldberg et al. 2011).

Based on the predicted impacts of ocean acidification on tropical Pacific habitats, coral reefs are considered to be the most vulnerable marine habitat in the tropical Pacific region, with reductions in reef-building calcification rates and structural integrity expected.

Although adult reef fish have not been shown to be directly vulnerable to ocean acidification, with no documented affects of CO_2 concentrations up to 1000 ppm on growth or larval development, they are expected to be at risk from the indirect effects of ocean acidification impacts on their habitat, particularly coral reefs (Pratchett et al. 2011). Of greater concern is the effect that elevated CO_2 concentrations have on the sensory ability of larval reef fish to use olfactory cues to distinguish their preferred settlement habitat or to avoid predators (Munday et al. 2009, Dixson et al. 2010, Ferrari et al. 2011, Devine et al. 2012). Although only demonstrated in a limited number of reef fish species, any effects of ocean acidification on these processes could have serious implications for the replenishment potential of reef fish populations (Munday et al. 2010). Some possible effects also remain unknown, such as the effect of ocean acidification on the early life stages across a broader range of reef species, the possible synergistic effects of elevated sea surface temperature and acidification, and whether the genetic variation exists in reef fish populations to enable them rapidly adapt to changing seawater chemistry (Cheung et al. 2015).

Some commercially important molluscs and crustaceans, such as pearl oysters, shrimp, and marine ornamentals (e.g. giant clams), are predicted to be vulnerable to ocean acidification through reductions in shell production and quality under lower pH conditions (e.g. Kroeker et al. 2013; see Section 2.3.1).

Fish and shellfish are cornerstones of food security for the people of the tropical Pacific, with fish providing 50–90% of animal protein in the diet of coastal communities, and the national fish consumption per person in many PICTs being more than 3–4 times the global average (Bell et al. 2009, 2011a). In rural areas, much of this fish (60–90%) is caught by subsistence fishing. Many people in the Pacific island region also catch and sell fish: an average of 47% of households in surveyed coastal communities in 17 PICTs derived either their first or second income in this way (SPC 2008) (Table 2).

There are four main types of coastal fisheries associated with nearshore habitats to a depth of 50 metres in the tropical Pacific: (1) demersal (bottom-dwelling) fish, (2) nearshore pelagic fish (mainly tuna), (3) targeted commercial invertebrates, and (4) shallow subtidal and intertidal invertebrates. The main species caught by these fisheries, the main fishing methods, and the uses of the resources (subsistence and income) vary depending on the PICT. Demersal fish are estimated to make up 50–60% of total coastal fisheries production. Due to the strong association of demersal fish with reef habitat and the likely impacts of elevated seawater CO_2 concentrations on larval stages, this important fishery is expected to have moderate to high vulnerability to ocean acidification. Nearshore pelagic fish comprise about 30% of coastal fisheries catches, but these oceanic fish are expected to have low vulnerability to ocean acidification (see Section 2.3). Some species of subtidal and intertidal invertebrates are expected to be affected by ocean acidification because several of them have shells or other body parts made of calcium carbonate.

Overall, the production of demersal fish is estimated to decrease as a result of ocean acidification, primarily due to the indirect effects of reef habitat degradation caused by declining calcification rates of corals. In contrast, tuna catches are expected to increase in the medium-term (by 2050) in some PICTs (see Section 2.3). The productivity of targeted and intertidal invertebrate groups is expected to decrease but not as much as that of demersal fish (Pratchett et al. 2011).

There is special interest in the effects of ocean acidification on sea cucumbers, given their importance as a source of income for remote Pacific island communities. However, there has been no research on the effects of projected ocean acidification on the main species of sea cucumbers harvested in the region. Research on other sea cucumbers, and related sea urchins (Brennand et al. 2010, Byrne 2011, Byrne et al. 2011), suggests that these species may have some sensitivity to reduced concentrations of carbonate ions in seawater. Larval survival may be affected, and the size and strength of the calcareous spicules in the outer layer of their skin is likely to be reduced as acidification of the ocean increases (Pickering et al. 2011).

Based on the predicted effects of ocean acidification on coral reef habitats and larval reef fish, and on the body parts of invertebrates, this assessment has determined that the coastal fisheries in the Pacific island region with the highest relative vulnerability to ocean acidification are (1) demersal fish associated with coral reefs and (2) invertebrates with calcareous parts.

2.2 OTHER COASTAL HABITATS

Other structural components of coral reefs (crustose coralline algae) and other coastal habitats (seagrasses and mangroves) are also expected to respond to changes in ocean chemistry. Coralline marine algae are mostly calcified crustose species that play a very important role in consolidating the reef structure of coral atolls in many PICTs. Increased ocean acidification will have negative effects on the growth and reproduction of crustose coralline algae, thus increasing the fragility of coral reefs and increasing the exposure of coastal areas to extreme storm and wind events.

In contrast, seagrasses and other non-calcareous marine plants, such as mangroves and macroalgae, may benefit. Seagrass density has been shown to increase in response to a lower pH, with possible co-benefits to resident animals as the plants provide more food and protection from predators (Garrarda et al. 2014). Seagrasses also undergo a high rate of photosynthesis that may serve to buffer changes in ocean chemistry. Similarly, mangroves are expected to benefit from increased atmospheric CO_2 with increases in growth and productivity (Waycott et al. 2011). Such ecosystems were therefore not considered vulnerable to ocean acidification for the purposes of this assessment.

2.3 OCEAN HABITATS AND PELAGIC FISHERIES

Ocean acidification is expected to have indirect and direct effects on the rich tuna resources of the tropical Pacific—resources that are critical to the economic development of many Pacific island countries and which will be required to play an increasing role in the food security of Pacific island people (Bell et al. 2015a). The indirect effects are likely to occur through changes to the oceanic food webs on which tuna depend (Le Borgne et al. 2011). The direct effects are not as well understood but are likely to occur through the effects of lower pH on the reproductive potential of tuna, the physiology of tuna, and the behaviour and survival of larvae (Lehodey et al. 2011, Bromhead et al. 2015). The main projected indirect and direct effects of ocean acidification on tuna are summarised below.

2.3.1 Indirect effects due to changes in oceanic food webs

Although the effects of ocean acidification on oceanic food webs are not fully understood and are likely to be complex, increases in the partial pressure of carbon dioxide (pCO_2) in the ocean are expected to alter biological communities in at least three ways (Le Borgne et al. 2011). First, phytoplankton (haptophytes) and zooplankton (e.g. pteropods) that use aragonite to construct their skeletons will find it increasingly difficult to do so as ocean acidification increases (Fabry et al. 2008). Second, increases in pCO_2 are likely to exacerbate the effects of low oxygen concentrations on organisms living in the deep ocean (Brewer and Peltzer 2009). Third, an increase in diazotrophy (organisms in the food web that do not depend on fixed nitrogen, e.g. bacteria) is expected to occur, which is likely to change the relative abundance and species composition of grazers and microbial populations. Such organisms are important components of oceanic food webs (Figure 5).

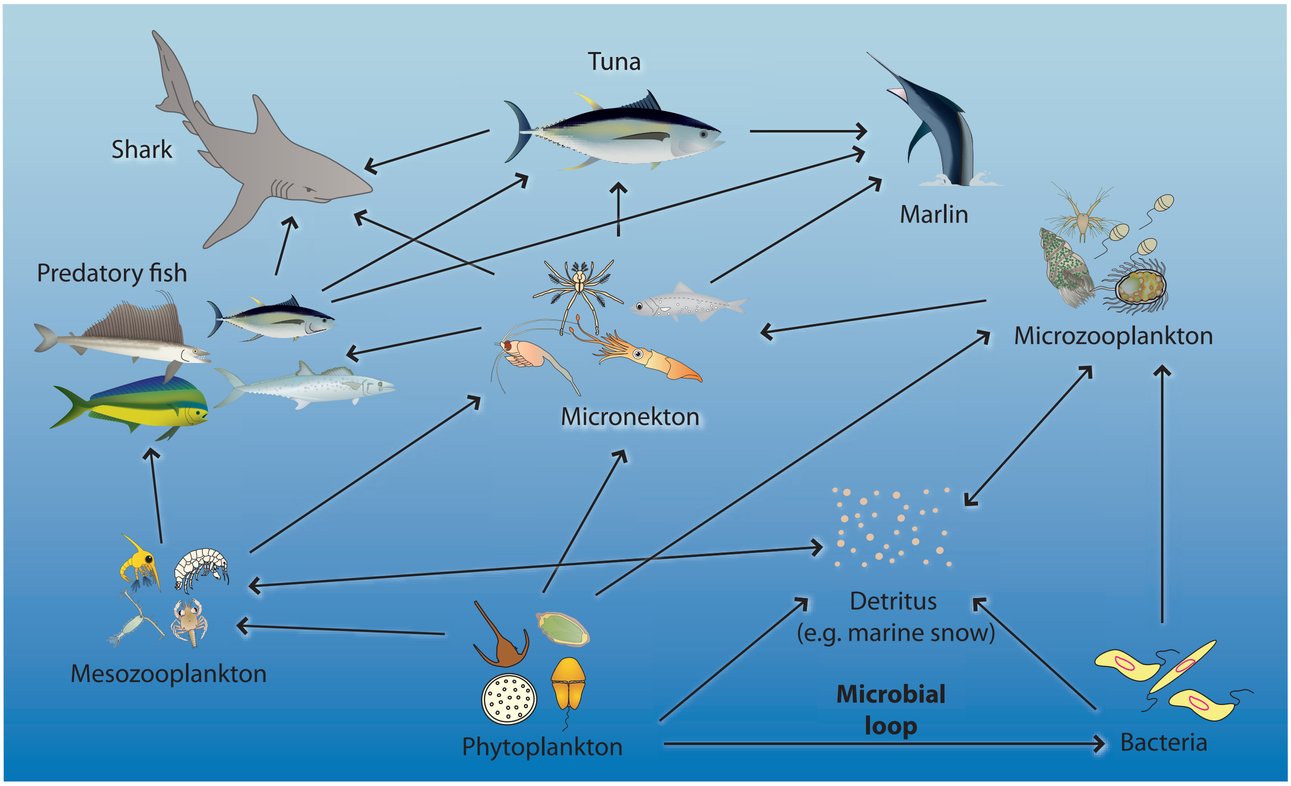


FIGURE 5. Generalised food web supporting tuna and other large pelagic fish (Source: Le Borgne et al. 2011).

The projected declines in aragonite saturation levels to between 3.0 and 3.5 by 2050 (Section 1) are expected to reduce calcification rates for organisms like pteropods by 2–9% (Le Borgne et al. 2011). Such rates are low compared to those projected for the Southern Ocean (Orr et al. 2005). Although these declines are expected to be greatest near the surface, the depth of the aragonite saturation horizon (below which aragonite dissolves) (Appendix A) is also expected to decrease over time. Pteropods and other calcifying phytoplankton and zooplankton will need to expend more energy to form aragonite as the saturation horizon for aragonite becomes shallower and supersaturation levels in the surface waters decrease. However, organisms with shells made of calcite (the other form of calcium carbonate) are expected to be less sensitive because greater decreases in pH are needed for 'shoaling' of the calcite saturation horizon (Orr et al. 2005).

Although ocean acidification could have unpredictable and cascading effects on oceanic food webs, the calcareous organisms likely to be affected directly are a minor part of the ecosystem. In surface waters, these organisms usually comprise <5% of the phytoplankton, ~5% of the zooplankton, and ~2% of the micronekton (Le Borgne et al. 2011). Calcifying animals living at greater depths will be more vulnerable due to the reduced depth of the aragonite saturation horizon.

Overall, the indirect effects of ocean acidification on tuna resources are expected to be minor because of the small contribution of calcareous organisms to micronekton, which is the primary prey of tuna. However, the loss of the calcareous organisms due to ocean acidification could have a significant effect on the transfer of anthropogenic carbon from the photic zone to the deep ocean via the 'biological carbon sink' (Watson and Orr 2003).

2.3.2 Direct effects on tuna

Little research has been done on the direct effects of ocean acidification on the four main species of tuna targeted in the tropical Pacific: skipjack, yellowfin, bigeye, and South Pacific albacore (Lehodey et al. 2011). However, studies to investigate the effects of lower pH on sperm vitality, egg fertilisation, and egg and larval development have begun for yellowfin tuna. Preliminary trials indicate that declines in ocean pH greater than those expected to occur by 2050 could cause significant reductions in survival of yellowfin tuna larvae (Bromhead et al. 2015).

Tuna could be directly sensitive to changes in pH in at least two other ways. First, an increase in carbonic acid from more acidic seawater could lead to a narrowing of the optimal thermal performance window and, consequently, to altered resistance, metabolic rate, and behaviour of tuna (Pörtner and Farrell 2008). In particular, the additional energy required to compensate for acidosis could lead to lower rates of growth and egg production. Second, the growth and formation of the ear bones (otoliths) of tuna may be susceptible to lower pH because otoliths are composed of aragonite. If so, the effects could be significant because otoliths are important for orientation and hearing, especially during the larval stage of fishes (Munday et al. 2009).

The direct effects of ocean acidification on tuna remain poorly understood but have potential to exacerbate future changes in the distribution and abundance of these economically important tuna due to alterations in sea surface temperature, reductions in primary productivity due to stratification of the ocean, changes in the convergence between the Western Pacific Warm Pool and the Pacific Equatorial Upwelling, and expansion of oxygen-poor zones resulting from global warming (Ganachaud et al. 2011, Le Borgne et al. 2011, Lehodey et al. 2011, 2013).

2.4 AQUACULTURE

2.4.1 Pearl oysters

Despite the value of pearl farming to the tropical Pacific (Pickering et al. 2011), there has been limited research on the effects of ocean acidification on the production of pearls from the black-lipped pearl oyster *Pinctada margaritifera*. However, research on the closely related *Pinctada fucata* (Welladsen et al. 2010) suggests that survival and growth of wild *P. margaritifera* spat, which provide the oysters for pearl farms in the tropical Pacific, are expected to decrease as shells are weakened by lower aragonite concentrations. Reduced availability of aragonite is also expected to affect pearl quality because aragonite is a key component of nacre (Pickering et al. 2011).

2.4.2 Shrimp

Like some other crustaceans, penaeid shrimp typically exert high biological control over calcification by gradually accumulating intracellular stocks of carbonate ions to harden their chitin and protein exoskeletons, usually in the less soluble form of calcite. Therefore, formation of the exoskeleton in shrimp is not highly sensitive to the projected reductions in aragonite saturation expected to result from ocean acidification. However, the species of shrimp farmed in New Caledonia, *Litopenaeus stylirostris*, may be more sensitive to acidification of seawater than other species of penaeid shrimp because of its thinner exoskeleton (Pickering et al. 2011). Given the detrimental effects of marks such as 'black spot' on the price received for shrimp by farmers in New Caledonia, any deformities due to the effects of ocean acidification on the thinner exoskeleton of the species would be expected to reduce profits.

2.4.3 Seaweed

Higher projected concentrations of dissolved CO_2 in seawater are likely to stimulate the growth of seaweed (*Kappaphycus alvarezii*) farmed in Kiribati, Fiji, Solomon Islands and Papua New Guinea. Like all plants, *K. alvarezii* depends on CO_2 for photosynthesis and might be expected to have a faster growth rate as the concentrations of CO_2 in the ocean increase. However, as explained by Pickering et al. (2011), other consequences of increased CO_2 emissions for the tropical Pacific—increases in sea surface temperature and rainfall—are likely to retard the growth of seaweed. Thus, any potential benefits to seaweed farming from the higher levels of dissolved CO_2 in seawater are unlikely to eventuate in many of the locations currently used to grow *K. alvarezii.*

2.4.4 Marine ornamentals

The declining pH of the tropical Pacific Ocean is expected to affect the growth and shell formation of calcifying species farmed for marine ornamental aquarium markets, primarily corals, giant clams, and more recently live-rock (Pickering et al. 2011). Corals, live-rock, and giant clams are likely to have their skeleton and shell formation affected by increased seawater acidification. These aquarium products will also be impacted by other features of climate change, such as increasing sea surface temperature, which causes bleaching, and the detrimental effects of increased runoff from changes in rainfall patterns.

Aquaculture commodities in the tropical Pacific that are expected to be most vulnerable to ocean acidification are pearl oysters, shrimp, and marine ornamentals, while seaweed may benefit in some locations depending on the influences of increasing sea surface temperature and rainfall.

3

IMPLICATIONS FOR GOVERNANCE AND MANAGEMENT

The key implications of ocean acidification for governance and management centre around identifying the extent to which declines in the pH of the tropical Pacific Ocean are likely to affect the regional and national plans and policies that PICTs have put in place to maximise the sustainable benefits from fisheries and aquaculture for economic development, food security and livelihoods. The development of these plans and policies, the implications of ocean acidification for these plans and policies, the adaptations that can be made to reduce the risks, and the nature of further research needed to improve our understanding of the impacts of ocean acidification are summarised below.

3.1 REGIONAL AND NATIONAL FISHERIES PLANS AND POLICIES

Given the great significance of fisheries and aquaculture to Pacific island economies, and to the food security and livelihood opportunities for Pacific island people, a concerted effort has been made in recent years to understand the factors most likely to drive the sector and to do the strategic planning needed to secure desired outcomes. The strategic planning began in earnest in 2007, when the theme of the 5th Conference of the Pacific Community was 'The Future of Pacific Fisheries' (SPC 2007). This led to the Va'vau Declaration on Pacific Fisheries Resources 'Our Fish, Our Future' by Pacific Island Leaders[3] later that year, and an analysis of the importance of fish for food security (Bell et al. 2009). These initiatives were followed by the Pacific Islands Regional Coastal Fisheries Management Policy (commonly known as the 'Apia Policy')[4] and a joint study by the Pacific Islands Forum Fisheries Agency (FFA) and the Secretariat of the Pacific Community (SPC) on 'The Future of Pacific Island Fisheries' (Gillett and Cartwright 2010), which outlined three scenarios for Pacific island fisheries, depending on the response of management to the many drivers affecting the sector. In 2011, SPC published the results of a comprehensive study designed to assess the vulnerability of tropical Pacific fisheries and aquaculture to climate change, which included a range of national adaptations and supporting policies to minimise the risks and maximise the opportunities[5].

The Future of Pacific Island Fisheries study was revisited by Ministers of Fisheries across the region in 2015 within the new Framework for Pacific Regionalism. Together, the Ministers identified seven goals for tuna fisheries and coastal fisheries and 11 strategies to achieve these goals (Table 3). The resulting Regional Roadmap for Sustainable Pacific Fisheries[6] was endorsed by Pacific Island Leaders in August 2015. Importantly, an annual report card[7] of progress is to be provided by the Ministers of Fisheries each year.

3 http://www.forumsec.org/resources/uploads/attachments/documents/THE%20Vava'u%20declaration.pdf

4 http://www.spc.int/DigitalLibrary/Doc/FAME/Reports/Anon_2008_ApiaPolicy.pdf

5 http://www2008.spc.int/index.php?option=com_content&view=article&id=969:climate-book&catid=257

6 http://www.ffa.int/system/files/FoF%20Roadmap%20FINAL.pdf

7 http://www.ffa.int/system/files/FoF%20Roadmap%20FINAL.pdf

TABLE 3. Goals, indicators, and strategies for the Regional Roadmap for Sustainable Pacific Fisheries. (Source: FFA)

Goal	Indicators	Strategies
Tuna		
1. Sustainability	Within 3 years, there will be agreed Target Reference Points for the four key tuna species. Within 10 years, the status of each species will be clearly moving towards these targets. Impacts of fishing on sharks, turtles, and seabirds will have been significantly reduced. Management measures will not be undermined by illegal, unreported, unregulated fishing.	Create effective zone-based management Continue to reduce IUU fishing Progressively restrict fishing on the high seas by foreign fleets Prioritise the supply of raw materials to processors in the region Establish high standards for employment in the fishing and processing industry Establish regional processing hubs in partnership between countries
2. Value	The region's tuna catch in 2024 will be worth double what it is in 2014. Value rather than volume of the catch will increase, by eliminating oversupply and targeting higher value products and markets. Value of access fees will increase for countries that wish to continue licensing foreign vessels.	
3. Employment	18,000 new jobs will be created in the tuna industry within 10 years through processing and as vessel crew, observers, and fisheries management staff. Standards to ensure that employment is safe and worthwhile will be harmonised.	
4. Food security	The supply of tuna for domestic consumption in the region will increase by 40,000 tonnes per year by 2024. Depending on national circumstance, small-scale catches, supplies from processors in the region, and by-catch from industrial vessels will all contribute to this increase.	
Coastal fisheries		
Empowerment	Within 10 years, national policies and legislation will be in place to provide for the involvement of coastal communities in the management of their fisheries resources. Supported by national controls on export commodities, communities will drive local management regimes with clear user rights.	Provide relevant information to inform management and policy Re-focus fisheries agencies to support coastal fisheries management Ensure effective collaboration and coordination of stakeholders Develop and enforce strong and up-to-date legislation, policy and plans Ensure equitable access to benefits and involvement in decision making
Resilience	Within 10 years, national strategies to manage the various threats to coastal ecosystems will be implemented. (Such threats include pollution, damage from outside the fishing sector, climate change, and ocean acidification.)	
Livelihoods	Within 10 years, national policies to develop alternative livelihoods for coastal communities that are impacted by declining fisheries resources will have been adopted.	

The coastal fisheries component of the new Regional Roadmap for Sustainable Pacific Fisheries is based largely on the outcomes of a landmark meeting at SPC in March 2015 on developing innovative approaches to deal with the declines in coastal fisheries resources. The meeting resulted in a broad range of stakeholders agreeing to a manifesto titled ‘A New Song for Coastal Fisheries – Pathways to Change – the Noumea Strategy’. The overarching expected outcomes of the New Song are improved wellbeing of coastal communities and productive and healthy ecosystems and fish stocks. The eight key outcome areas expected from the New Song are given in Appendix B.

In addition to the regional plans and policies outlined above, FFA[8] has assisted Pacific island countries to develop national tuna management plans, and SPC has assisted its members to develop national aquaculture management plans[9].

Broadly, the various regional and national plans are designed to (1) ensure that the growing populations in the region have access to 35 kg of fish per person per year, (2) identify the number of livelihoods that can be sustained from coastal fisheries and the development of aquaculture, and (3) optimise the benefits of the rich tuna resources of the region for economic development and government revenue.

3.2 IMPLICATIONS OF OCEAN ACIDIFICATION FOR STRATEGIC PLANNING

3.2.1 Food security

The implications of increased CO_2 emissions for the important role that fish plays in the food security of PICTs depend not only on the projected effects of declining pH on the coral reefs and demersal fish species that provide much of the coastal fisheries production across the region but also on the effects of increases in sea surface temperature on coral reefs and the demersal fish. Human population growth, the area of coral reef per capita, and the distance of reefs from population centres are also important factors affecting fish supply. Based on these criteria, PICTs fall into three groups with respect to their capacity to provide the 35 kg of fish per person per year recommended for good nutrition of Pacific island people (Bell et al. 2011a):

1. PICTs where coastal fisheries are expected to meet the increased demand for fish for the foreseeable future;
2. PICTs where the area of coral reef should be able to produce the fish needed in the future, but where it will be difficult to distribute the fish to urban centres from remote islands, atolls, and reefs; and
3. PICTs where coral reefs and other coastal habitats do not have the potential to produce the fish needed for good nutrition of their populations.

The implications of ocean acidification and the drivers mentioned above for each group are described below.

8 http://www.ffa.int

9 http://www.spc.int/aquaculture/index.php?option=com_content&view=section&layout=blog&id=1&Itemid=33

Group 1: Cook Islands, Marshall Islands, New Caledonia, Palau, Pitcairn Islands, and Tokelau

For these PICTs, there are few implications for the projected effects of ocean acidification on coral reefs. They will all continue to have large ratios of coral reef area per person under predicted rates of population growth. Thus, the projected decrease in production of fish associated with coral reefs due to ocean acidification and global warming under RCP8.5 is not expected to affect access to the fish needed for food security by 2050. Possible implications are that fishers supplying urban markets may have to travel greater distances to maintain harvest levels as catch per unit effort of reef-associated fish decreases due to increased CO_2 emissions. A possible increase in ciguatera fish poisoning in PICTs outside the equatorial zone due to the degradation of reefs (Pratchett et al. 2011) could also cause localised problems.

Group 2: FSM, Fiji, French Polynesia, Kiribati, Niue, Tonga, Tuvalu, and Wallis and Futuna

The degradation of coral reefs due to ocean acidification and global warming is not expected to significantly affect the potential availability of reef-associated fish per person in many of the PICTs in Group 2 by 2050 (Bell et al. 2011a). However, the effects of ocean acidification and increased sea surface temperature on coral reefs can be expected to affect catch per unit effort at locations from where it is cost-effective to send fish to the urban markets, reducing the supply of reef fish and affecting the viability of small-scale fisheries based on reef-associated species. As populations grow and reefs degrade, greater reliance will need to be placed on other sources of fish.

Group 3: American Samoa, Guam, Nauru, CNMI, PNG, Samoa, Solomon Islands, and Vanuatu

There are significant implications of the combined effects of population growth and reef degradation due to ocean acidification and coral bleaching for per capita fish supply for several of these PICTs. In many cases, the availability of fish from coral reefs per person per year is already below the recommended 35 kg per person per year, and the gap will widen over time. The main implications centre on the need to take swift and effective action to provide access to the fish required for good nutrition of growing populations in the face of climate change. These actions are (1) improving the management of coastal habitats and fish stocks to reduce the gap to be filled between the fish needed for food security and the sustainable harvests available from coastal fisheries, (2) assessing how best to fill the gap with other sources of fish, and (3) promoting the 'vehicles' needed to deliver the fish required (Bell et al. 2011a).

The rich tuna resources of the region provide the most practical way of increasing access to fish, although expanding small pond aquaculture and developing fisheries for small pelagic fish also have a role to play (see Section 3.3). Indeed, the role of tuna in providing fish for PICTs in Group 3 in the future is profound: not only does the amount of fish needed increase over time, tuna also has to supply an increasing percentage of the total fish required. Another important implication, therefore, is that countries in Group 3 will need to allocate more of the tuna resources caught within their waters to local food security. Across the region, ~6% of present-day tuna harvests from PICTs will be needed for this purpose by 2035. For Papua New Guinea, the largest country in the region, ~10% of average tuna harvests from the nation's waters may be needed for local food security of coastal and urban communities in 2035 (Bell et al. 2015a).

Guam and CNMI are in a different category to the other PICTs in Group 3 because although there is a low ratio of coral reef per capita, the relatively high income per person provides access to other sources of protein.

3.2.2 Livelihoods

The implications of the projected changes in coastal fisheries and aquaculture production due to ocean acidification for plans to create additional sustainable livelihoods are that livelihoods may need to be derived from a different mix of resources in the future. For example, within the coastal fisheries sector, the effort of small-scale fishers will need to be increasingly transferred from demersal fish associated with coral reefs to nearshore pelagic fish, particularly skipjack and yellowfin tuna. Transferring effort to pelagic species is not only expected to maintain the livelihoods of fishers as declines in coastal fisheries occur, it is also likely to create additional job opportunities in several PICTs because the abundance of tuna is expected to increase in some countries (Lehodey et al. 2013). Even in PICTs where skipjack tuna abundances are projected to decrease by 2050, there should still be sufficient tuna resources to allocate the necessary proportion of catches to small-scale fisheries to create new livelihoods, provided stocks are managed sustainably (Bell et al. 2013).

The projected decline of coral reefs due to ocean acidification and warming is also likely to have implications for the tourism sector. A key challenge will be finding ways to maintain the attractiveness of coral reefs as net erosion of reefs occurs due to the effects of ocean acidification and the increased frequency of coral bleaching (Hoegh-Guldberg et al. 2011).

Overall, ocean acidification is expected to have a negative effect on livelihood opportunities in the pearl farming and shrimp farming industries. The pearl industry in the tropical Pacific is already suffering from over-supply of pearls and competition from freshwater pearls. Less efficient operations due to ocean acidification, especially difficulties in producing pearls of high quality, can be expected to exacerbate the problems and reduce the opportunities for livelihoods. Shrimp farming in New Caledonia already faces issues in marketing internationally due to competition from shrimp farming in other countries. Any effects of lower pH on product quality can be expected to make marketing even more difficult. Although seaweed farming could be enhanced by the beneficial effects of higher pCO_2 for photosynthesis, any advantages are likely to be over-shadowed by the detrimental effects of higher sea surface temperature and rainfall, which can cause outbreaks of epiphytic algae and tissue necrosis (Pickering et al. 2011). Overall, therefore, the number of suitable sites for growing seaweed is expected to decline markedly by 2050.

For these reasons, much of the potential growth in aquaculture jobs lies in freshwater fish farming (Pickering et al. 2011), which is likely to be enhanced by the projected increases in rainfall and temperature due to global warming (Lough et al. 2011). Governments will need to provide incentives for the private sector to invest in the freshwater fish hatcheries and other infrastructure required to capitalise on these opportunities.

3.2.3 Reef dependent-communities

An assessment of community dependence on coral reefs globally found that more than 50% of countries and territories with very high reef dependence are located in the tropical Pacific, including French Polynesia, which has the highest dependence on reefs. For 10 countries and territories (7 of which are in the Pacific island region), dependence was assessed as high or very high. These PICTs are Cook Islands, Fiji, Marshall Islands, New Caledonia, Solomon Islands, Samoa, and Tonga (World Resource Institute 2012).

Reef ecosystems provide important goods and services for Pacific island coastal communities, particularly food security, livelihoods, income, and coastal protection (see Section 2.1). The implications of ocean acidification on food security and livelihoods alone, are significant (section 3.2.1 and 3.2.2) and in combination are likely to present a significant challenge for reef-dependent communities in the Pacific.

A sub-regional assessment of the vulnerability of reef-dependent communities in the 22 PICTs was conducted which focused on the projected impacts of ocean acidification on reefs and the goods and services they provide in terms of demersal and invertebrate fisheries for food security, income from reef fisheries and tourism, employment in aquaculture, and coastal protection. The semi-quantitative assessment rated each PICT on a 3-point scale (1 = low, 2 = medium, 3 = high) based on their:

➔ exposure to reef habitat declines as an index of:

- future declines in aragonite saturation given their location in the tropical Pacific Ocean (see Figure 2); and
- area of reef to land area (see Table 2);

➔ sensitivity to coastal fisheries declines as an index of:

- food security group based on reef-associated coastal population, annual fish consumption, projected coastal fisheries declines, and distance of reefs from population centres (see Table 2 and Section 3.2.1);
- estimated number of national coastal aquaculture jobs;
- estimated national contribution of tourism to GDP (%); and
- coastal household earnings from fisheries based on surveyed households (see Table 2); and

➔ capacity to adapt based on social indicators of health, education, size of the economy and governance (Bell et al. 2011a).

Sensitivity indicators for food security and coastal household earnings were weighted higher than all other indicators due to the critical reliance on coastal fisheries as both a source of protein and income for many coastal households. Food security was weighted the highest, contributing ~40% of the sensitivity score; coastal household earnings contributed ~30%, while tourism and aquaculture jobs contributed ~15% each to the sensitivity score.

The PICTs that were assessed as having reef-dependent communities with the highest relative vulnerability to ocean acidification impacts on reefs and their fisheries (for food security and artisanal livelihoods), aquaculture (for jobs), and tourism (for contribution to economic revenue) were (in order from most vulnerable) Solomon Islands, Kiribati, PNG, FSM, Tonga, and Tuvalu. The PICTs that had the lowest relative vulnerability to ocean acidification impacts on reefs and the goods and services they provide were Niue, CNMI, Tokelau, New Caledonia, and Guam (Table 4, see Supplementary Material).

Examination of the results of the relative vulnerability assessment identified some key factors contributing to high vulnerability. These factors were also primarily large reef area relative to land area, a high percentage of household earnings from coastal fisheries, and education level as a key component of low adaptive capacity. For Solomon Islands and PNG, food security issues in terms of the gap between fish required and the fish available to feed coastal populations was also an important factor. In contrast, PICTs with relatively low vulnerability consistently had high adaptive capacity and generally had lower ratios of reef to land areas. Tokelau and Guam were special cases because data were unavailable for household earnings, which may have influenced their vulnerability ranking.

There were no sub-regional scale patterns of vulnerability, with Melanesia, Micronesia and Polynesia all equally represented by PICTs that are highly vulnerable to the impacts of ocean acidification on reefs and their goods and services (Table 4).

TABLE 4. Assessment of the vulnerability of PICTs to the impacts of ocean acidification on coral reefs and the goods and services they provide: food security, livelihoods based on fishing and aquaculture, tourism and coastal protection.
All values are normalised to the highest value except the overall vulnerability score, which was calculated using the method from Johnson and Welch (2016).

PICT	Exposure Index	Sensitivity Index	Adaptive Capacity Index	Vulnerability V=(PI*AC index)+1	Vulnerability Ranking
MELANESIA					
Fiji	0.50	0.87	0.51	1.22	8
New Caledonia	0.83	0.58	0.16	1.08	20
PNG	0.50	0.81	0.74	1.30	3
Solomon Islands	0.50	1.00	0.65	1.32	1
Vanuatu	0.50	0.94	0.47	1.22	8
MICRONESIA					
FSM	0.83	0.68	0.48	1.27	4
Guam	0.50	0.84	0.15	1.06	21
Kiribati	0.83	0.68	0.55	1.31	2
Marshall Islands	0.83	0.48	0.48	1.19	12
Nauru	0.50	0.65	0.48	1.15	14
CNMI	0.50	0.84	0.28	1.12	18
Palau	0.83	0.48	0.37	1.15	14
POLYNESIA					
American Samoa	0.83	0.65	0.40	1.22	8
Cook Islands	0.83	0.61	0.40	1.21	11
French Polynesia	1.00	0.81	0.23	1.19	12
Niue	0.50	0.68	0.38	1.13	17
Pitcairn Islands	*Could not be assessed due to lack of data*				
Samoa	0.67	0.90	0.39	1.23	7
Tokelau	0.83	0.26	0.42	1.09	19
Tonga	0.83	0.71	0.46	1.27	4
Tuvalu	0.83	0.58	0.49	1.24	6
Wallis & Futuna	0.83	0.54	0.30	1.14	16

Efforts to reduce dependence on marine resources will present part of the solution as the impacts of ocean acidification manifest in the Pacific island region. However, planning and prioritizing at local scales are often hindered by a lack of information about dependence on specific ecosystem services, and previous efforts to develop alternative livelihoods in coastal areas have frequently proven unsuccessful (Ireland et al. 2004). Activities such as agriculture, freshwater aquaculture, eco-tourism or fair trade may represent viable alternatives but will only be sustainable where such development takes into account local aspirations, needs, perceptions and cultural ties to reefs (Cattermoul et al. 2008).

3.2.4 Economic development and government revenue

As explained in Section 2.3, the direct impacts of ocean acidification on the industrial tuna fisheries of the Western and Central Pacific Ocean, which supply >50% of the world's tuna (Williams and Terawasi 2015), cannot be assessed at the present time. In any event, these impacts will need to be considered in the context of the projected effects of global warming on the contributions of the dominant tuna species to the economies of PICTs. Preliminary modelling by Lehodey et al. (2013) shows that by 2050, catches of skipjack tuna are expected to decline in the western part of the Western and Central Pacific Ocean and increase in the east.

Based on this preliminary modelling, Kiribati, Tuvalu, Tokelau, Cook Islands and French Polynesia are likely to have future opportunities to negotiate increased access fees from distant water fishing nations. In contrast, the eastward shift in the distribution of skipjack tuna could pose some problems for tuna catches and processing in the western part of the region (Bell et al. 2011a). Assuming that ocean acidification is likely to have an overall negative effect on the abundance of skipjack tuna for the reasons outlined in Section 2.3, the potential economic benefits for countries in the east could be reduced, and the economic losses for countries in the west could be exacerbated.

3.3 PRIORITY ADAPTATIONS

Adapting coral reef fisheries to the effects of ocean acidification must be considered in the context of the many other drivers expected to affect the ability of these fisheries to provide fish for the food security and livelihoods of Pacific island coastal communities. Human population growth (Bell et al. 2009, 2011a), other impacts on coral reefs and associated fisheries caused by increases in sea surface temperature, changes to the velocity of ocean currents and increases in the severity of tropical cyclones (Hoegh-Guldberg et al. 2011, Pratchett et al. 2011) represent just some of these drivers.

As mentioned in section 3.2.1, adaptation actions will need to focus on (1) improving the management of the coastal zone and coastal fish stocks to reduce the gap to be filled between the fish needed for food security and sustainable fish harvests from coral reefs (Bell et al. 2011a) and (2) developing practical ways to fill the gap with tuna (Bell et al. 2015a). Some appropriate adaptation options have been identified by Bell et al. (2011c, 2013) and Johnson et al. (2013). These adaptations can be summarised as:

- maintaining whatever natural adaptive capacity coral reefs have to cope with ocean acidification and global warming by managing catchment vegetation to reduce the transfer of sediments and nutrients onto coral reefs, preventing pollution, managing waste, and eliminating direct damage to corals;
- sustaining production of coral reef fisheries through climate-informed, community-based ecosystem approaches to fisheries management (CEAFM) (Heenan et al. 2015). Such CEAFM approaches should be based on primary fisheries management (Cochrane et al. 2011) intended to keep production of demersal fish and invertebrates within sustainable bounds. CEAFM will need to be progressively more precautionary to allow for the increased uncertainty associated with ocean acidification and climate change (Bell et al. 2011c);
- diversifying catches of coastal demersal fish to match changes in species composition due to (1) local increases in the abundance of some species not currently harvested due to changes in distribution and (2) an increase in herbivorous species as a result of the increased algal cover that accompanies the degradation of coral reefs (Hoegh-Guldberg et al. 2011). However, harvesting of herbivorous fish needs to be constrained to ensure that they remain plentiful enough to remove the algae that inhibit the survival and growth of corals (Pratchett et al. 2011);

- transferring some fishing effort by coastal communities from coral reefs to oceanic species, particularly tuna, by installing fish aggregating devices (FADs) (SPC 2012, Bell et al. 2015b) close to the coast to increase access to fish for growing rural communities and to improve resilience of reefs to ocean acidification and climate change;
- increasing access to tuna for urban populations by assisting small-scale enterprises to distribute small tuna and bycatch available from purse-seine fleets transhipping catches to fish cargo vessels in the major ports across the region (Bell et al. 2015a);
- developing coastal fisheries for small pelagic fish species, e.g. mackerel, anchovies, pilchards, sardines, and scads;
- improving simple post-harvest methods, such as traditional smoking, salting, and drying, to extend the shelf life of fish when good catches of tuna or small pelagic fish are made;
- developing hatchery and grow-out systems for expansion of semi-intensive and intensive freshwater pond aquaculture; and
- allowing mangrove and seagrass habitats to migrate landward as sea level rises.

3.4 FURTHER RESEARCH

The great importance of coastal and oceanic fisheries to Pacific island countries and territories warrants investments to gain a better understanding of the direct and indirect effects of ocean acidification on fish stocks. Given the significant contributions of tuna fisheries to the government revenue and GDP of many Pacific island nations, and the fact that tuna will have to supply much of the additional fish needed for food security in the region as human populations grow (Bell et al. 2015a), research on the effects of ocean acidification on tuna is a priority. The preliminary research on yellowfin tuna (Bromhead et al. 2015) needs to be expanded, and comparable research is needed on the species that is the mainstay of the purse-seine fishery: skipjack tuna (Williams and Terawasi 2015). Gaining a better understanding of the likely effects of ocean acidification on replenishment of coral reef fish populations will also assist managers to plan to fill the gap in fish supply for many (Group 3) Pacific island countries and territories by progressively transferring coastal fishing effort from coral reef fish to tuna.

A better understanding of the effects of ocean acidification on the main species cultured in the coastal waters of the Pacific island region is also needed. Research is required to identify whether sites for growing pearls and marine ornamentals can be located where the adverse effects of both higher water temperatures and lower pH on nacre formation can be reduced or whether co-culture with seaweed could help reduce the negative and skeleton effects of ocean acidification locally by using seaweed to remove CO_2 from the surrounding water. Selective breeding programmes, similar to those underway for rock oysters elsewhere in the temperate Pacific (Parker et al. 2011), are also needed to determine whether such programmes may be a viable option for maintaining pearl quality as pH decreases. Research is also required to determine if there will be any adverse effects of ocean acidification on the exoskeleton of *Litopenaeus stylirostris*, the most widely farmed shrimp in the tropical Pacific region.

For the above research to be meaningful, there needs to be a concerted effort to establish and maintain long-term monitoring programmes for ocean acidification in the Pacific island region. There is a critical lack of data on ocean chemistry and pH change in the tropical Pacific. Simple measures like obtaining funding for PICTs to purchase and maintain monitoring instruments would provide baseline data to help inform adaptation and policy decisions at national and regional levels.

CONCLUSIONS AND RECOMMENDATIONS

In the tropical Pacific, ocean acidification and other changes to the ocean will affect coastal fisheries through degradation of coral reefs and the effects on the early life stages of reef fish and invertebrates. Coastal fisheries based on reef-associated demersal fish and sea cucumbers are of particular concern. Ocean acidification will also impact tourism; aquaculture of pearl oysters, marine ornamentals, and possibly shrimp; and the role that coral reefs play in coastal protection.

The PICTs with rapidly growing, reef-dependent communities that are most vulnerable to declines in reef condition, demersal and invertebrate fisheries, and aquaculture caused by ocean acidification are those with limited ability to adapt by developing alternative sources of protein or income. These PICTs will require additional assistance as ocean acidification accelerates.

Regional dependence on food and livelihoods derived from coastal fisheries is very high: coral reef fisheries provide more than 50% of dietary animal protein in many PICTs, and a high proportion of household income is obtained from coastal fisheries. Therefore, specific recommendations to help vulnerable PICTs adapt to the effects of ocean acidification include:

- incorporating ocean acidification into ecosystem-based and coastal zone management plans to increase the resilience of coastal ecosystems and communities;
- diversifying sources of fish to reduce dependence on coastal demersal fisheries for food security by increasing access to tuna and expanding freshwater pond aquaculture;
- evaluating the direct effects of ocean acidification on tuna and improving knowledge of the food webs that support tuna, through modelling the effects of ocean acidification on mid trophic levels (micronekton);
- improving the resilience of aquaculture in the region by reducing the vulnerability of pearl and shrimp farming to ocean acidification through selective breeding for acidification-resistant strains, investigating the scope for polyculture of seaweed and pearl oysters, and assessing the potential of new species for aquaculture;
- investing in case studies to provide a more in-depth understanding of the vulnerability of key resources to ocean acidification, as suggested by Cheung et al. (2015). Priority case studies include:
    - pearl farming in French Polynesia, assessing potential reduced quality of pearl production due to reduced aragonite saturation; and
    - coral reef fisheries, measuring the impact of combined effects of warming, ocean acidification and coral bleaching on degradation of reefs;
- assessing the feasibility of adaptation measures, ecological impacts, and costs; and
- improving monitoring of ocean acidification to provide a better understanding of likely impacts.

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APPENDIX A
THE CHEMISTRY OF OCEAN ACIDIFICATION

As explaned by Ganachaud et al (2011), when carbon dioxide (CO_2) is dissolved in the surface waters of the ocean, certain chemical reactions take place. In particular, CO_2 combines with water to form carbonic acid (see Equation 1 below). The carbonic acid (H_2CO_3) dissociates into hydrogen ions (H^+) and bicarbonate ions (HCO_{3-}) (Equation 2). The bicarbonate can also split into a further hydrogen ion and a carbonate ion (CO_3^{2-}) (Equation 3).

$$CO_2 + H_2O <\!\!-\!\!> H_2CO_3 \qquad (1)$$

$$H_2CO_3 <\!\!-\!\!> H^+ + HCO_{3-} \qquad (2)$$

$$HCO_3 <\!\!-\!\!> H^+ + CO_3^{2-}- \qquad (3)$$

Rather than creating a chain reaction, these equations represent two-way reactions that equilibrate continuously so that three dissolved inorganic carbon species occur simultaneously: carbonic acid, bicarbonate and carbonate (with relative concentrations of about 1%, 91% and 8%, respectively). These contributions shift, however, depending on the physical, chemical or biological conditions of the ocean.

The fourth component in these reactions is the hydrogen ion (H+). If there are more H^+, the water becomes more acid, i.e. its pH ($= -\log^{10}[H^+]$) decreases.

Fortunately, these chemical reactions self-regulate in such a way as to minimise the changes in pH. For example, if extra CO_2 is dissolved in the surface ocean (as is presently occurring), the balance shifts via chemical reactions (1) and (2) to higher concentrations of HCO_{3-} and H^+, thus reducing pH. However, some of the excess hydrogen ions are removed as they combine with free CO_3^{2-} via reaction (3).

This process greatly reduces the rate at which acidification of the ocean occurs (although not entirely), but there is an environmental 'cost' because free carbonate ions are removed from the water. This tempering of the pH by free carbonate ions is known as 'carbonate buffering'. However, as more CO_2 is added to the ocean, the number of free carbonate ions decreases. As a result, the capacity for buffering will be reduced, and pH is expected to continue to decline.

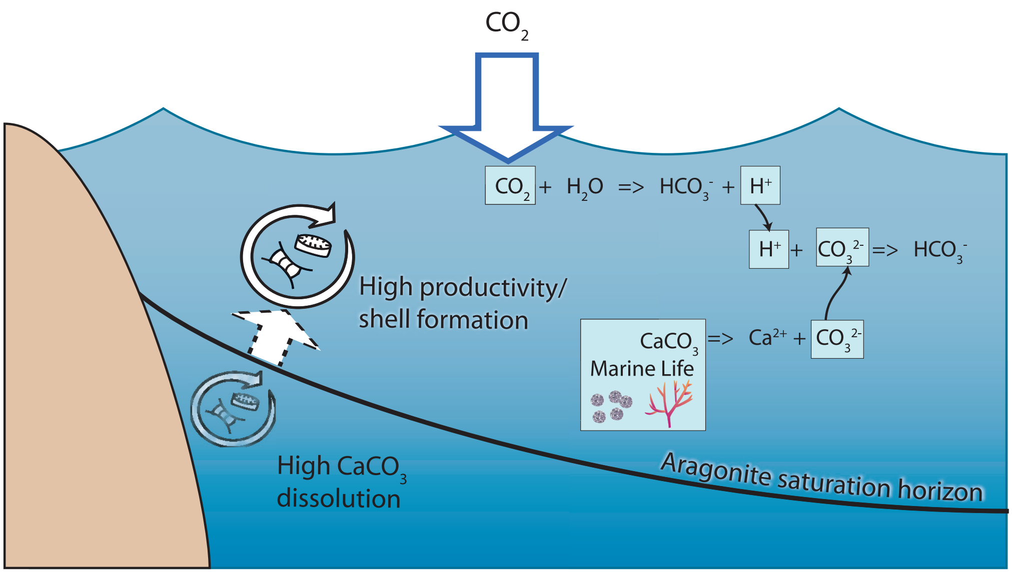

FIGURE A1. Summary of ocean acidification. Source: Ganachaud et al. (2011)

Both increased acidity (lower pH) and lower CO_3^{2-} concentration ('carbonate saturation') can have adverse effects on the growth and survival of marine organisms (see below), especially those that build their shells and skeletons from $CaCO_3$, which is formed when calcium combines with carbonate (Ca^{2}+ + CO_3^{2-} $CaCO_3$). As concentrations of CO_3^{2-} decrease, such species find it more difficult to secrete $CaCO_3$. At some 'saturation' concentration of carbonate, the ambient water becomes corrosive to $CaCO_3$, and the shells and skeletons of organisms actually begin to dissolve. This saturation level is sensitive to ocean temperatures, however, and cold, high-latitude regions reach 'under-saturation' before tropical and subtropical waters. Also, as depth increases, a threshold is reached where $CaCO_3$ starts to dissolve due to increased pressure. This threshold is known as the 'aragonite saturation horizon' (see Figure A1).

Aragonite Saturation State

Surface tropical seawaters are generally supersaturated with respect to the carbonate minerals (e.g. calcite, aragonite and high-magnesium calcites) from which marine organisms construct their shells and frameworks. As mentioned above, at deeper water depths seawater becomes under-saturated, and these minerals begin to dissolve, imparting an important control (amongst other factors) on the distribution of coral reefs. The degree to which seawater is saturated with respect to these minerals is referred to as 'saturation state' and is denoted by the Greek term Ω (omega).

The effects of ocean acidification on calcification rate appears not to be directly related to changes in pH per se, but instead to corresponding changes in the degree to which seawater is supersaturated with respect to the carbonate minerals (e.g. aragonite) (Langdon and Atkinson, 2005). A change in carbonate ion concentration results in a proportional change in Ωarg such that as ocean acidification continues, the surface ocean Ωarg values will decline. As the saturation state declines, it is harder for marine calcifiers to precipitate the calcium carbonate they need to build their skeletons (see Figure A2). By the year 2065, rates could decline 60 ± 20% relative to preindustrial levels.

A growing number of studies have now demonstrated a relationship between coral calcification rates and aragonite saturation state. Figure A2 shows that prominent coral reef ecosystems do not currently reside in waters exhibiting oceanic Ωarg < 3, perhaps representing a critical threshold (Guinotte et al. 2003). The colours denote a convention employed by Guinotte et al. (2003): surface waters exhibiting Ωarg > 4 are deemed 'optimal' (blue), values of 3.5–4.0 are 'adequate' (green), values of 3.0–3.5 are 'low' (yellow/orange), and waters with values less than 3.0 are considered 'extremely marginal' (red).

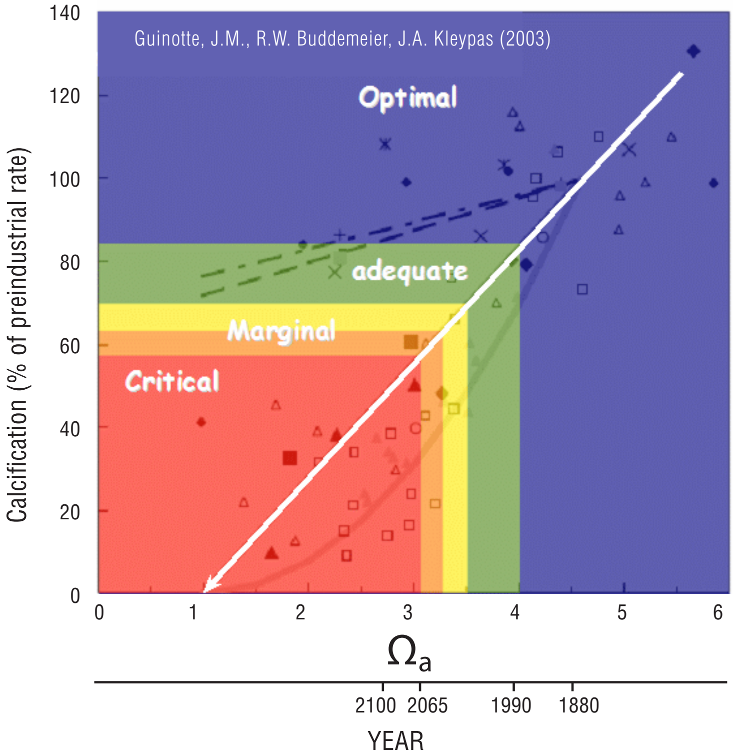

FIGURE A2. Aragonite saturation and calcification relationship; colours denote suitability for calcification by marine organisms, such as corals, plankton and shellfish (Source: Langdon and Atkinson 2005).

APPENDIX B
THE 'NEW SONG' INTERMEDIATE OUTCOMES

The eight intermediate outcome areas needed to reach the overarching goals of the 'New Song' for coastal fisheries management in Pacific island countries and territories (Source: SPC 2015).

OUTCOME # 1: Informed, empowered coastal communities with clearly defined user rights

Intermediate outcomes	Key players	Indicators
Informed and empowered communities – robust awareness and communication programmes	Community leaders, fisheries authorities, stakeholders, NGOs, women, churches, faith-based groups, youth, fishers, ministries of education, other government departments, CEAFM networks.	Awareness surveys # of communities practising CBNRM Compliance rates
Coastal fisheries management and marine ecosystems included in school curricula	Ministries of education, heads of fisheries, regional organisations (SPC, SPREP)	Curricula # of schools using curricula
Legal and regulatory frameworks recognising community empowerment	Heads of state, government ministers, attorneys general, fisheries agencies, traditional leaders and communities, SPC and SPREP, NGOs, government departments	# of national and sub-national laws updated and supporting community-based management # of national and sub-national policies and strategies guiding coastal fisheries management # of community-based management or action plans being implemented
Community management programmes	Traditional leaders / council / community fisheries agencies, networks, private sector, NGOs	Community management plans legally recognised # of traditional management practices supported
Strong partnerships at all levels	Traditional leaders / council / community, fisheries agencies, networks, private sector, NGOs, provincial government/equivalent	# of joint partnership programmes # of MOUs Evidence of active and strong partnerships

OUTCOME # 2: Adequate and relevant information to inform management and policy

Intermediate outcomes	Key players	Indicators
Government and community managers have good quality information to inform decisions	Fishers, managers (village chiefs, local fisheries administrators), networks, scientists, skilled data collectors	# of active databases, disaggregated by social factors # of fishers/communities providing high quality data # of trained data collectors, including in social and economic methods # of appropriate surveys and assessments completed Evidence that data is being used to inform decisions
Science is translated into simple and informative material to guide community management	Community members and fisheries staff with resource management people, academics, networks, capacity providers (SPC, FFA, MPI, NGOs), scientists	Management plans guided by data # of resources available to the community # of fisheries programmes integrated into school curricula # of evidence-based decisions Curricula
Communities have a greater understanding of status, biology and habitats of key species (in addition to existing local ecological knowledge)	Communities (traditional knowledge), managers, networks, government, research institutes, extension staff	# of extension staff Data easily accessible # of communities receiving feedback # of relevant publications being produced Incorporation of coastal fisheries management in school curricula # of schools with above curricula

OUTCOME #3: Recognition of, and strong political commitment and support for, coastal fisheries management at a national and sub-national scale

Intermediate outcomes	Key players	Indicators
Informed and supportive politicians at the national and sub-national levels	Permanent secretaries, directors (primary) community leaders/voters, faith-based organisations, NGOs	Change in budget allocation # of policies, statements, MOUs # of workshops and training for members of parliament
Raised public support of coastal fisheries through engaging awareness campaigns with consistent and community-relevant messaging and creative information-sharing tactics (e.g. use of celebrities, role models, etc.)	Communication organisations, fisheries working groups, media, spokespersons (celebrities, etc.)	# of media materials and activities produced related to coast # of people reached by media campaigns relating to coastal fisheries
Coastal fisheries management is a permanent agenda item at regional meetings (e.g. MSG, SPC, Secretariat of the Pacific Regional Environment Programme, FFA)	Heads of fisheries, CROP agencies, Fisheries Technical Advisory Committee	# of agenda items relating to coastal fisheries # of decisions taken at regional meetings

OUTCOME #4: Re-focused fisheries agencies that are transparent, accountable, and adequately resourced, supporting coastal fisheries management and sustainable development, underpinned by CEAFM

Intermediate outcomes	Key players	Indicators
Coastal fisheries management is adequately resourced	Ministers, heads of fisheries, SPC, planning departments, donors, ministries of finance	$ assigned to coastal fisheries management # of people assigned to coastal fisheries management # of staff with appropriate skills (social, gender, economic, ecological)
Documented coastal fisheries management activities, which are regularly reviewed	Heads of fisheries and other relevant agencies, SPC, planning departments, donors, communities, NGOs	# of documented activities Outcomes of review
Coastal fisheries management activities are integrated and coordinated with other relevant stakeholders	Heads of fisheries and other relevant agencies SPC, donors, communities, NGOs	# of plans demonstrating integrated and coordinated partnerships
Reviewed and integrated coastal fisheries management activities	Fisheries agencies, ministers, NGOs	# of reviews
Coastal fisheries staff conducting effective CEAFM activities	Donors, regional training organisations (e.g. SPC), fisheries agencies	# of trainees Training including appropriate range of topic areas (including social, ecological, economic)
Raised community awareness of coastal fisheries	Media, fisheries agencies, regional organisations, communities	# of published materials

OUTCOME # 5: Strong and up-to-date management policy, legislation and planning

Intermediate outcomes	Key players	Indicators
Coastal fisheries policy guiding management	All resource owners/users along with agencies in charge of natural resources (fisheries, environment, etc.), SPC	# of polices guiding coastal management # of countries with up-to-date policy
Updated legislation that allows policy to be implemented and empowers communities	Attorneys general, fisheries and other national agencies, regional organisations, SPC, parliaments	# of pieces of legislation guiding coastal management # of countries with sufficient legislation for effective management Compliance rates
Effective policy implementation through plans, monitoring and evaluation	Policy makers, fisheries agencies	# of updated plans # of references to regional inshore fisheries strategy
Illegal, unsustainable and unregulated fishing is minimised	Law enforcement services, community authorised officers, customs	# of prosecutions # of infringements recorded

OUTCOME # 6: Effective collaboration and coordination among stakeholders and key sectors of influence

Intermediate outcomes	Key players	Indicators
Coastal fisheries management is included in broader development processes	Ministries of strategic planning and finance, development NGOs, donors, communities	# of development programmes that include CEAFM activities
National forums are coordinating and providing cross-sector advice relevant to coastal fisheries management	Governments, NGOs, churches, faith-based organisations, private sector	# of forums Frequency of meetings # of meaningful decisions relevant to coastal fisheries
Church groups are integrated into coastal fisheries management activities	Churches, communities, faith-based organisations	Evidence of religious leaders advocating for good fisheries management
Private sector, finance providers and land-based organisations are involved in CEAFM	Cooperatives, financial institutions, donors, wholesalers, fishermen's associations, land,-based organisations (e.g. forestry, agriculture), finance providers	Active participation of private sector on advisory committees # of instances of private sector providing investment in support of sustainable fisheries services # of private sector investors # of communities provided with financial support # of land-based experts participating in dialogues
Regional and national coordination of policy	Regional organisations, donors, national governments	Regional commitments embedded in national policies and plans
Increased spread and quality of CEAFM among communities	Sub-national governments, communities, NGOs, CEAFM networks	Collaboration and learning among communities and practitioners Country-specific indicators of spread

OUTCOME # 7: More equitable access to benefits and decision making within communities, including women, youth and marginalised groups

Intermediate outcomes	Key players	Indicators
Equitable access to the resource and benefits from coastal fisheries within communities	Communities, champions for change, gender researchers	# of gender-differentiated studies # of community action plans in which access to benefits for women, youth and marginalised groups are improved Indicators of wellbeing are gender-differentiated and socially disaggregated Engagement of women and youth in fisheries activities
Greater inclusivity of decision-making while acknowledging cultural norms and traditional values	All demographic and social groups within a community, including village leaders	# of women, youth, others involved in decision making forums New stakeholder groupings are developed in decision-making forums
Decision-making processes are transparent and the roles of government and traditional authorities are clear	Communities, leaders	# of community members aware of decisions and decision-making processes
Plans take account of equity issues, especially those involving gender and youth	Communities, leaders, women and youth	# of plans that explicitly address equity issues

OUTCOME # 8: Diverse livelihoods reducing pressure on fisheries resources, enhancing community incomes, and contributing to improved fisheries management

Intermediate outcomes	Key players	Indicators
Diverse livelihoods, contribute to coastal fisheries management	Communities, private sector, fisheries agencies	Healthy stocks Diversity of livelihoods Proportion of income from coastal fisheries
Enhance value of wild-caught fisheries	Fishers, private sector	Total household income
Aquaculture, tourism and inshore FADs cost effectively contribute to sustainable livelihoods	National departments, private sector, communities, SPC and NGOs	Household income Status of fish stocks

SPREP PROE

SPC Secretariat of the Pacific Community

USP THE UNIVERSITY OF THE SOUTH PACIFIC

NEW ZEALAND FOREIGN AFFAIRS & TRADE Manatū Aorere

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