Commonwealth Marine Economies Programme

Enabling safe and sustainable marine economies across Commonwealth Small Island Developing States

www.cmeprogramme.org | CME.ProgrammeEnquiries@fco.gov.uk

Funded by
UK Government

PACIFIC MARINE CLIMATE CHANGE REPORT CARD
Science Review 2018: *pp* 74-98

Effects of Climate Change on Fish and Shellfish Relevant to Pacific Islands, and the Coastal Fisheries they Support

Johanna Johnson, C$_2$O Pacific, Australia and James Cook University (JCU), Australia; Ian Bertram, Pacific Community (SPC), New Caledonia; Andrew Chin, JCU; Bradley R. Moore, SPC and University of Tasmania, Australia; Morgan Pratchett, JCU; David J. Welch, JCU and C$_2$O Pacific, Australia and Vanuatu; Ashley Williams, Australian Bureau of Agricultural and Resource Economics and Sciences, Australia; Johann Bell, University of Wollongong, Australia; Hugh Govan, University of the South Pacific, Fiji.

EXECUTIVE SUMMARY

In the Pacific Islands region, fish and invertebrates (specifically shellfish) fulfil important ecological roles in coastal and oceanic habitats, and many species are targeted by fisheries, making vital contributions to food security, livelihoods, government revenue and cultural heritage. Climate change is 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. In particular, declines in the productivity of demersal fish and invertebrates, and a more eastward distribution of some tuna species, are expected to present the greatest challenges for the use of fisheries resources by Pacific communities and economies. Some invertebrates which are important aquaculture commodities (such as pearl oysters and shrimp) will also be impacted by global warming and ocean acidification. The projected declines in coastal fish and invertebrate populations will widen the gap between fish needed by growing human populations and sustainable harvests, with shortages expected in some Pacific nations (e.g. Papua New Guinea, Solomon Islands) by 2035. There will also be a need to diversify livelihoods based on fisheries and aquaculture operations in the region because some of these operations are expected to be negatively affected, and others favoured, by climate change. In some cases, building the resilience of Pacific communities to climate change will involve reducing dependence on, or finding alternative uses of, vulnerable marine resources.

What is Already Happening?

Fish and invertebrates in coastal habitats – coral reefs, seagrass meadows, mangroves and intertidal flats (Figure 1) – fulfil important ecological roles and provide a significant source of protein and artisanal livelihoods for communities in the Pacific Islands region. For the purposes of this paper, we have divided the fish and invertebrates of the Pacific into four broad groups: (i) demersal (bottom dwelling) fish, including shallow- and deep-water species (ii) shellfish (crustaceans, molluscs and echinoderms) in shallow subtidal and intertidal habitats, (iii) pelagic species, often dominated by tuna and tuna-like species, and (iv) sharks and rays. Tuna are also found throughout oceanic waters of the Pacific Ocean and are critically important for national revenue and livelihoods in many nations, and there are four species targeted by industrial fleets (albacore,

Centre for Environment Fisheries & Aquaculture Science

United Kingdom Hydrographic Office

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

bigeye, skipjack and yellowfin tuna) (see Science Review 2018: Oceanic Fisheries paper).

Figure 1. Examples of coastal habitats and the fisheries they support: A) Mangrove-coral connectivity in the Western Province, Solomon Islands, B) a fish market in Fiji, C) a fish market in Manus, PNG, D) invertebrates for sale in Suva, Fiji. Photo credits: A) Andrew Olds, B & D) David Welch, C) Brad Moore.

(i) Demersal fish and (ii) Invertebrates (shellfish)

There are approximately 7,000 species of fish in the Pacific islands region, and demersal fish are a key component of coastal ecosystems. They have specialised roles in reef ecosystems that include corallivores that eat corals (e.g. butterflyfish), herbivores that eat algae (e.g. rabbitfish), generalist species (e.g. damselfish), and predators (e.g. groupers). A range of families of demersal fish are harvested for subsistence and for local sale in the Pacific Islands region, the most common being parrotfish (Scaridae), surgeonfish (Acanthuridae), trevallies and scads (Carangidae), soldierfish and squirrelfish (Holocentridae), wrasse (Labridae), emperors (Lethrinidae), snappers (Lutjanidae), mullet and goatfish (Mullidae), groupers (Serranidae), and rabbitfish (Siganidae) (Table 1). The species harvested within these families vary among Pacific Island countries and territories (PICTs) (Figure 2) due to gradients in biodiversity, differences in fishing gear, habitat availability, local dietary preferences, and cultural differences and taboos (Pratchett *et al*. 2011a).

Current pressures on coastal fish habitats in the Pacific include coastal development, resource extraction (e.g. fishing, sand and coral mining) and land-based pollution (UNEP 2017). These pressures are already impacting coastal habitat condition (UNEP 2017), with indirect impacts on the demersal fish and invertebrates that depend on these habitats. In addition, current fishing effort is high due to rapidly growing human populations and the high demand for seafood. Targeting spawning aggregations and destructive fishing practices and gears (e.g. small mesh nets) used in most PICTs, place additional pressure on fish and invertebrate populations. All these impacts will be exacerbated by climate change.

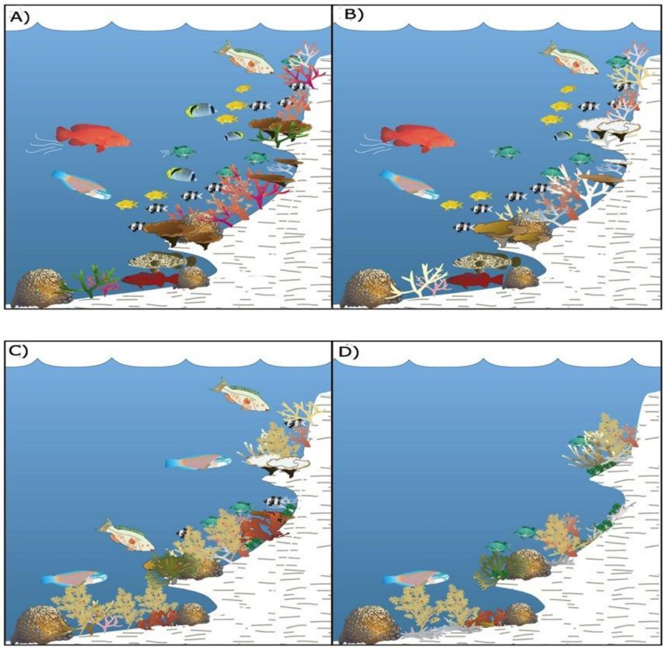


Figure 2. Changes in the state of Pacific coral reef ecosystems caused by climate change: Structurally complex coral reef habitats that support high species diversity (A); once bleached (B); become overgrown with algae (C); and then collapse to form rubble banks (D); leading to declines in fish diversity and abundance of coral-dependent species (C and D). Predatory fish are expected to decline due to reductions in coral dependent prey species, while generalist species (e.g., herbivores) may become more abundant on algae dominated reefs due to access to more food, at least in the short- to medium-term. Adapted from Pratchett *et al*. (2011a), reproduced with permission from the Pacific Community, New Caledonia. (Symbols courtesy of the Integration and Application Network: www.ian.umces.edu/symbols/).

The status of demersal fish stocks is not well known in many PICTs due to lack of regular fisheries data collection. In-water assessments at 63 sites across 17 PICTs conducted in the early to mid-2000s found that demersal fish populations at 54% of sites were in ‘average-to-low’ or ‘poor’ condition (Pinca *et al*. 2010).

Table 1. Percent contribution to total catches (in terms of weight, kg) of major demersal fish families observed during creel surveys of artisanal fishers at selected Pacific Island locations. The average catch per trip per fishing method is given in the last row. H = handline/bottom fishing, S = night-time spearfishing. FSM = Federated States of Micronesia (source: SPC unpublished data). "Others" includes Balistidae, Caesionidae, Ephippidae, Gerreidae, Megalopidae, Monodactylidae, Pomacanthidae, Pomacentridae, Priacanthidae and Scombridae.

Demersal Fish Family	Location (country)									
	Pohnpei, FSM		Tarawa, Kiribati		Majuro, Marshall Islands		Koror, Palau		Funafuti Tuvalu	
	H	S	H	S	H	S	H	S	H	S
Acanthuridae	1.2	47.9	0.2	n/a	-	37.1	-	27.7	-	55.7
Carangidae	39.6	1.9	3.1	n/a	-	0.5	18.5	-	6.2	1.6
Haemulidae	0.2	0.6	-	n/a	-	-	-	2.9	-	-
Holocentridae	9.3	2.2	1.8	n/a	0.6	12.2	0.2	2.5	3.3	4.3
Kyphosidae	-	3.3	-	n/a	-	1.7	-	-	-	-
Labridae	0.1	0.6	-	n/a	-	0.3	-	0.2	-	-
Lethrinidae	5.4	4.1	17.0	n/a	20.3	0.6	41.4	2.2	17.2	2.8
Lutjanidae	29.2	2.3	71.4	n/a	8.3	2.6	33.1	2.6	40.5	5.4
Mullidae	0.1	3.2	-	n/a	-	1.3	-	12.6	0.1	0.6
Scaridae	-	16.0	-	n/a	-	11.4	-	38.5	-	11.3
Serranidae	10.1	10.0	3.0	n/a	70.8	9.2	3.4	6.2	18.1	6.7
Siganidae	-	6.7	-	n/a	-	19.9	-	4.6	-	1.6
Sphyraenidae	3.2	0.2	3.2	n/a	-	-	0.3	-	11.9	10.0
Others	1.6	1.0	0.3	n/a	-	3.2	3.1	-	2.7	-
Average catch (kg)	20.6	27.9	73.6	n/a	28.5	50.0	23.7	53.7	31.2	99.2

In addition, fishing impacts are evidenced by small average sizes of key species, targeting of juveniles, and fishing down the food web (i.e. disproportionately fewer higher-order species; predators) in many PICTs (e.g. Welch 2016, Pinca *et al*. 2010). Available data from household surveys indicate that the total annual demersal fish catch for the region is ~86,000 tonnes (Table 2), with 70% taken for subsistence (Bell *et al*. 2018). However, subsistence catches in the region are likely to be grossly under-estimated (Zeller *et al*. 2007, Gillett 2016).

Many invertebrate species are harvested in the Pacific islands for subsistence, sale at local markets and/or export. For the purposes of this paper, we consider only the shellfish – crustaceans, molluscs and echinoderms – that are important for coastal fisheries and aquaculture. Harvesting of sea cucumbers to supply the bêche-de-mer (dried sea cucumber) export trade supports livelihoods across the region (Kinch *et al*. 2008, Purcell *et al*. 2009). However, the ease with which sea cucumbers can be collected and their high value has led to widespread overfishing, with fisheries in many PICTs now closed. Bivalve molluscs, in particular giant clams and ark shells, are among the most commonly harvested invertebrates in PICTs. The largest of the giant clams, *Tridacna gigas*, is now considered rare as a result of heavy fishing pressure in the past (Bell *et al*. 2005, Pinca *et al*. 2010). Ark shells (*Anadara spp*.) are also an important fishery and commonly found in mud and seagrass habitats. They constitute higher landings than clams in countries with appropriate habitats, such as Fiji and Kiribati (e.g. Lee *et al*. 2018). In Fiji, ark shells are harvested in quantities second only to freshwater clams for bivalve fisheries (Gonzalez *et al*. 2015).

A variety of crustaceans, e.g. mangrove crabs (*Scylla* spp.), spiny lobsters (*Panulirus* spp.), slipper lobsters (*Parribacus* spp.) and coconut crabs (*Birgus latro*) are also harvested in the region, largely for subsistence and sale at local markets. Coconut crabs, which are long-lived and slow-growing, are particularly vulnerable to over-harvesting (Fletcher and Amos 1994) and are locally depleted on numerous Pacific islands. Some commercially important molluscs and crustaceans, such as pearl oysters, shrimp and marine ornamentals (e.g. giant clams), are vulnerable to climate change and ocean acidification. For these organisms, reductions in growth, poor shell production and quality will occur under increasing SST and lower pH conditions (e.g. Kroeker *et al*. 2013).

Table 2. Estimates of annual catches (in tonnes and as a percentage of total catch) for the three main categories of Pacific Island coastal fisheries. Data are based on catches for 2014 reported by Gillett (2016) and calculated using the method described by Bell *et al*. (2018). PNG = Papua New Guinea; FSM = Federated States of Micronesia; CNMI = Commonwealth of the Northern Mariana Islands.

PICT	**Demersal fish**		**Nearshore pelagics**		**Invertebrates**		**Total catch**
	Tonnes	%	Tonnes	%	Tonnes	%	Tonnes
Melanesia							
Fiji	17,406	64.5	5,430	20.1	4,164	15.4	27,000
New Caledonia	2,667	55.0	560	11.5	1,623	33.5	4,850
PNG	16,984	40.9	16,082	38.8	8,434	20.3	41,500
Solomon Islands	14,957	56.5	7,850	29.7	3,662	13.8	26,469
Vanuatu	2,119	54.2	929	23.8	858	22.0	3,906
Micronesia							
FSM	3,832	72.6	1,166	22.1	282	5.3	5,280
Guam	33	28.9	78	68.4	3	2.6	114
Kiribati	13,942	73.4	3,949	20.8	1,109	5.8	19,000
Marshall Islands	2,875	63.9	1,346	29.9	279	6.2	4,500
Nauru	115	30.8	252	67.6	6	1.6	373
CNMI	254	51.5	185	37.5	54	11.0	493
Palau	973	46.0	783	37.0	359	17.0	2115
Polynesia							
American Samoa	97	59.9	49	30.2	16	9.9	162
Cook Islands	154	36.2	253	59.4	19	4.5	426
French Polynesia	3,914	48.8	3,254	40.6	848	10.6	8,016
Niue	22	13.3	132	80.0	11	6.7	165
Pitcairn Island	5	55.6	3	33.3	1	11.1	9
Samoa	3,817	38.2	3,723	37.2	2,461	24.6	10,001
Tokelau	140	35.0	220	55.0	40	10.0	400
Tonga	4,892	70.9	668	9.7	1,340	19.4	6,900
Tuvalu	918	64.0	455	31.7	62	4.3	1,435
Wallis and Futuna	645	72.1	83	9.3	166	18.6	894
Total	90,761	55.3	47,450	28.9	25,797	15.7	164,008

Increasing thermal stress has been observed to have both indirect and direct impacts on demersal fish and invertebrates in the Pacific Islands region. Indirect impacts include habitat declines due to coral bleaching that have been shown to impact reef fish populations over time (Pratchett *et al*. 2009, 2011b, Khalil *et al*. 2013). Extensive coral bleaching was reported across much of the Pacific in 2015–2016, with associated bleaching of giant clams. Declines in diversity and abundance of coral reef fishes due to coral bleaching have been observed elsewhere (Pratchett *et al*. 2011), and it is likely that these events had significant effects on local fish communities in the region. At the same time, mass fish kills were observed on the Coral Coast of Fiji and in Vanuatu. In both locations, water temperatures on reef flats were reported to be consistently over 30°C and in Fiji as high as 35°C (Welch and Johnson 2017). The influence of higher water temperatures on oxygen concentrations are thought to be responsible for this mass fish mortality.

Beyond these large focused events, however, few direct effects of climate change have been documented for the majority of wild demersal fish and invertebrate species in the Pacific Islands region, largely due to a lack of regular and long-term monitoring in most locations. In addition, in temperate environments climate change effects are typically exemplified by range shifts of species to higher latitudes and an overall ‘tropicalization’ of ecosystems (Johnson *et al*. 2011, Verges *et al*. 2014). The largely tropical nature of the region, the relatively weak latitudinal structure observed for many demersal fish and invertebrate species, and the general lack of suitable habitat adjacent to the north and south, precludes such observations in the Pacific Islands.

Coral trout (*Plectropomus spp.*) are an important reef predator and are targeted by fisheries throughout the Pacific region. Experimental studies show that the thermal optimum for *P. leopardus* is 27-30°C (Frisch *et al*. 2016, Pratchett *et al*. 2017), while wild stocks occupy areas where sea surface temperatures can exceed 30°C. These fishes may be able to moderate their exposure and sensitivity to increasing temperatures by exploiting thermal refugia or moderating food intake and energetic expenditure during warmer periods (Scott *et al*. 2017). Even so, ocean warming will increasingly jeopardize the sustainability of ongoing harvesting of coral trout, especially at low latitudes (Pratchett *et al*. 2017). A range of climate-induced effects on biology and behaviour in wild coral trout populations have been recorded to date, including shifts in dietary composition (Wen *et al*. 2016) and declines in abundance (Williamson *et al*. 2014) and catch rates (Tobin *et al*. 2010). These impacts will also be compounded by increasing coral loss and the structural collapse of shallow-reef habitats due to severe coral bleaching (e.g. Hughes *et al*. 2017). These studies provide information to predict what is likely to happen for coral trout under future climate change scenarios, and the combination of ocean warming and degradation of coral reef habitats is expected to significantly reduce yields from coral trout fisheries.

(iii) Pelagic fish

A range of large and small pelagic fish species are found in Pacific waters. Although there are few data quantifying biomass or the catches of these species, it is estimated that ~30% (around 43,000 t) of the total coastal fisheries catch in the region is comprised of nearshore pelagic species (Bell *et al*. 2018), while four species of tuna are targeted by oceanic fisheries (see Oceanic Fisheries paper, this volume). The most common larger species are skipjack tuna *Katsuwonus pelamis*, South Pacific albacore *Thunnus alalunga*, bigeye tuna *Thunnus obesus*, yellowfin tuna *Thunnus albacares*, wahoo *Acanthocybium solandri*, mahi mahi *Coryphaena hippurus*, rainbow runner *Elegatis bipinnulata*, Spanish mackerel *Scomberomorus commerson*, billfish (Istiophoridae) and sharks (SPC 2013). The smaller pelagic species mainly comprise mackerels (Scombridae), scads (Carangidae), flying fish (Exocoetidae), pilchards and sardines (Clupeidae) and anchovies (Engraulidae) (Pratchett *et al*. 2011a).

Observations of climate change impacts on pelagic fish species have been more elusive than for demersal fish (Pecl *et al*. 2017). In the Pacific islands region, this is due to the strong influence of climate variability on the distribution of tuna and billfish (Hobday and Evans 2013). For example, the locations where skipjack tuna biomass is predicted to be highest are strongly influenced by the El Niño Southern Oscillation (ENSO), varying by up to 4,000 km of longitude between strong El Niño and La Niña events (Lehodey *et al*. 1997). The status of the tuna species in the region is generally well understood (see Science Review 2018: Oceanic Fisheries paper). In contrast, little is known about the status of the other pelagic species, with the exception of some billfish and shark species (Johnson *et al*. 2017).

(iv) Sharks and rays

Over 130 species of sharks and rays are believed to occur in the Pacific (Lack and Meere 2009) although this is likely to be an under-estimate, especially for PICTs closer to the Indo-Pacific centre of biodiversity. For example, at least 133 species of sharks and rays occur in the Great Barrier Reef (Chin *et al*. 2010) and species are still being described (Last *et al*. 2016). Sharks and rays are mainly taken in two distinct fisheries: (i) pelagic species caught in association with tuna fisheries; and (ii) coastal species taken as target or incidental catch by small-scale coastal fishers. However, there are reports of some illegal, unreported and unregulated (IUU) fishing activity targeting sharks (oceanic and coastal) in the Pacific, primarily for their fins (Rika 2017).

The main pelagic sharks captured include silky sharks (*Carcharhinus falciformis*), blue sharks (*Prionace glauca*), ocean whitetip sharks (*C. longimanus*), as well as hammerheads (*Sphyrna spp.*), thresher sharks (*Alopias spp.*) and mako sharks (*Isurus spp.*) (SPC Oceanic Fisheries Program 2010). Significant numbers of sharks have been caught in association with tuna fisheries that historically retained fins for the shark fin trade. However, long-term, accurate data on the catch of sharks in these fisheries are limited and there is great uncertainty about species-specific catch rates, catch fate and trade (Clarke *et al*. 2006). However, there are several indications that sharks are under significant pressure in the Pacific (Lack and Meere 2009, Clarke *et al*. 2013). As a result, several species of pelagic sharks have been listed on Appendix II of the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES), and the Western and Central Pacific Fisheries Commission (WCPFC) has a no-retention requirement on some of these species (WCPFC 2015). Some other species of conservation interest, such as whale sharks (*Rhincodon typus*) and mobulid rays (*Mobula spp.*), are also sometimes caught as bycatch by purse-seine vessels (SPC Oceanic Fisheries program 2010).

Coastal sharks are mainly caught by small-scale fishers who consume the meat directly, or sell shark meat and fins for income (Glaus et at. 2015, Hylton *et al*. 2017). Stingrays may be particularly important to some indigenous peoples. Very little is known about the catch of sharks and rays in Pacific small-scale fisheries and the status of coastal populations but there are anecdotal accounts of declines in some areas. While most conservation and management attention is focused on pelagic fisheries, emerging evidence is documenting the importance of sharks and rays in Pacific coastal fisheries. Shark fin can be a valuable income source for some coastal communities alongside bêche-de-mer, and loss of this resource can have significant effects (Vieira *et al*. 2017).

There is limited information about the effects of climate change on sharks and rays in the Pacific, apart from a systematic risk assessment in the Great Barrier Reef (Chin *et al*. 2010). No observed changes have been reported and the lack of data on existing patterns of diversity and occurrence make it difficult to identify climate related changes in range and movements. However, experimental evidence suggests that some species may be adversely affected by rising sea temperatures and ocean acidification (Rosa *et al*. 2017).

What Could Happen?

(i) Demersal fish and (ii) Invertebrates (shellfish)

Increased greenhouse gas emissions will have direct and indirect effects on demersal fish and invertebrates in the Pacific Island region. These impacts include the effects of global warming and ocean acidification on the habitats that support fish and invertebrates. Coastal habitats – coral reefs, mangrove forests, seagrass meadows and intertidal flats – are expected to decline due to changes in temperature, pH, light and hydrology (Figure 2) (Waycott *et al*. 2007, 2011, Collier and Waycott 2009, Hoegh-Guldberg *et al*. 2011; see Corals, Seagrass and Mangrove papers, this volume), while oceanic habitats and food webs are expected to be modified due to climate-driven changes in temperature, pH, stratification, oxygen and hydrology (Le Borgne *et al*. 2011, Johnson *et al*. 2017; see Oceanic Fisheries paper, this volume).

Climate-induced degradation of tropical marine habitats poses the most immediate and greatest threat to the biodiversity and functioning of demersal fish (Pratchett *et al*. 2008). Highly degraded coral reefs, for example, support less than one-third of the biodiversity of reef fishes found on reefs with high coral cover and topographic complexity. Ocean warming and acidification will also have direct effects on reef fish physiological performance and fitness (Munday *et al*. 2011, 2012). Many coral reef fishes appear to be living very close to their upper thermal optimum, such that any significant increases in ocean temperature will constrain metabolic performance, with effects on movement, prey capture, reproduction and growth. Under laboratory conditions, ocean acidification has been demonstrated to have significant effects on sensory responses and individual behaviour of fishes, which will affect recruitment, predator avoidance, and individual survival (Munday *et al*. 2011, 2012), however increasing sea surface temperature (SST) is expected to be the more immediate and greater threat.

Continued declines in the areal extent and condition of critical coastal habitats, particularly coral reefs, are expected to exert increasing pressure on marine fishes. Importantly, there is limited evidence of compensatory responses among tropical fish assemblages (Pratchett *et al*. 2014), meaning that species losses erode not only the biodiversity and functional redundancy of these systems (i.e. the capacity for species loss to be compensated by remaining species contributing similarly to ecosystem functioning) but directly contribute to declines in productivity. There is also increasing evidence of non-linear or threshold responses, whereby the effects of habitat loss are highly magnified when habitats become highly degraded (Pratchett *et al*. 2014). Increasing habitat degradation and fragmentation will also compromise the capacity of fish populations and assemblages to recovery in the aftermath of major disturbances.

Although many demersal fish and invertebrates are adapted to variable diurnal and seasonal temperature cycles, and are relatively tolerant of short-term changes, the projected increases in SST are likely to exceed the optimum thermal levels of many species. Increases in metabolic rate caused by higher SST will alter biological processes, reproductive success, recruitment and juvenile growth of many demersal fish and invertebrate species, resulting in changes in distribution and abundance (Gagliano *et al*. 2007, Munday *et al*. 2008, Donelson *et al*. 2010). For example, fish and invertebrate species dependent on reef habitats are unlikely to occur on reefs where their thermal optima no longer overlap. On the other hand, tuna and other mobile pelagic fish are expected to be able to move more easily to areas with optimal thermal conditions.

Projected changes in the direction and strength of ocean currents are also expected to affect many demersal fish and invertebrate species in the Pacific Island region. Alterations in circulation patterns are likely to result in changes to spatial and temporal patterns of larval dispersal and settlement (Bell *et al*. 2011a). Consequently, replenishment of demersal fish and invertebrate stocks may become more reliant on local reproduction. Interactions between altered ocean circulation and the other effects of increased CO_2 emissions described above are also likely to affect the dispersal of demersal fish and invertebrates in at least two ways. First, connectivity among populations may be reduced further by reductions in pelagic larval duration due to increases in SST and the effects of ocean acidification on settlement success. Second, the combination of altered ocean circulation and increased thermal stratification is expected to reduce the mixing of deep, nutrient-rich waters with the surface waters surrounding many PICTs, resulting in reductions in the productivity of coastal ecosystems with significant implications for larval survivorship. However, any such effects may be diminished around some high islands due to the projected increase in nutrient inputs from terrestrial runoff (Pratchett *et al*. 2011a).

The increased concentration of carbon dioxide (CO_2) in seawater is expected to have negative effects on the growth and survival of early life history stages of demersal fish because they lack specialised internal pH regulatory systems (Frommel *et al*. 2011, 2014, Miller *et al*. 2012). The effects of elevated CO_2 levels on the sensory ability of early life history stages of demersal fish are expected to be even more significant. Increased boldness and activity (Munday *et al*. 2013), altered auditory responses (Simpson *et al*. 2011), loss of lateral movement (Domenici *et al*. 2012), and impaired olfactory function (Munday *et al.* 2009, Dixson *et al*. 2010, Cripps *et al.* 2011, Devine *et al*. 2012) have been observed in juvenile demersal fish reared in elevated CO_2 seawater. Such changes are expected to affect the homing and settlement behaviour of juveniles, and their ability to detect and avoid predators (Munday *et al*. 2013). Although more recent work has demonstrated that these impacts may be less severe than previously documented (Jarrold *et al*. 2017), this may still have negative implications for population replenishment and further studies on species exploited by fisheries are needed. Potential negative, synergistic effects between elevated SST and ocean acidification has had limited attention although recent work suggest that temperature changes will have the greatest consequences (Miller *et al*. 2015). The scope for genetic variation within reef fish populations to adapt to changing seawater chemistry is also unknown (Cheung *et al*. 2015).

Ocean acidification is expected to affect calcifying invertebrates, including molluscs, crustaceans and echinoderms because, like corals, their shells, exoskeletons or skeletal elements are composed of aragonite (or high-magnesium calcite in some species) (Ries *et al*. 2009). Calcifying molluscs reared under lower pH form thinner shells, and have reduced growth and lower survival rates, than those reared under normal pH conditions (Shirayama and Thornton 2005, Watson *et al*. 2012, Gazeau *et al*. 2013). Lower rates of calcification are expected to result in declines in the size and growth of molluscs for export (e.g. trochus, green snail and pearl oysters), and in the abundance of bivalves and gastropods gleaned for local consumption. Shellfish important for aquaculture in the tropical Pacific that are expected to be most vulnerable to climate change and ocean acidification are pearl oysters, shrimp and marine ornamentals, while seaweed may benefit in some locations depending on the influences of increasing SST and rainfall.

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 limited long-term research on the direct effects of projected ocean acidification on the main species of sea cucumbers harvested in the Pacific region (Collard *et al*. 2014). Research on other sea cucumber species, and related sea urchins (Brennand *et al*. 2010, Byrne 2011, Byrne *et al*. 2011), suggests that these species may be sensitive 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).

The indirect effects of climate change on coastal fisheries will result largely from changes in the quantity (area) and quality (condition) of coastal fish habitats. As live coral cover declines, abundances of coral-dependent demersal fish and invertebrate species are expected to decrease. Generalist demersal fish species, such as emperors, snappers and goatfish, are not likely to be affected significantly, at least in the short-term, because they use a range of habitats. In contrast, the proportions of herbivorous demersal fish species, including surgeonfish, parrotfish and rabbitfish, are likely to increase as the cover of live coral declines and macroalgae increases (Hoegh-Guldberg *et al*. 2011, Johnson *et al*. 2017). However, in the medium to long term, significant reductions in entire demersal fish assemblages are likely (see below) due to declines in the extent and structural complexity of coral reef, mangrove and seagrass habitats, and consequent effects on recruitment and survival.

Changes in the quantity and quality of coastal habitats projected under climate change are also likely to have deleterious effects on invertebrate populations (Przeslawski *et al*. 2008, Kroeker *et al*. 2013). In particular, there will be fewer places within coral reefs for species to forage and shelter from potential predators, resulting in reductions in the diversity and abundance of invertebrate species (Pratchett *et al*. 2011a). However, habitat degradation will not be limited to the effects of coral bleaching, ocean acidification and more intense cyclones on coral reefs. Sea-level rise will reduce the area of mangrove, seagrass and intertidal habitats, particularly where land barriers such as steep terrain or coastal infrastructure limit shoreward migration (Waycott *et al*. 2011). Species with specialist habitat requirements, such as the sea cucumber *Holothuria scabra*, which settles only in shallow seagrass meadows (Mercier *et al*. 2000), are likely to be affected.

There is also concern that the progressive degradation of coral reefs could increase the incidence of ciguatera fish poisoning and other problems related to toxic algae. The organisms responsible for ciguatera and ciguatera-like symptoms are dinoflagellate microalgae in the genera *Gambierdiscus*, *Prorocentrum* and *Ostreopsis*. These microalgae live as epiphytes on dead coral, turf algae and macroalgae, and are ingested by grazing herbivorous fish. The microalgae produce a range of toxins that bio-accumulate through the food chain (Dalzell 1993, Laurent *et al*. 2005, Roué *et al*. 2013). Greater availability of the preferred substrata of these microalgae – dead coral and macroalgae – resulting from increased coral bleaching events and cyclones of greater intensity will likely increase the incidence of ciguatera in the region (Pratchett *et al*. 2011a, b, Rongo and van Woesik 2013).

For reef fish that sustain important tropical coastal fisheries across the Pacific (Bell *et al*. 2013), the combined effects of ocean warming and acidification will almost certainly lead to greater interannual variability in reproduction and replenishment, and overall declines in fisheries productivity (Table 3; Figure 3). However, more recent work has shown that previous studies may have over-estimated the impacts of acidification (Jarrold *et al*. 2017) creating uncertainty for future fisheries management.

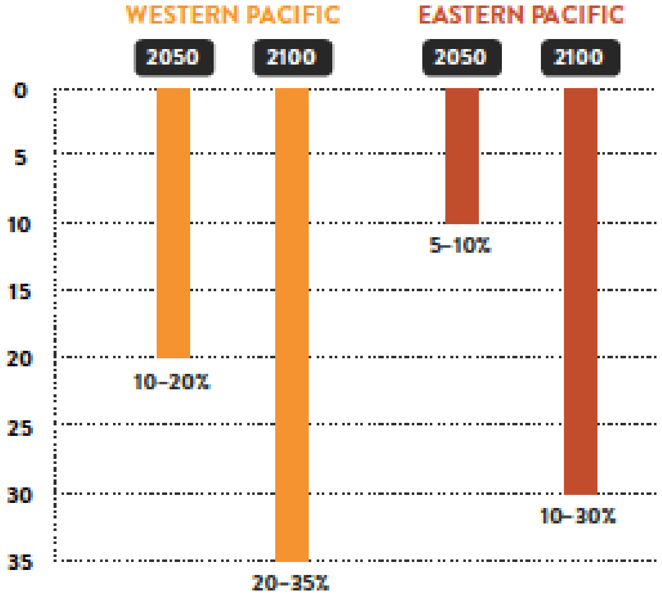


Figure 3. Coastal fisheries productivity declines projected for 2050 and 2100 under a high emissions scenario (source: Bell *et al*. 2016).

(iii) Pelagic fish

Recent modelling for the Pacific Ocean (Dueri *et al*. 2014, Lehodey *et al*. 2015, Matear *et al*. 2015, Senina *et al*. 2015) suggests that the effects of climate change on ocean dynamics will affect the future distribution and abundance of tuna and other pelagic species. The four main tuna species (albacore, bigeye, skipjack and yellowfin tuna) are expected to respond directly to changes in water temperature, oxygen, ocean currents, ocean acidification and the location of the Western Pacific Warm Pool (the warm pool), and indirectly to changes in the structure of the food web (Lehodey *et al*. 2010a, 2011, Bromhead *et al*. 2015).

Projected warming of the tropical Pacific Ocean and decreases in the strength of major currents and in the formation of eddies, are likely to have two primary effects on the spatial distributions of the four tuna species. The first involves potential changes in the timing and location of spawning, and in recruitment success. The magnitude of these effects will depend

Table 3. Projected changes in production of the three categories of coastal fisheries, and total coastal fisheries production, in 2050 and 2100 under a high emissions scenario. The main direct and indirect effects of climate change projected to affect each coastal fisheries category are also provided. Note that availability of nearshore pelagic fish is expected to increase in the eastern part of the region (source: Pratchett *et al*., 2011a and the Pacific Community, New Caledonia).

Variable		**Coastal fisheries category**				**Total coastal fisheries** (assumes that the proportions of the three coastal fisheries categories remain constant)	
		Demersal fish	**Nearshore pelagic fish**		**Invertebrates**		
Contribution to coastal fisheries production		56%	28%		16%	West	East
			West* (15°N–20°S and 130°E-170°E)	East* (15°N–15°S and 170°E-150°W)			
Change in production due to climate change	2050	–20%	–10%	+20%	–5%	–10 to –20%	–5 to –10%
	2100	–20 to –50%	–15 to –20%	+10%	–10%	–20 to –35%	–10 to –30%
Main direct and indirect effects of climate change		Habitat loss, and reduced recruitment (due to increasing temperature and reduced water movement)	Reduced production of zooplankton in food webs for non-tuna species and changes in distribution of tuna		Habitat degradation, declines in aragonite saturation due to ocean acidification		

on the phenological adaptation of each species. Assuming limited adaptation, spawning tuna are expected to avoid areas with temperatures above their thermal optimum to prevent overheating. The exact location of spawning areas would differ among tuna species because albacore, bigeye and yellowfin tuna spawn where SST is greater than 24-25 °C (Schaefer 2001), whereas skipjack tuna prefer SST greater than 28-29 °C (Lehodey *et al*. 2011). The early life stages are expected to be more sensitive and vulnerable to changes in water temperatures and circulation, and to changes in oxygen and pH, than adults (Lehodey *et al*. 2011, Bromhead *et al*. 2015).

Projected changes in primary productivity due to climate change are also likely to affect where tuna spawn. In particular, spawning areas are projected to shift to the central and eastern equatorial region where productivity is projected to remain relatively high, and could extend into the Tasman Sea (Lehodey *et al*. 2015).

The second potential impact relates to changes in the vertical distribution of fish. Increased stratification of the water column due to higher SST may alter the vertical distribution of tuna and affect their access to food during the diel vertical migrations of their prey (Le Borgne *et al*. 2011). Increases in temperature and concomitant decreases in oxygen in subsurface waters are expected to have less impact on skipjack tuna, which inhabit the surface layer. In contrast, greater impacts are expected to occur for yellowfin tuna and albacore, which swim between the surface and subsurface, and for bigeye tuna, which descend to deeper layers. The higher tolerance of bigeye tuna to low oxygen levels may reduce the impacts for this species unless anoxic conditions or ‘dead zones’ (oxygen concentration < 1 ml/L) develop. The dynamic relationship between tuna and their environment, combined with their life history characteristics, results in complex interactions, feedback loops and non-linear effects. This complexity has been modelled by the dynamic Spatial Ecosystem and Populations Dynamics Model (SEAPODYM) (Lehodey *et al*. 2008; Senina *et al*. 2008) and Apex Predator Ecosystem Model Estimation (APECOSM-E) model (Dueri *et al*. 2012) which simultaneously evaluate interactions between environmental changes, biological function and spatial dynamics of tuna populations.

Preliminary simulations of climate change impact on albacore (Lehodey *et al*. 2015), skipjack tuna (Lehodey *et al*. 2013b, Dueri *et al*. 2014, Matear *et al*. 2015), bigeye tuna (Lehodey *et al*. 2010b, 2013a) and yellowfin tuna (Senina *et al*. 2015) use outputs from global coarse resolution Earth Climate models. They point to declining abundances in the western Pacific Ocean and/or distribution shifts towards the eastern Pacific (see Oceanic Fisheries paper, this volume). These changes are driven largely by the projected weakening of equatorial upwelling and current systems, and the warming of waters and associated increase of water stratification in the western region leading to lower primary production (Steinacher *et al*. 2010, Bopp *et al*. 2013).

Tuna populations are thought to be especially sensitive to changes in the food web that supports them, ranging from changes in primary productivity to the abundance of their micronekton prey (Lehodey *et al*. 2011). In particular, decreases in micronekton are likely to increase natural mortality of tuna and lower the overall production of tuna fisheries in the region. The expected eastward shift of the convergence zone between the warm pool and the Pacific equatorial divergence (Le Borgne *et al*. 2011) could lead to decreases in tuna abundance in the warm pool where primary productivity is relatively low (Lehodey *et al*. 2011). However, the projected increases in rainfall in equatorial areas (Lough *et al*. 2011) could increase the supply of nutrients in the archipelagic waters of PNG, with subsequent increases in productivity creating better feeding grounds. In addition, current Earth climate models may have too coarse resolution to provide accurate projections of change in primary productivity (Matear *et al*. 2015). While the projected changes in productivity of the Western Central Pacific Ocean remain uncertain, it is clear that the high mobility of tuna is expected to assist them to adapt to changes in oceanic habitats and the availability of micronekton by moving to favourable foraging areas where there are fewer physiological constraints (Lehodey *et al*. 2011; see Oceanic Fisheries paper, this volume).

Modelling of the effects of climate change on the preferred habitats of two other large pelagic fish commonly caught by small-scale fishers, wahoo and mahi mahi, using a multi-species distribution approach, indicates that: 1) climate change is likely to result in poleward migration of both species; and 2) conditions for mahi mahi are likely to deteriorate more rapidly than those for wahoo (Bell *et al*. 2018).

(iv) Sharks and Rays

Predicting the effects of climate change on Pacific sharks and rays is challenging due to: (i) the lack of knowledge about the status and ecology of these species; (ii) the diversity of these species (e.g. they have six different modes of reproduction); and (iii) their position as higher order predators, which means that indirect impacts may depend on the impacts to – and responses of – lower trophic level species to climate change.

A comprehensive risk assessment for tropical sharks and rays identified direct and indirect pressures, and used a semi-quantitative risk assessment approach to individually rank 133 shark and ray species for climate change vulnerability (Chin *et al*. 2010). As a group, sharks and rays are generally larger, more mobile species that are fairly adaptable and resilient. This means they can respond to changing conditions by moving to more favourable conditions and exploiting new resources (Chin and Kyne 2007). Applying this assessment to the wider Pacific region, climate change impacts can be described by examining specific groups of sharks and rays.

Pelagic sharks are highly dependent on food resources, and their occurrence is closely linked to that of their prey species, which in turn, respond to oceanographic factors. As such, changes in the distribution of pelagic fishes will likely result in changing distribution patterns of pelagic sharks (Chin *et al*. 2010). These changes in movement and distribution could also affect reproduction, as pelagic shark stocks are structured by sex and size (Wearmouth and Sims 2008), and increased unpredictability in phenology such as location and timing of upwellings could affect provisioning and survival. However, if pelagic sharks are able to respond to changing conditions and prey distribution, they may be able to adapt to climate impacts.

Coastal sharks occur on mud and sand flats, reef flats, seagrass beds, coral reefs and reef lagoons. Increased rainfall and runoff and increasing temperatures may cause direct physiological stress that affect shark movement and behaviour (Schlaff *et al*. 2014). Additionally, these factors, as well as more intense storms, can significantly alter the quality and availability of suitable habitat, and can also alter coastal productivity and the availability of prey species. Many coastal sharks and rays are mobile and may be able to relocate to more favourable conditions. However, their survival depends on the availability of these alternative habitats and locations, their ability to locate and move to these areas, and their ability to successfully establish viable populations in these areas (Chin *et al*. 2010). Species with specific habitat requirements such as reef sharks or species that use specific coastal nurseries, may also be severely impacted by the loss of coral reefs and certain coastal habitats that are highly vulnerable to climate change. Consequently, some coastal species may be able to adapt to changing conditions but changes in local abundance and distribution are likely. Other species with specific habitat requirements may experience declines if those habitats are degraded or lost.

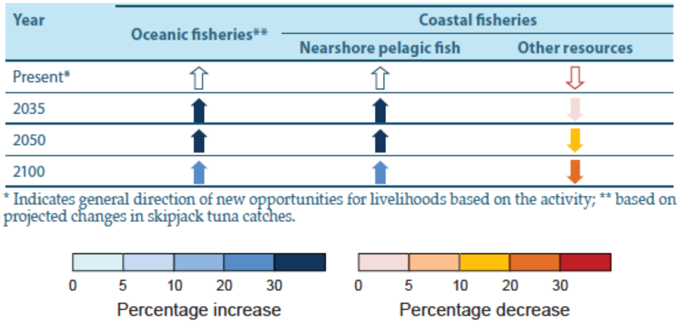
Importantly, these impacts may be exacerbated in spatially small and/or isolated locations that have limited habitat availability.

Some species of sharks and rays, such as river sharks (*Glyphis spp.*) and sawfishes (*Pristis spp.*) are especially rare and globally threatened due to a combination of their biology, habitat specificity, over-harvesting and habitat loss (Dulvy *et al*. 2014). These sharks also rely on specific coastal habitats such as rivers and estuaries and thus, are likely restricted to the high island countries and territories of Melanesia. Changing rainfall patterns, storm intensity, and sea level rise could reduce habitat availability and cause direct mortality. Given the precarious conservation status of these species and extant threats, climate change could cause localised depletion and even localised extinction of these species in PICTs where they occur.

Deep water sharks are extremely poorly understood and climate change effects on these species cannot currently be reliably predicted.

A central factor in predicting climate change effects on sharks and rays in the Pacific region is the assumption that many species are able to physiologically tolerate a range of conditions, and when limits are exceeded, relocate to more favourable conditions. Certainly, these adaptive behaviours are already widely evident (Schlaff *et al*. 2014), and sharks have survived mass extinction events through evolutionary history. As such, physiological and/or behavioural adaption is an expected climate change response (Chin *et al*. 2010). Nevertheless, a significant unknown is the effect of rising sea temperature and ocean acidification on shark and ray physiology. Experimental data are becoming available and suggest that these changes may have significant impacts on some sharks and rays. Recent research suggests that increased temperature and acidity may affect body condition, growth, pigmentation, and the ability to detect and pursue prey (Gervais *et al*. 2016, Rosa *et al*. 2017). However, some species may be tolerant of extreme conditions (Heinrich *et al*. 2014). The limited available information suggests that sharks and rays exposed to extreme environmental ranges, such as a reef flat specialist like the epaulette shark *Hemiscyllium ocellatum*, may be able to physically tolerate increased temperature and acidity much better than species such as pelagic sharks (Heinrich *et al*. 2014), but effects on other key traits such as hunting ability are still largely unexplored.

In summary, many current pressures are impacting fish and shellfish and the coastal fisheries they support in the short-term, and climate change adds a medium- to long-term threat that will affect oceanic and coastal fisheries in different ways (Table 4).



Year	Oceanic fisheries**	Coastal fisheries	
		Nearshore pelagic fish	Other resources
Present*	⇧	⇧	⇩
2035	⬆	⬆	⬇
2050	⬆	⬆	⬇
2100	⬆	⬆	⬇

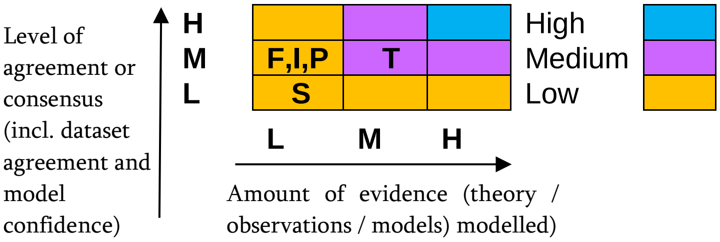
* Indicates general direction of new opportunities for livelihoods based on the activity; ** based on projected changes in skipjack tuna catches.

Table 4. Summary direction of future trajectory of oceanic and coastal fisheries resources under a high emissions climate change scenario, particularly as a source of livelihoods opportunities. "Other resources" refers to demersal fish and invertebrates (shellfish).

Confidence Assessment

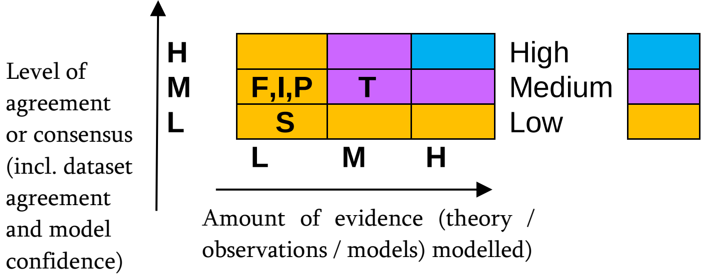
T = tuna;
P = pelagic fish (not including tuna);
F = demersal fish;
I = invertebrates (shellfish);
S= sharks & rays

What is already happening



Extensive experimental research (albeit on a relatively limited range of reef fish species) has provided mechanistic insight into the various ways that environmental change will impact on the physiology and abundance of demersal fish (Munday *et al*. 2008, Donelson *et al*. 2010). Field-based studies have found significant changes in abundance of many reef fish following acute disturbances that cause extensive and widespread habitat degradation (reviewed by Wilson *et al*. 2006, Pratchett *et al*. 2008, 2014), and Pratchett *et al*. 2008 documented the impacts of coral bleaching on reef fish. Interspecific differences in vulnerability to habitat degradation and climate change can be explained based on their individual resource requirements and physiological limits. However, there is still some uncertainty surrounding the acclimation and adaption capacity for different species, which could moderate effects of on-going environmental change (Pratchett *et al*. 2017).

What could happen in the future



The confidence in predicting future effects of climate change on demersal fish and invertebrate populations in the Pacific region described above follows that of Bell *et al*. (2011a), who consider declines in overall demersal fisheries production with a high to very high degree of confidence. This consideration largely results from the expected (and observed) effects of climate change on coastal habitats, in particular coral reefs, mangroves and seagrass.

Confidence regarding climate change impacts on sharks and rays is low due to the diversity of species and lack of basic information on patterns of occurrence and distribution, physiology, and ecology. As larger, more mobile species, sharks and rays are difficult to observe in the field, which confounds efforts to monitor population changes. They are also very difficult to study under experimental conditions, restricting physiological studies to small benthic species. Their high trophic position also means that impacts will depend on complex ecological relationships that are extremely variable, especially in complex tropical environments.

Knowledge Gaps

(i) Demersal fish and (ii) Invertebrates

Much uncertainty still exists about the effects of climate change on demersal fish and invertebrates. For example, the effects of increasing temperature and ocean acidification have mostly been tested on small-bodied, site-attached, demersal fish species. There has been relatively limited comparable research on larger reef fishes that support major tropical fisheries (but see Messmer *et al*. 2017). These studies therefore need to be replicated on exploited species to confirm whether the results are applicable or if exploited species will respond differently. Moreover, assessments of changes to key environmental variables (e.g. increasing SST or declining pH) have largely been conducted in isolation, but are likely to have synergistic effects and will co-occur with on-going environmental change.

Priority knowledge gaps to better increase our understanding of the effects of climate change on demersal fish, invertebrates and coastal fisheries, and the consequences for food security and livelihoods include:

1. Further examination of the synergistic effects of increasing ocean acidification, SST and other anthropogenic stressors, on the biology and ecology of demersal fish and invertebrates, and the ability of target fisheries species to adapt to these changes.
2. Monitoring shifts in the distributions of species, and the effects of climate-induced changes in species composition on ecosystems, by establishing long-term monitoring at specific sites to measure distributional shifts and biological impacts as well as environmental conditions, such as pH, SST and habitat condition.
3. Undertaking a cost-benefit analysis of the key adaptation options for food security to inform sustainable and adaptive management that can supply fish for food, noting that a holistic approach needs to incorporate a range of adaptation tools (see ‘Adaptation Options and Supporting Policies’ section).

Dedicated sampling programs will be needed to monitor the effects of climate change on reef fish and their habitats, and the fisheries they support, to provide information for adaptive management. These programs will require an experimental approach that controls for the effects of other stressors, such as fishing pressure, poor land management practices and pollution (SPC 2013). Regional standardisation of both fisheries-independent (e.g. in-water surveys) and fisheries-dependent (e.g. creel and market surveys) methodologies for data collection, storage, analysis and reporting will also be needed for purposes of Pacific-wide comparison and advice. Importantly, the status of coastal fisheries resources in PICTs is either uncertain or overexploited due to rapidly growing human populations and other pressures, such as coastal development. Therefore, there is an urgent need to better understand the most effective options for sustainable management of coastal resources to address these existing pressures recognising that the expected effects of climate change will potentially constrain fisheries productivity and food availability. For example, marine protected areas (MPAs) are commonly applied but are rarely compared to other management options or assessed for their cost-effectiveness or feasibility. The Noumea Strategy (SPC 2015) clearly states that over-reliance on site-based approaches, such as MPAs, is unlikely to achieve widespread goals of fisheries management and hence proposes other ecosystem-based fundamental approaches.

(iii) Tuna and pelagic fish

Much of the research needed to improve understanding of the projected effects of climate change on tuna in the tropical Pacific centres on strengthening SEAPODYM. Importantly however, the focus to date has been on the four main species of tuna due to their high economic value.

1. Extend the application of SEAPODYM-like models to include the dynamics of other pelagic fish species and projections of how their populations will be affected under climate change.
2. Research to further develop and parameterise the biogeochemical SEAPODYM model (as described by Lehodey *et al*. (2011)):
   - assess the effects of higher atmospheric concentration of CO_2 on the C:N ratio of organic matter in the ocean and influences on primary production and the carbon cycle; and
   - define the optimal range and thresholds of temperature and dissolved O_2 concentrations for the different life history stages of the four species of tuna.
3. Further evaluation of the potential impacts of increased ocean acidification on tuna (Bromhead *et al*. 2015) and other mobile pelagic species, particularly on production of gametes, fertilisation, embryonic development, and hatching and larval behaviour and ecology of tuna.

SEAPODYM results will also be improved by creating an ensemble of simulations from a range of global climate models endorsed by IPCC to estimate the likely effects of global warming on tuna distribution and abundance (Senina *et al*. 2015).

Delineation of the spatial structure of tuna stocks will also improve our understanding of the likely effects of climate change on these important resources. At present, the models assume that each species of tuna is a panmictic stock across the tropical Pacific basin. There is growing evidence that for yellowfin and bigeye tuna at least that there are multiple stocks of each species. Once the spatial structure of each tuna species has been identified, the effects of climate change will need to be modelled for each self-replenishing population (stock).

It will also be important to develop a wider range of modelling approaches for the other large pelagic species commonly caught by small-scale fishers, e.g. wahoo and mahi mahi. In particular, data should be assembled to apply SEAPODYM to these species.

(iv) Sharks and Rays

The level of confidence in describing current and future impacts of climate change on sharks and rays in the Pacific is low. This is largely because sharks and rays in the Pacific have received little attention. Indeed, taxonomy and species diversity are still being explored (e.g. Hylton *et al*. 2017). At the same time, the diversity of life history characteristics, ecological niches, potential adaptability, and linkages with lower trophic levels in food webs, makes it difficult to generalise about climate change responses and impacts. Predicting climate change impacts may require case-by-case assessments such as has been done for the Great Barrier Reef (Chin and Kyne 2007), and even then, many unknowns remain about species ecology and physiology. As such, much of the forecasting about expected responses and effects of climate change is based on ecological theory instead of demonstrated case studies. Indeed, there is a general lack of data and assessments on climate change impacts on sharks and rays. While experimental studies on physiological limits and responses are increasing, they are currently limited to a few (mainly benthic) species that can be feasibly maintained in experimental conditions. Lastly, sharks and rays in some areas of the Pacific are already heavily impacted by human activities and it is difficult to disentangle climate change impacts from existing threats and impacts.

Nevertheless, securing the future of the Pacific's sharks and rays in a changing climate could be aided by targeted research as described below:

1. A systematic review of the diversity and status of sharks and rays in each PICT to describe biodiversity and identify key threats.
2. For highest risk species, targeted inter-disciplinary research to identify, trial and evaluate management options.
3. Improved data on the extent of the most significant existing threats, i.e. fishing. Specifically, improved data on catch composition and fate, risk assessment, improved stock assessment, especially for small-scale fisheries that are not well studied and generally under-valued.

The challenges facing sharks and rays are complex due to their biological and ecological diversity, and the range of uses, values and interactions they have with fisheries and communities. This means that case-by-case research and conservation programs need to be devised to tailor management and conservation actions to specific contexts (Dulvy *et al*. 2017).

Socio-economic Impacts

The socio-economic risks from climate change impacts on fish and shellfish in the Pacific region relate to changes to the coastal fisheries that they support and fall under three main areas: (i) food security, (ii) livelihoods, and (iii) economic development and government revenue. These all relate to the primary goods and services and cultural significance that fish and shellfish provide to Pacific communities. In addition, given the finite amount of coastal marine resources and increasing population pressure, there is growing “competition” between subsistence fishers for food, and commercial fishers for income, leading to poaching and the undermining of management arrangements.

The key implications of climate change for coastal fisheries 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 PICTs have put in place to maximize 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.

Food security

Fish and shellfish are cornerstones of food security for the people of the tropical Pacific - fish provides 50–90% of animal protein in the diet of coastal communities, and national fish consumption per person in many PICTs is 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 coastal fishing.

The implications of climate change for the important role that fish and shellfish play in the food security of PICTs depends not only on the projected effects of increases in SST and ocean acidification on the coral reefs that provide much of the coastal fisheries production across the region, but also on population growth, the area of coral reef per capita and the distance of reefs from population centres and the effectiveness of management strategies. 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*. 2011b, 2018): (1) PICTs with coastal fisheries that 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) those PICTs where coral reefs and other coastal habitats do not have the potential to produce the fish needed for good nutrition of the population (see Table 5).

Table 5. Summary table of the three food security groups based on assessment of their capacity to provide the 35 kg of fish per person per year recommended for good nutrition of Pacific Island people under projected population growth (dominant influence) and climate change (longer-term influence). Source: Bell *et al.* (2017).

Group 1: Coastal fisheries are expected to meet the increased demand for fish for food in the foreseeable future	**Group 2:** Coastal fisheries should be able to produce the fish needed in the future but difficult to distribute to urban centres from remote islands & atolls	**Group 3:** Coastal fisheries cannot meet the increased demand for fish for food for their growing populations
Cook Islands	FSM	American Samoa
Marshall Islands	French Polynesia	Fiji
New Caledonia	Kiribati	Guam
Palau	Niue	Nauru
Pitcairn Islands	Tonga	CNMI
Tokelau	Tuvalu	PNG
	Wallis & Futuna	Samoa
		Solomon Islands
		Vanuatu

For PICTs in group 2 and 3, a gap is emerging between the amount of fish recommended for food security and sustainable harvests from coastal fisheries. For the reasons explained in ‘What could happen in the future?’, climate change and ocean acidification are expected to increase that gap. It should also be noted that food security is a wider issue than the supply of protein. Wild capture fisheries also provide nutritional security by providing essential minerals, vitamins and fatty acids that support community health (Kawarazuka and Béné 2010). Some of these nutrients are difficult to obtain from other sources, and thus, climate change impacts on fisheries can also affect community health.

Livelihoods

Many people in the Pacific Island region 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 (Pinca *et al*. 2010). The main implication of the projected changes in production of coastal fisheries for livelihoods is that income may decline for artisanal fishers. Within the coastal fisheries sector, the effort of small-scale fishers will need to be increasingly transferred from demersal fish associated with coastal habitats, to currently under-utilised species such as large and small pelagic species, including skipjack and yellowfin tuna (Bell *et al*. 2011c) and squid. Transferring effort to pelagic species is not only expected to maintain the livelihoods of fishers as coastal fisheries decline, it may also create additional job opportunities in several PICTs in the eastern Pacific because of the projected increases in the abundance of tuna. Some small-scale fishers derive important incomes from high value export goods such as sea cucumber and shark fins (Vieira *et al*. 2017). The loss of these resources could impact the limited cash revenue flowing into these communities and thus their purchasing power for vital services and commodities. Alternative use of coastal resources for livelihood opportunities in sports fishing, tag and release venture and eco-tourism will be worth exploring.

The projected shift to the east in the distributions of tuna is expected to alter the availability of full-time jobs, and opportunities to earn income from industrial fisheries and canneries (Bell *et al*. 2011b). For aquaculture, livelihood opportunities are expected to decline in mariculture for species vulnerable to ocean acidification, such as pearl oyster.

A recent assessment of the vulnerability of reef-dependent communities in PICTs to the effects of ocean acidification on food security and livelihoods from fishing, aquaculture and tourism found that communities in Solomon Islands, Kiribati, PNG, FSM, Tonga and Tuvalu were the most vulnerable. Communities that had the lowest relative vulnerability to the impacts on the goods and services provided by reefs were: Niue, CNMI, Tokelau, New Caledonia and Guam (Johnson *et al*. 2016).

For PICTs with tourism capacity, healthy reefs with abundant fish life, sharks and rays may act as a tourism attraction and provide significant income at national and local levels. Shark and ray tourism is important in many PICTs such as French Polynesia and Fiji (Brunnschweiller 2010, Clua *et al* 2011), and could make a substantial contribution to GDP (Vianna *et al*. 2012), particularly if expanded in smaller states like Palau, the Cook Islands and Niue.

Economic development and government revenue

Based on the available modelling for the four species of tuna, which projects increases in abundance in the east and decreases in the west, the progressive redistribution of tuna could confer livelihood advantages in the medium term. The advantages include opportunities for countries like Kiribati, Tuvalu and Tokelau, which have a high dependence on access fees from distant water fishing nations (DWFNs), to obtain even more government revenue from tuna fishing if average levels of effort increase in their EEZs. The modelling suggests that the total catch, essentially driven by the skipjack fishery, will be maintained until 2050, even under a high emissions scenario, and will decrease later in the century. These benefits will depend on PNA members and industrial fleets complying fully with the Vessel Day Scheme (VDS) and with the target reference points for catches of all tuna species. They will also depend on PNA members continuing to develop more flexible management systems to cope with the changing spatial distribution of tuna stocks and fishing effort.

The increasing shift of tuna resources towards international waters of the central-eastern Pacific Ocean will also make monitoring and management regulations more difficult to impose, and total tuna business opportunities are expected to be reduced in the second half of the century if projected lower primary productivity eventuates.

Despite ongoing investments in coastal fisheries development and increased fishing effort, the value and volume of coastal fisheries landings has not substantially increased in the last 15 years. This is consistent with the view that the fish resources that support coastal fisheries in the region are fully or over-exploited (Gillett 2016). Govan (2015) also found that most governments are not allocating adequate operational resources for coastal fisheries management compared to the value of the coastal fisheries, and that this was particularly the case in the lesser-developed countries with projected near-term deficits in coastal fish production. Governments will need to increase their regular budg*et al*locations to coastal fisheries management, which will be vital to ensuring sustainable management systems are established and maintained. Increasing the effectiveness of coastal fisheries management may substantially increase returns to coastal fisheries and national revenue. For instance, Carleton *et al*. (2013) estimate that the value of the bêche-de-mer fishery could be doubled. Furthermore, there is considerable scope for recovery of the costs of management through reviewing currently low commercial licensing fees and penalties (Govan 2017).

Adaption Options and Supporting Policies

Decisions about the most appropriate options for PICTs to adapt to the effects of climate change on fish and invertebrates supporting coastal fisheries must take into account the many other drivers that affecting the sector (Gillett and Cartwright 2010). Rapid human population growth, political will and good governance structures, and the impacts of land use on coastal habitats and stocks of fish and invertebrates, represent just some of these drivers.

The adaptation options recommended here focus on: (i) maximising resilience by supporting PICTs to recognise the need for increased investment in management and to implement national, locally-relevant and ecosystem-based management of fish habitats and fisheries, (ii) adoption and further downscaling of climate change assessments for national coastal fisheries and aquaculture to prioritise adaptations, and (iii) development of clear climate change risk management plans that are specific to the sector (Welch and Johnson 2017). While actions to sustainably use fish and invertebrates in the face of a changing climate are key, they will need to be coupled with support for responsible fisheries transitions (e.g. to different gears, techniques, or species, such as squid or small pelagics), alternative use of marine resources (e.g. sports fishing, ecotourism), and alternative protein and income sources as harvest controls increase.

A range of practical adaptation options have been identified by Bell *et al*. (2011c, 2013) and Johnson *et al*. (2013). The recommended adaptation options are those considered to be either 'win-win', in that they will deliver short-term and long-term benefits, or 'lose-win', where the economic and social costs exceed the benefits in the near term, but where investments position economies and communities to receive net benefits in the longer term under a changing climate. 'Win-lose' investments (i.e. those that offer short-term benefits but do not address long-term requirements, such as support to increase coastal fishing effort or capacity through construction of larger vessels or more effective gear types) represent maladaptation to climate change and should not be considered. The recommended adaptations are not new – they have already been proposed as an integral part of effective coastal zone management (Ehler *et al*. 1997, Gilman 2002, Wilkinson and Brodie 2011) and ecosystem-based fisheries management (Garcia and Cochrane 2005, Leslie and McLeod 2007, SPC 2010, Tallis *et al*. 2010); and to address the effects of population growth on the availability of fish for food security (SPC 2008, Bell *et al*. 2009, Bell *et al*. 2011c).

In addition, it is important that adaptations are designed and delivered in ways that are acceptable to the people they are intended to benefit. This pre-requisite is expected to be relatively easy to achieve in many cases because of how Pacific Island people traditionally respond to and cope with extreme events, such as cyclones and droughts (Ruddle and Johannes 1989, Reenberg *et al*. 2008, UNESCO 2010). However, improvements can be made to traditional ways of responding to extreme events by: (i) increasing the participation of women in all aspects of planning and applying adaptations (equal access to and sharing of benefits), and (ii) ensuring that any barriers to involvement in negotiations to select and implement adaptations by the people likely to be affected are removed.

Policies are required to support the implementation of the adaptation options described above at local and regional scales. Various policies have been suggested in recent years, including in the regional vulnerability assessment of tropical Pacific fisheries and aquaculture (Bell *et al*. 2011c), the Noumea Strategy ('A New Song for Coastal Fisheries – Pathways to Change; SPC 2015) and elsewhere (e.g. Bell *et al*. 2018, Dunstan *et al*. 2018). It is important to note that owing to the focus on supporting community-based approaches, the Noumea Strategy identifies the need to substantially improve provincial fisheries offices and other decentralized mechanisms for government service delivery in many PICTs (Govan 2017).

The main categories of adaptations to maintain the benefits of coastal fisheries for food security and livelihoods are summarised below, and specific adaptations and matching supporting polices are listed in Table 6.

Table 6. Summary of key adaptions and supporting policies to maintain or improve benefits of small-scale fisheries for food security, livelihoods and economic development in the Pacific Islands region.

Focus	Adaptation option	Supporting policies
Adaptations for maintaining the role of fish for food security	• Improving management of coastal habitats • Improving management of coastal fisheries resources • Diversifying fish catches • Alternative uses of coastal resources • Improving fish handling and preservation • Boosting pond aquaculture	Improved governance for sustainable use and protection of coastal fish habitats, including better land-use practices for agriculture, forestry and mining; strengthen fisheries governance and legislation to apply community-based management; promote access to fish expected to increase in abundance; limit export of demersal fish and ecologically-significant invertebrates; develop ecotourism to relieve fishing pressure on demersal fish and invertebrate stocks; apply targeted subsidy and training programs to support key adaptations.
Adaptations to minimise the loss of livelihoods from fisheries, and capitalise on the benefits	• Conservation and restoration of fish habitats • Securing supplies of tuna required to base more tuna fishing and processing operations within PICTs • Switching fishing effort to nearshore pelagic species • Installing nearshore FAD to improve access to tuna • Developing climate-resilient strains for coastal aquaculture • Alternative uses of coastal resources • Marketing environmentally-friendly products	Improved governance for sustainable use and protection of coastal fish habitats, including better land-use practices for agriculture, forestry and mining; include nearshore FADS as part of the national infrastructure for food security; transfer some access rights and revenues from industrial tuna fisheries to small-scale fisheries; evaluate whether industrial fishing exclusion zones provide adequate access to tuna for small-scale fishers; develop ecotourism to relieve fishing pressure on demersal fish and invertebrate stocks; apply targeted subsidy and training programs to support key adaptations.
Adaptations to maximise benefits from tuna to economic development and government revenue	• Development of flexible management measures to allow fishing effort to shift eastward • Optimising productivity of tuna resources across the region	Adopt collaborative and flexible management, monitoring and decision-making processes to ensure proposed interventions and appropriate and effective.

Food security

In general, adaptation actions for maintaining the important role of fish for food security in the region (SPC 2008, Bell *et al*. 2009, 2011c) centre on: (i) 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), (ii) diversifying fish catches to target species expected to be least impacted by climate change, or more resilient to environmental change, to maintain the overall catch of fish, such as nearshore pelagic species, particularly tuna (Bell *et al*. 2015a,b); (iii) alternative uses of coastal resources, (iv) improved fish handling, processing and preservation; and (v) boosting pond aquaculture (Bell *et al*. 2011a).

A community-based ecosystem approach to fisheries management (CEAFM) co-management framework (e.g. SPC 2010), integrates customary marine tenure and other social capital, local governance, traditional knowledge, self-interest and self-enforcement capacity, and provides the most effective way to implement many of these adaptations. However, it will be necessary to establish cooperative management arrangements that support many more communities than currently is the case; only 8% of coastal communities are recorded as receiving coastal fisheries management support (Govan 2015). Regional policies therefore provide strong emphasis on enabling frameworks such as information and awareness and legislative and institutional reform.

Livelihoods

The adaptations required to minimise the loss of livelihoods derived from fish and invertebrate fisheries and aquaculture, and capitalise on the opportunities, include: (i) conserving and restoring fish habitats; (ii) the need to secure the supplies of tuna required to base more tuna fishing and processing operations within PICTs; (iii) switching fishing effort from demersal fish to the nearshore fishery for large and small pelagic species; (iv) installing nearshore FADs to improve access to tuna for small-scale commercial fishers; (v) developing climate-resilient strains for coastal aquaculture; (vi) alternative use of coastal resources; and (vii) marketing environmentally-friendly products.

Community-based adaptation is a key pathway for minimising the negative impact of climate change on the fish and invertebrates that communities depend on, and capitalising on any opportunities. The climate-informed ecosystem approach to fisheries management (Heenan *et al*. 2015) provides a suitable road-map for adaptation. Johnson and Welch (2010, 2015) outlined a semi-quantitative approach for Pacific Island communities to identify their vulnerability to climate change and their most effective adaptation options. A community-scale assessment of vulnerability to the projected impacts of climate change on coastal species and habitats considers implications for demersal and invertebrate fisheries for food security, income from reef fisheries and tourism for livelihoods, employment in aquaculture, and reef area as a proxy for coastal protection. Results provide insight into the main drivers of community vulnerability and the adaptations that are most likely to effectively minimise vulnerability (Johnson *et al*. 2016).

Economic development and government revenue

The adaptations to maximise the economic benefits from tuna for PICTs in the central and eastern Pacific Ocean, and to minimise the impacts for PICTs in the west, revolve around: (i) development of flexible management measures to allow fishing effort to shift east, while ensuring that large quantities of tuna can still be channelled through the established and proposed fish processing operations in the west, and (ii) optimising the productivity of tuna resources across the region.

Citation

Please cite this document as:

Johnson, J.E. *et al*. (2018) Impacts of Climate Change on Fish and Shellfish Relevant to the Pacific Islands. Pacific Marine Climate Change Report Card: Science Review 2018, pp 74-98.

The views expressed in this review paper do not represent the Commonwealth Marine Economies Programme, individual partner organisations or the Foreign and Commonwealth Office.

References

Bell, J.D., Rothlisberg, P.C., Munro, J.L., Loneragan, N.R., Nash, W.J., Ward, R.D. Andrew, N.L. (2005) Restocking and stock enhancement of marine invertebrate fisheries. *Advances in Marine Biology*, 49, 1-370.

Bell, J.D., Kronen, M., Vunisea, A., Nash, W.J., Keeble, G., Demmke, A., Pontifex, S., Andréfouët, S. (2009) Planning the use of fish for food security in the Pacific. *Marine Policy*, 33, 64-76.

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

Bell, J.D., Reid, C., Batty M.J., Allison, E.H., Lehodey, P., Rodwell, L., Pickering, T.D., Gillett, R., Johnson, J.E., Hobday, A.J., Demmke, A. (2011b) Implications of climate change for contributions by fisheries and aquaculture to Pacific Island economies and communities. In J.D. Bell, J.E. Johnson & A.J. Hobday (Eds) *Vulnerability of tropical Pacific fisheries and aquaculture to climate change,* 733-801. Noumea, New Caledonia, Secretariat of the Pacific Community.

Bell, J.D., Andrew, N.L., Batty, M.J., Chapman, L.B., Dambacher, J.M., Dawson, B. *et al*. (2011c) Adapting tropical Pacific fisheries and aquaculture to climate change: management measures, policies and investments. In J.D. Bell, J.E. Johnson & A.J. Hobday (Eds) *Vulnerability of tropical Pacific fisheries and aquaculture to climate change*, 803-874. Noumea, New Caledonia, Secretariat of the Pacific Community.

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

Bell, J.D., V. Allain, E. H. Allison, S. Andréfouët, N.L. Andrew, M.J. Batty, M. Blanc, J.M. Dambacher, J. Hampton, Q. Hanich, S. Harley, A. Lorrain, M. McCoy, N. McTurk, S. Nicol, G. Pilling, D. Point, M.K. Sharp, P. Vivili, P. Williams (2015a) Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories. *Marine Policy*, 51, 584-591.

Bell, J.D., Albert, J., Andréfouët, S., Andrew, N.L., Blanc, M., Bright, P., Brogan, D., Campbell, B., Govan, H., Hampton, J., Hanich, Q., Harley, S., Jorari, A., Lincoln Smith, M., Pontifex, S., Sharp, M.K, Sokimi, W., Webb, A. (2015b) Optimising the use of nearshore fish aggregating devices for food security in the Pacific Islands. *Marine Policy*, 56, 98-105.

Bell, J., Taylor, M., Amos, M., Andrew, N. (2016). *Climate change and Pacific Island food systems*. CCAFS and CTA. Copenhagen, Denmark and Wageningen, the Netherlands.

Bell, J.D., Cisneros-Montemayor, A., Hanich, Q., Johnson, J.E., Lehodey, P., Moore, B., Pratchett, M., Reygondeau, G., Senina, I., Virdin, J., Wabnitz, C. (2018) Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands. *Marine Policy*, 88: 303–314.

Bopp, L., Resplandy, L., Orr, J.C., Doney, S.C., Dunne, J.P., Gehlen, M., Halloran, P., Heinze, C.,Ilyina,T., Séférian, R., Tjiputra, J., Vichi, M. (2013) Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences*, 10, 6225–6245.

Bromhead, D., Scholey, V., Nicol, S., Margulies, D., Wexler, J., Stein, M., Hoyle, S., Lennert-Cody, C., Williamson, J., Havenhand, J., Ilyina, T., Lehodey, P. **(**2015) The potential impact of ocean acidification upon eggs and larvae of yellowfin tuna (*Thunnus albacares*). *Deep Sea Research II*, 113, 268–279.

Brunnschweiler, J.M. (2010) The Shark Reef Marine Reserve: a marine tourism project in Fiji involving local communities. *Journal of Sustainable Tourism,* 18(1), 29-42.

Brennand, H.S., Soars, N., Dworjanyn, S.A., Davis, A.R., Byrne, M. (2010) Impact of ocean warming and ocean acidification on larval development and calcification in the sea urchin *Tripneustes gratilla*. *PLoS One*, 5(6): e11372.

Byrne, M. (2011) Impact of ocean warming and ocean acidification marine invertebrate life history stages: Vulnerabilities and potential for persistence in a changing ocean. *Oceanography and Marine Biology: An Annual Review*, 49: 1-42.

Byrne M., Ho M., Wong E., Soars N.A., Selva kumaraswam y P., Shepard-Brennand H., Dworjanyn S.A., Davis A.R. (2011) Unshelled abalone and corrupted urchins: development of marine calcifiers in a changing ocean. *Proceedings of the Royal Society B: Biological Sciences*, 278 (1716): 2376-2383.

Byrne, M., Lamare, M., Winter, D., Dworjanyn, S.A., Uthicke, S. (2013) The stunting effect of a high CO_2 ocean on calcification and development in sea urchin larvae, a synthesis from the tropics to the poles. *Philosophical Transactions B* 368, 20120439.

Carleton, C., Hambrey, J., Govan, H., Medley, P. (2013) *Effective management of sea cucumber fisheries and the bêche-de-mer trade in Melanesia: bringing the industry under rational control*. A report prepared by Nautilus Consultants on Behalf of the Secretariat of the Pacific Community (SPC). http://bit.ly/159yYGW

Cheung, W.W.L., Brodeur, R.D., Okey, T.A., Pauly, D. (2015) Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. *Progress in Oceanography*, 130, 19–31.

Chin, A., Kyne, P.M. (2007) Vulnerability of chondrichthyan fishes of the Great Barrier Reef to climate change. In: Johnson, J.E., Marshall, P.A. (Eds) *Climate change and the Great Barrier Reef: A Vulnerability Assessment.* Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Townsville, p 394-425

Chin, A., Kyne, P.M., Walker, T.I., McAuley, R.B. (2010) An integrated risk assessment for climate change: analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef. *Glob Change Biol,* 16(7), 1936-1953 doi:10.1111/j.1365-2486.2009.02128.x

Clarke, S.C., McAllister, M.K., Milner-Gulland, E.J., Kirkwood, G.P., Michielsens, C.G., Agnew, D.J., Pikitch, E.K., Nakano, H. Shivji, M.S. (2006) Global estimates of shark catches using trade records from commercial markets. *Ecology letters*, 9(10), 1115-1126.

Clarke, S.C., Harley, S.J., Hoyle, S.D., Rice, J.S. (2013) Population trends in Pacific oceanic sharks and the utility of regulations on shark finning. *Conservation Biology*, 27(1), 197-209. doi:10.1111/j.1523-1739.2012.01943.x

Clua, E., Buray, N., Legendre, P., Mourier, J., Planes, S. (2011) Business partner or simple catch? The economic value of the sicklefin lemon shark in French Polynesia. *Marine and Freshwater Research,* 62(6), 764-770

Collard, C.M., Eeckhaut, I., Dehairs, F., Dubois, P. (2014) Acid-base physiology response to ocean acidification of two ecologically and economically important holothuroids from contrasting habitats, *Holothuria scabra* and *Holothuria parva*.

Environmental Science and Pollution Research 21: 13602-13614.

Collier, C. Waycott, M. (2009) *Drivers of change to seagrass distributions and communities on the Great Barrier Reef: Literature review and gaps analysis.* Report to the Marine and Tropical Sciences Research Facility, Reef and Rainforest Research Centre Limited, Cairns, Australia.

Cripps, I.L., Munday, P.L., McCormick, M.I. (2011) Ocean acidification affects prey detection by a predatory reef fish. *PLoS One*, 6, e22736.

Dalzell, P. (1993) *Management of ciguatera fish poisoning in the South Pacific.* South Pacific Commission, Noumea, New Caledonia.

Devine, B., Munday, P.L., Jones, G.P. (2012) Homing ability of adult cardinalfish is affected by elevated carbon dioxide. *Oecologia*, 168, 269–276.

Dixson, D.L., Munday, P.L., Jones, G.P. (2010) Ocean acidification disrupts the innate ability of fish to detect predator olfactory cues. *Ecology Letters,* 13, 68-75.

Domenici, P., Allan, B., McCormick, M.I., Munday, P.L. (2012) Elevated carbon dioxide affects behavioural lateralization in a coral reef fish. *Biology Letters*, 8, 78–81.

Donelson, J.M., Munday, P.L., McCormick, M.I., Pankhurst, N.W., Pankhurst, P.M. (2010). Effects of elevated water temperature and food availability on the reproductive performance of a coral reef fish. *Marine Ecology Progress Series,* 401, 233–243.

Dueri, S., Faugeras, B., Maury, O. (2012) Modelling the skipjack tuna dynamics in the Indian Ocean with APECOSM-E: Part 1. Model formulation. *Ecological Modelling,* 245, 41–54.

Dueri, S., Bopp, L., Maury, O. (2014) Projecting the impacts of climate change on skipjack tuna abundance and spatial distribution. *Global Change Biology,* doi: 10.1111/gcb.12460

Dulvy, N.K., *et al*. (2014) Extinction risk and conservation of the world's sharks and rays. *eLife 3* doi:10.7554/eLife.00590

Dulvy, N.K., *et al*. (2017) Challenges and Priorities in Shark and Ray Conservation. *Curr Biol* 27(11):R565-R572 doi:https://doi.org/10.1016/j.cub.2017.04.038

Dunstan, P.K., Moore, B.R., Bell, J.D., Holbrook, N.J., Oliver, E.C.J., Risbey, J., Foster, S.D., Hanich, Q., Hobday, A.J., Bennett, N.J. (2018) How can climate predictions improve sustainability of coastal fisheries in Pacific Small-Island Developing States? *Marine Policy*, 88, 295–302. doi.org/10.1016/j.marpol.2017.09.033

Ehler, C.N., Cicin-Sain, B., Knecht, R., South, R., Weiher, R. (1997) Guidelines to assist policy makers and managers of coastal areas in the integration of coastal management programs and national climate-change action plans. *Ocean & Coastal Management*, 37(1), 7–27.

Fletcher, W.J., Amos, M. (1994) *Stock assessment of coconut crabs.* ACIAR Monograph No. 29. Australian Center for International Agricultural Research, Canberra, Australia.

Frisch, A.J., Cameron, D.S., Pratchett, M.S., Williamson, D.H., Williams, A.J., Reynolds, A.D., Hoey, A.S., Rizzari, J.R., Evans, L., Kerrigan, B., Muldoon, G. (2016) Key aspects of the biology, fisheries and management of coral grouper. *Reviews in Fish Biology and Fisheries*, 26(3), 303-325.

Frommel, A.Y., Maneja, R., Lowe, D., Malzahn, A.M., Geffen, A.J., Folkvord, A., Piatkowski, U., Reusch, T.B.H., Clemmesen, C. (2011) Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. *Nature Climate Change*, 2, 42–46.

Frommel, A.Y., Maneja, R., Lowe, D., Pascoe, C.K., Geffen, A.J.,, Folkvord, A., Piatkowski U., Clemmesen, C. (2014) Organ damage in Atlantic herring larvae as a result of ocean acidification. *Ecological Applications*, 24, 1131–1143.

Gagliano, M., McCormick, M.I., Meekan, M.G. (2007) Survival against the odds: Ontogenetic changes in selective pressure mediate growth-mortality trade-offs in a marine fish. *Proceedings of the Royal Society B*, 274, 1575–1582.

Garcia, S.M., Cochrane, K.L. (2005) Ecosystem approach to fisheries: a review of implementation guidelines*. ICES Journal of Marine Science,* 62(3), 311-318. doi: 10.1016/j.icesjms.2004.12.003

Gazeau, F., Parker, L.M., Comeau, S., Gattuso, J.P., O'Connor, W.A., Martin, S., Pörtner, H.O., Ross, P.M. (2013) Impacts of ocean acidification on marine shelled molluscs. *Marine Biology,* 160, 2207–2245.

Gervais, C., Mourier, J., Rummer, J. (2016) Developing in warm water: irregular colouration and patterns of a neonate elasmobranch. *Marine Biodiversity,* 4(46), 743-744.

Gillett, R. (2016) *Fisheries in the economies of Pacific Island Countries and Territories.* Published and printed at the Pacific Community, 2016 BP D5 98848, Noumea Cedex, New Caledonia. 688pp.

Gillett, R., Cartwright, I. (2010) *The Future of Pacific Island Fisheries.* Pacific Islands Forum Fisheries Agency, Honiara, Solomon Islands and Secretariat of the Pacific Community, Noumea, New Caledonia.

Gilman, E. (2002) Guidelines for coastal and marine site-planning and examples of planning and management intervention tools. *Ocean and Coastal Management,* 45, 377–404.

Glaus, K.B.J., Adrian-Kalchhauser, I., Burkhardt-Holm, P., White, W.T., Brunnschweiler, J.M. (2015) Characteristics of the shark fisheries of Fiji. *Scientific Reports*, 5, 17556 doi:10.1038/srep17556

Gonzalez, R., Ram-Bidesi, V.,Leport, G., Pascal, N., Brander, L., Fernandes, L., Salcone, J., Seidl, A. (2015) *National marine ecosystem service valuation:* Fiji. MACBIO (GIZ/IUCN/SPREP): Suva, Fiji.

Govan, H. (2015) *Preliminary review of public expenditure of the Fisheries Agencies of Pacific Island Countries and Territories: Policy, operational budget and staffing support for coastal fisheries*. Report for Secretariat of the Pacific Community (SPC), FAME Division. Noumea. DOI: 10.13140/RG.2.1.4949.9363. http://bit.ly/FishPEIR

Govan, H. (2017) Ocean Governance – Our Sea of Islands. In: *A Sustainable Future for Small States: Pacific 2050*. Katafono, R. (Ed), Commonwealth Secretariat, London. ISBN: 978-1-84929-163-7 / (e-book): 978-1-84859-957-4. http://bit.ly/Govan2017-OG

Heenan, A., Pomeroy, R., Bell, J.D., *et al*. (2015) A climate-informed, ecosystem approach to fisheries management. *Marine Policy*, 57, 182–192.

Heinrich, D.D.U., *et al*. (2014) A product of its environment: the epaulette shark (*Hemiscyllium ocellatum*) exhibits physiological tolerance to elevated environmental CO_2. *Conservation Physiology,* 2(1), cou047-cou047 doi:10.1093/conphys/cou047

Hobday, A.J. Evans, K. (2013) Detecting climate impacts with oceanic fish and fisheries data. *Climatic Change*, 119, 49–62.

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

Hughes, T.P., Kerry, J.T., Álvarez-Noriega, M., Álvarez-Romero, J.G., Anderson, K.D., Baird, A.H. *et al*. (2017). Global warming and recurrent mass bleaching of corals. *Nature,* 543, 373–377.

Hylton, S., White, W,T., Chin, A. (2017) The sharks and rays of the Solomon Islands: a synthesis of their biological diversity, values and conservation status. *Pacific Conservation Biology*. doi:https://doi.org/10.1071/PC17012

Jarrold *et al*. (2017) Diel CO_2 cycles reduce severity of behavioural abnormalities in coral reef fish under ocean acidification. *Scientific Reports* 7, Article number: 10153(2017). doi:10.1038/s41598-017-10378-y

Johnson, C.R., Banks, S.C., Barrett, N.S., Cazassus, F., Dunstan, P.K., Edgar, G.J., Frusher, S.D., Gardner, C., Haddon, M., Helidoniotis, F., Hill, K.L., Holbrook, N.J., Hosie, G.W., Last, P.R., Ling, S.D., Melbourne-Thomas, J., Miller, K., Pecl, G.T., Richarson, A.J., Rigway, K.R., Rintoul, S.R., Ritz, D.A., Ross, D.J., Sanderson, J.C., Shepherd, S.A., Slotvvinski, A., Swadling, K.M., Taw, N. (2011) Climate change cascades: shifts in oceanography, species' ranges and subtidal marine community dynamics in eastern Tasmania. *Journal of Experimental Marine Biology and Ecology*, 400(1–2), 17–32.

Johnson, J.E., Welch, D.J. (2010) Marine fisheries management in a changing climate: a review of vulnerability. *Reviews in Fisheries Science*, 18(1), 106-124.

Johnson, J.E., Welch, D.J. (2015) Climate change implications for Torres Strait fisheries: Assessing vulnerability to inform adaptation. *Climatic Change*, DOI: 10.1007/s10584-015-1583-z

Johnson, J.E, Bell, J., De Young, C. (Eds) (2013) *Priority Adaptations to Climate Change for Pacific Fisheries and Aquaculture: Reducing Risks and Capitalizing on Opportunities.* FAO Fisheries and Aquaculture Proceedings No. 28, Rome, 122pp.

Johnson, J.E., Bell, J.D., Sen Gupta, A. (2016) *Pacific Islands ocean acidification vulnerability assessment.* SPREP, Apia, Samoa, 40pp.

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

Kawarazuka, N., Béné, C. (2010) Linking small-scale fisheries and aquaculture to household nutritional security: an overview. *Food Security,* 2(4):343-357 doi:10.1007/s12571-010-0079-y

Khalil, M.T., Cochran, J.E., Berumen, M.L. (2013) The abundance of herbivorous fish on an inshore Red Sea reef following a mass coral bleaching event. *Environmental biology of fishes*, 96(9), 1065-1072.

Kinch, J., Purcell, S., Uthicke, S., Friedman, K. (2008) Population status, fisheries and trade of sea cucumbers in the Western Central Pacific. *In* V, Toral-Granda, V. Lovatelli & M. Vasconcellos (Eds) *Sea cucumbers. A Global Review of Fisheries and Trade.* Food and Agriculture Organization of the United Nations, Rome, Italy. pp. 7–55.

Kroeker, K.J., Gambi, M.C., Micheli, F. (2013) Community dynamics and ecosystem simplification in a high-CO2 ocean. *PNAS,* 110(31), 12721–12726, doi: 10.1073/pnas.1216464110

Lack, M., Meere, F. (2009) *Regional Action Plan for Sharks: Guidance for Pacific Island Countries and Territories on the Conservation and Management of Sharks.*

Last, P.R., de Carvalho, M.R., Corrigan, S., Naylor, G.J., Séret, B., Yang, L. (2016) *The Rays of the World project–an explanation of nomenclatural decisions.* Rays of the World: Supplemental information. CSIRO Publishing, Melbourne, 40, 1-10.

Laurent, D., Yeeting, B., Labrosse, P., Gaudechoux, J-P. (2005) *Ciguatera field reference guide*. IRD Editions 2005.

Le Borgne, R., Allain, V., Matear, R.J., Griffiths, S.P., McKinnon, A.D., Richardson, A.J., & Young, J.W. (2011) Vulnerability of open ocean food webs in the tropical Pacific to climate change. *In* J.D. Bell, J. E. Johnson & A.J. Hobday (Eds) *Vulnerability of Fisheries and Aquaculture in the Tropical Pacific to Climate Change,* pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia.

Lee, S., Lewis, A., Gillett, R., Fox, M., Tuqiri, N., Sadovy, Y., Batibasaga, A., Lalavanua, W., Lovell, E. (2018) *Fiji Fishery Resource Profiles. Information for Management on 44 of the Most Important Species Groups.* Gillett, Preston and Associates and the Wildlife Conservation Society, Suva, Fiji. 240pp.

Lehodey, P., Bertignac, M., Hampton, J., Lewis, A., Picaut, J. (1997) El Niño-Southern Oscillation and tuna in the western Pacific. *Nature,* 389, 715–718.

Lehodey, P., Senina, I., Murtugudde, R. (2008) A Spatial Ecosystem And Populations Dynamics Model (SEAPODYM) - Modelling of tuna and tuna-like populations. *Progress in Oceanography*, 78, 304-318.

Lehodey, P., Murtugudde, R., Senina, I. (2010a) Bridging the gap from ocean models to population dynamics of large marine predators: a model of mid-trophic functional groups. *Progress in Oceanography,* 84, 69–84.

Lehodey, P., Senina, I., Sibert, J., Bopp, L, Calmettes, B., Hampton, J., Murtugudde, R. (2010b) Preliminary forecasts of population trends for Pacific bigeye tuna under the A2 IPCC scenario. *Progress in Oceanography,* 86, 302–315.

Lehodey, P. *et al*. (2011) Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In: Bell J.D., Johnson J.E. and Hobday A.J. (Eds) *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change,* Secretariat of the Pacific Community, 433-492.

Lehodey, P., Senina, I., Calmettes, B, Hampton, J., Nicol, S. (2013a) Modelling the impact of climate change on Pacific skipjack tuna population and fisheries. *Climatic Change*, DOI 10.1007/s10584-012-0595-1, 119 (1), 95-109.

Lehodey, P., Senina, I., Titaud, O., Calmettes, B., Nicol, S., Hampton, J., Caillot, S., Williams, P. (2013b) *Project 62: SEAPODYM applications in WCPO.* 9th regular session of the Scientific Steering Committee, 6-14 August 2013, Pohnpei, Federated States of Micronesia. WCPFC SC9 2012/EB WP03 Rev 1. http://www.wcpfc.int/meetings/2013/9th-regular-session-scientific-committee

Lehodey, P., Senina, I., Nicol, S., Hampton, J. (2015) Modelling the impact of climate change on South Pacific albacore tuna. *Deep Sea Research,* 113, 246–259.

Leslie, H.M., McLeod, K.L. (2007) Confronting the challenges of implementing marine ecosystem-based management. *Frontiers in Ecology and Environment*, 5(10), 540–548. doi:10.1890/060093

Lough, J.M., Meehl, G.A., Salinger, M.J. (2011) Observed and projected changes in surface climate of the tropical Pacific. In: Bell JD, Johnson JE, Hobday AJ (Eds) *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change.* Secretariat of the Pacific Community, Noumea, New Caledonia, 40-99.

Matear, R.J., Chamberlain, M.A., Sun, C., Feng, M. (2015) Climate change projection for the western tropical Pacific Ocean using a high-resolution ocean model: Implications for tuna fisheries. *Deep Sea Res.* Part II Top. Stud. Oceanography, 113, 22–46. doi:10.1016/j.dsr2.2014.07.003

Miller, G.M., Kroon, F.J., Metcalfe, S., Munday, P.L. (2015) Temperature is the evil twin: effects of increased temperature and ocean acidification on reproduction in a reef fish. *Ecological Applications,* 25, 603–620. doi:10.1890/14-0559.1

Mercier, A., Battaglene, S.C., Hamel, J.F. (2000) Settlement preferences and early migration of the tropical sea cucumber *Holothuris scabra*. *Journal of Experimental Biology & Ecology*, 249, 89-110.

Messmer, V., Pratchett, M.S., Hoey, A.S., Tobin, A.J., Coker, D.J., Cooke, S.J., Clark, T.D. (2017) Global warming may disproportionately affect larger adults in a predatory coral reef fish. *Global Change Biology,* 23(6), 2230-2240.

Miller, G.M., Watson, S.A., Donelson, J.M., McCormick, M.I., Munday, P.L. (2012) Parental environment mediates impacts of increased carbon dioxide on a coral reef fish. *Nature Climate Change*, 2, 858–861.

Munday, P.L., Jones, G.P., Pratchett, M.S., Williams, A. (2008) Climate change and the future of coral reef fisheries. *Fish and Fisheries*, 9, 261–285.

Munday, P.L., Dixson, D.L., Donelson, J.M., Jones, G.P., Pratchett, M.S., Devitsina, G.V., Doving, K.B. (2009) Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *Proceeding of the National Academy of Sciences USA,* 106, 1848–1852.

Munday, P.L., Wittenrich, M.L., Manassa, R., Dixson, D.L., Gagliano, M., Yan, H.Y. (2011) Ocean acidification erodes crucial auditory behaviour in a marine fish. *Biology Letters*, 7, 917–920.

Munday, P.L., McCormick, M.I., Nilsson, G.E. (2012). Impact of global warming and rising CO_2 on coral reef fishes: what hope for the future? *Journal of Experimental Biology*, 215: 3865–3873.

Munday, P.L., Pratchett, M.S., Dixson, D.L., Donelson, J.M., Endo, G.G.K., Reynolds, A.D., Knuckey, R. (2013) Elevated CO_2 levels affects the behaviour of an ecologically and economically important coral reef fish. *Marine Biology*, 160, 2137–2144.

Pecl, G.T., Araújo, M., Bell, J.D., Blanchard, J., Bonebrake, T.C., Chen, I.-C. *et al*. (2017) Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science,* 355(6332), eaa19214.

Pickering, T.D., Ponia, B., Hair, C.A., Southgate, P., Poloczanka, E.S., Patrona, L.D., Teitelbaum, A., Mohan, C.V., Phillips, M.J., Bell J.D., De Silva, S. (2011) Vulnerability of aquaculture in the tropical Pacific to climate change. In: Bell JD, Johnson JE, Hobday AJ (Eds) *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Secretariat of the Pacific Community, Noumea, New Caledonia, 647–731.

Pinca, S., Kronen, M., Friedman, K., Magron, F., Chapman, L., Tardy, E., Pakoa, K., Awira, R., Boblin, P., Lasi, F. (2010) *Regional Assessment Report: Profiles and Results from Survey Work at 63 Sites Across 17 Pacific Island Countries and Territories.* Secretariat of the Pacific Community, Noumea, New Caledonia, 512pp.

Pratchett, M.S., Munday, P.L., Wilson, S.K., Graham, N.A.J., Cinner, J.E., Bellwood, D.R., Jones, G.P., Polunin, N.V.C., McClanahan, T.R. (2008) Effects of climate-induced coral bleaching on coral-reef fishes: ecological and economic consequences. *Oceanography and Marine Biology: An Annual Review*, 46, 251-296.

Pratchett, M.S., Baird, A.H., McCowan, D.M., Coker, D.J., Cole, A.J. and Wilson, S.K. (2009) Protracted declines in coral cover and fish abundance following climate-induced coral bleaching on the Great Barrier Reef. In *Proceedings of the 11th International Coral Reef Symposium*'(Ed B. Riegl) Ft Lauderdale, Florida (pp. 1042-1046).

Pratchett, M.S., Munday, P.L., Graham, N.A.J., Kronen. M., Pinca. S., Friedman. K. *et al*. (2011a) Vulnerability of coastal fisheries in the tropical Pacific to climate change. In: J.D. Bell, J.E. Johnson & A.J. Hobday (Eds). *Vulnerability of tropical Pacific fisheries and aquaculture to climate change,* pp. 493–576. Noumea, New Caledonia. Secretariat of the Pacific Community.

Pratchett, M.S., Hoey, A.S., Wilson, S.K., Messmer, V., Graham, N.A. (2011b) Changes in biodiversity and functioning of reef fish assemblages following coral bleaching and coral loss. *Diversity,* 3(3), 424-452.

Pratchett, M.S., Hoey, A.S., Wilson, S.K. (2014) Reef degradation and the loss of critical ecosystem goods and services provided by coral reef fishes. *Current Opinion in Environmental Sustainability*, 7, 37-43.

Pratchett, M.S., Cameron, D., Donelson, J., Evan, L., Frisch, A.J., Hobday, A.J., Hoey, A.S., Marshall, N.A., Messmer, V., Munday, P.L., Pears, R., Pecl, G., Reynolds, A., Scott, M., Tobin, A., Tobin, R., Welch, D.J., Williamson, D.H. (2017) Effects of climate change on coral grouper (*Plectropomus* spp.) and possible adaptation options. *Reviews in Fish Biology and Fisheries,* 27, 297-316.

Przeslawski, R., Ahyong, A., Byrne, M. Wörheide, G., Hutchings, P. (2008) Beyond corals and fish: the effects of climate change on noncoral benthic invertebrates of tropical reefs. *Global Change Biology,* 12, 2773–2795.

Purcell, S.W., Gossin, H., Agudo, N.N. (2009) *Status and management of the sea cucmber fishery of la Grande Terre, New Caledonia.* The Worldfish Center Studies and Reviews 1901, Penang, Malaysia.

Reenberg, A., Birch-Thomsen, T., Mertz, O., Fog, B., Christiansen, S. (2008) Adaptation of Human Coping Strategies in a Small Island Society in the SW Pacific—50 Years of Change in the Coupled Human–Environment System on Bellona, Solomon Islands. *Human Ecology,* 36(6), 807-819.

Ries, J.B., Cohen, A.L., McCorkle, D. C. (2009) Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. *Geology* 37, 1131–1134.

Rika, N. (2017) *Bad boy: Vietnam earns villain status TUNA Pacific: Fisheries News and Views.* Pacific Islands Forum Fisheries Agency.

Rosa, R., Rummer, J.L., Munday, P.L. (2017) Biological responses of sharks to ocean acidification. *Biology Letters* 13(3) doi:10.1098/rsbl.2016.0796

Roué, M., Cruchet, P., Ung, A., Darius, T., Chinain, M., Laurent, D. (2013) Giant clams: New vectors of ciguatera? *Toxicon*, 75, 206.

Rongo, T., van Woesik, R. (2013) The effects of natural disturbances, reef state, and herbivorous fish densities on ciguatera poisoning in Rarotonga, southern Cook Islands. *Toxicon,* 64, 87–95.

Ruddle, K., Johannes, R.E. (Eds) (1989) *Traditional marine resource management in the Pacific basin: an anthology.* Unesco/ROSTSEA.

SPC [Pacific Community] (2008) *Fish and Food Security.* Policy Brief 1/2008. Secretariat of the Pacific Community, Noumea, New Caledonia.

SPC [Pacific Community] (2010) *A Community-based Ecosystem Approach to Fisheries Management: Guidelines for Pacific Island Countries.* Secretariat of the Pacific Community, Noumea, New Caledonia, The Nature Conservancy, Brisbane, Australia, and the Food and Agriculture Organization of the United Nations, Rome, Italy.

SPC Oceanic Fisheries Program (2010) *Non-Target Species Interactions with the Tuna Fisheries of the Western and Central Pacific Ocean*. Secretariat of the Pacific Community, Noumea, New Caledonia.

SPC [Pacific Community] (2013) *Status report: Pacific Islands reef and nearshore fisheries and aquaculture.* Secretariat of the Pacific Community, Noumea, New Caledonia. 60pp.

Schaefer, K.M. (2001) Reproductive biology of tunas. *Fish Physiology*, 19, 225-270.

Schlaff, A.M., Heupel, M.R., Simpfendorfer, C.A. (2014) Influence of environmental factors on shark and ray movement, behaviour and habitat use: a review. *Rev Fish Biol Fish* 24(4), 1089-1103 doi:10.1007/s11160-014-9364-8

Scott, M., Heupel, M., Tobin, A., Pratchett, M.S. (2017) A large predatory reef fish species moderates feeding and activity patterns in response to seasonal and latitudinal temperature variation. *Scientific Reports* 7, 12966.

Senina, I., Sibert, J., Lehodey, P. (2008) Parameter estimation for basin-scale ecosystem-linked population models of large pelagic predators: application to skipjack tuna. *Progress in Oceanography,* 78, 319-335.

Senina, I., Lehodey, P., Calmettes, B., Nicol, S., Caillot, S., Hampton, J., Williams, P. (2015) *SEAPODYM application for yellowfin tuna in the Pacific Ocean.* 11th Regular Session of the scientific committee, Pohnpei, Federated States of Micronesia, 5-13 August 2015, WCPFC-SC11-2015/EB-IP-01, 66pp.

Sheppard Brennand, H., Soars, N., Dworjanyn S.A., Davis, A.R., Bryne, M. (2010) Impact of ocean warming and ocean acidification on larval development and calcification in the sea urchin Tripneustes gratilla. *PLoS ONE* 5(6), e11372. doi: 10.1371/journal.pone.0011372.

Shirayama, Y., Thornton, H. (2005) Effect of increased atmospheric CO_2 on shallow water marine benthos. *Journal of Geophysical Research*, 110, C09S08, doi:10.1029/2004JC002618

Simpson, S.D., Munday, P.L., Wittenrich, M.L., Manassa, R., Dixson,, D.L., Gagliano, M., Yan, H.Y. (2011) Ocean acidification erodes crucial auditory behaviour in a marine fish. *Biology Letters*, 7, 917–920.

Steinacher, M., Joos, F., Frölicher, T.L., Bopp, L., Cadule, P., Cocco, V., Doney, S.C., Gehlen, M., Lindsay, K., Moore, J.K., Schneider, B., Segschneider, J. (2010) Projected 21st century decrease in marine productivity: a multi-model analysis. *Biogeosciences,* 7, 979–1005. doi:10.5194/bg-7-979-2010

Tallis, H., Levin, P.S., Ruckelshaus, M., Lester, S.E., McLeod, K.L., Fluharty, D.L., Halpern, B.S. (2010) The many faces of ecosystem-based management: making the process work today in real places. *Marine Policy,* 34(2), 340-348.

Tobin A., Schlaff, A., Tobin, R., *et al*. (2010) *Adapting to change: minimizing uncertainty about the effects of rapidly-changing environmental conditions on the Queensland Coral Reef Fin Fish Fishery*. Project 2008/103. Fishing & Fisheries Research Centre Technical Report No. 11, James Cook University, Townsville.

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

UNESCO (2010) *Global monitoring report 2010: Reaching the marginalized.*

Verges, A., Steinberg, P.D., Hay, M.E., Poore, A.G.B., Campbell, A.H., Ballesteros, E., Heck, K.L., Booth, D.J., Coleman, M.A, Feary, D.A., Figueira, W., Langlois, T., Marzinelli, E.M., Mizerek, T., Mumby, P.J., Nakamura, Y., Roughan, M., van Sebille, E., Sen Gupta, A., Smale, D.A., Tomas, F., Wernberg, T., Wilson, S.K. (2014) The tropicalization of temperate marine ecosystems: climate-mediated changes in herbivory and community phase shifts. *Proceedings of the Royal Society B-Biological Sciences*. 281(1789). doi:10.1098/rspb.2014.0846

Vianna, G.M.S., Meekan, M.G., Pannell, D.J., Marsh, S.P., Meeuwig, J.J. (2012) Socio-economic value and community benefits from shark-diving tourism in Palau: A sustainable use of reef shark populations. *Biol Conserv*, 145(1), 267-277. doi:10.1016/j.biocon.2011.11.022

Vieira, S., Kinch, J., White, W., Yaman, L. (2017) Artisanal shark fishing in the Louisiade Archipelago, Papua New Guinea: Socio-economic characteristics and management options. *Ocean & Coastal Management,* 137:43-56. doi:http://dx.doi.org/10.1016/j.ocecoaman.2016.12.009

WCPFC (2015) *Handbook of Conservation Management Measures and Resolution For WCPFC Regional Observer Programmes.* Western and Central Pacific Fisheries Commission.

Watson, S., Southgate, P.C., Miller, G.M., Moorhead, J.A., Knauer, J. (2012) Ocean acidification and warming reduce juvenile survival of the fluted giant clam, *Tridacna squamosa*. *Molluscan Research*, 32, 177–180.

Waycott, M., Collier, C., McMahon, K., Ralph, P., McKenzie, L., Udy, J., Grech, A. (2007) Vulnerability of seagrasses in the Great Barrier Reef to climate change. In: Johnson, J.E., Marshall, P.A. (Eds) *Climate change and the Great Barrier Reef: A Vulnerability Assessment.* Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Townsville, 193-236.

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

Wearmouth, V.J., Sims, D.W. (2008) Sexual segregation in marine fish, reptiles, birds and mammals: behaviour patterns, mechanisms and conservation implications. In: Sims DW (ed) *Adv Mar Biol. Advances in Marine Biology,* vol 54. Elsevier Academic Press Inc, San Diego, 107-170

Welch, D.J. (2016) *Broadscale assessment of the status of coastal finfish in North Efate, Vanuatu.* Report to the Pacific Community (SPC), Noumea, New Caledonia, and Agence Francaise de Developpement, Paris, France. Vanuatu RESCCUE project, 31pp.

Welch, D.J., Johnson, J.E. (2017) *Management of climate change-induced loss and damage in artisanal fisheries and aquaculture in the Pacific region.* C_2O Pacific report to BMZ-funded GIZ Global Programme on Risk Assessment and Adaptation to Climate Change.

Wen, C.K., Bonin, M.C., Harrison, H.B., Williamson, D.H., Jones, G.P. (2016) Dietary shift in juvenile coral trout (*Plectropomus maculatus*) following coral reef degradation from a flood plume disturbance. *Coral Reefs,* 35, 451–455.

Wilkinson, C., Brodie, J. (2011) *Catchment Management and Coral Reef Conservation: a practical guide for coastal resource managers to reduce damage from catchment areas based on best practice case studies.* Global Coral Reef Monitoring Network.

Williamson, D.H., Ceccarelli, D.M., Evans, R.D., Jones, G.P., Russ, G.R. (2014) Habitat dynamics, marine reserve status, and the decline and recovery of coral reef fish communities. *Ecology and Evolution,* 4, 337–354.

Wilson, S.K., Graham, N.A.J., Pratchett, M.S., Jones, G.P., Polunin, N.V.C. (2006) Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? *Global Change Biology*. 12, 2220-2234.

Zeller, D., Booth, S., Davis, G., Pauly, D. (2007) Re-estimation of small-scale fishery catches for US flag-associated island areas in the western Pacific: the last 50 years. *Fishery Bulletin*, 105 (2), 266-277.