Vulnerability of tropical Pacific fisheries and aquaculture to climate change

Supplementary material to support

Chapter 14:

Climate change impacts, vulnerabilities and adaptations: Western and Central Pacific Ocean marine fisheries

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Supplementary Material

This material provides additional information to support ‘Chapter 14: Climate change impacts, vulnerabilities and adaptations: Western and Central Pacific Ocean marine fisheries’ and has been arranged in the same general sequence as the main text.

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Modelling of projected changes in distribution and abundance of four tropical Pacific tuna species

The projected effects of climate change on the distribution and abundance of skipjack, yellowfin and bigeye tuna and South Pacific albacore were made using the end-to-end Spatial Ecosystem and Population Dynamics Model (SEAPODYM) (Lehodey et al., 2008). SEAPODYM incorporates information on fish physiology and its relationships with the direct effects of the physical and biogeochemical variability of the ocean (e.g., increasing ocean temperature, changes in dissolved oxygen concentrations, ocean circulation patterns, primary production and ocean acidification), and the indirect effects of changes in distributions and accessibility of the micronektonic food of juvenile and adult tuna. The model includes a definition of habitat indices, driving the movements and migrations of fish. Fish populations are simulated with age-structure growth, natural mortality and recruitment at the larval stage. Fishing mortality is included based on historical information from fisheries. A data assimilation technique based on adjoint code and maximum likelihood approaches is used to parameterize the model (Senina et al., 2008) before forecasting the future of tuna populations with climate change projections (Lehodey et al., 2013; 2015; 2017; Senina et al., 2016).

The projections for skipjack, yellowfin and bigeye tuna biomass are the average from simulations driven by the physical-biogeochemical fields predicted from three climate models from the 5th IPCC Coupled Model Intercomparison Project (CMIP5), i.e., IPSL, GFDL and NorESM, coupled to the PISCES biogeochemical model (Aumont et al., 2015) and forced by atmospheric carbon dioxide (CO_2), from historical records for the period 1860–2000, following the RCP8.5 IPCC emissions scenario. Note that the trend in atmospheric CO_2 release used in the more optimistic RCP2.6 scenario suggests that oceanic and tuna dynamics in the middle of the century under this scenario would approximate those in 2025 under the RCP8.5 scenario (Supplementary Table 6).

For the 2005 plots, total biomass (Mt per km^{-2}) was averaged over the 10-year period 2001–2010. Projections were also made for the 10-year periods 2046–2055 (2050) and 2091–2100 (2100), and averaged over all three models. Differences between 2050 and 2100 and 2000–2010 (2005) were then calculated.

SEAPODYM modelling of yellowfin tuna included the impact of ocean acidification on the survival rates of larvae (Lehodey et al., 2017), based on recent laboratory experiments.

SEAPODYM modelling of South Pacific albacore was performed using the forcing obtained from IPSL-CM4 model simulation with IPCC SRES A2 emission scenario (Lehodey et al., 2015). The historical biomass was averaged over the period 1996–2005 and the projections in 2050 and 2100 were averaged over the same periods as the other species of tuna.

It is also interesting to note that the stock assessments for all four species of tuna done by the Oceanic Fisheries Programme at the Pacific Community estimate time-series changes in recruitment, and that a decrease in recruitment is the main way that important effects of climate change on these stocks would be manifested in the assessments. Thus, the regular tuna assessments should be able to detect changes in productivity of tuna stocks due to climate change projected by SEAPODYM.

Adaptations for economic development (source: Bell et al., 2011, 2013)

Full implementation of the vessel day scheme

The vessel day scheme (VDS) for the purse-seine fishery, which allocates fishing effort among the exclusive economic zones (EEZs) of the eight countries that are the Parties to the Nauru Agreement (PNA) based on agreed criteria (Aqorau, 2009), provides an important means of accommodating the effects of ENSO events on redistribution of tuna, now and in the future. The VDS is intended to hold total fishing effort for PNA members constant, yet allow them to trade fishing days when the fish are concentrated either in the west or east. This effort management scheme ensures that all PNA members continue to receive some level of benefits, regardless of where tuna are concentrated. The built-in periodic adjustment of effort within the VDS should avoid the need for members further to the east to continually purchase vessel days from those in the west as tuna stocks move progressively east.

Diversify sources of fish for canneries

Creating incentives for tuna caught in other EEZs to be landed in Papua New Guinea (PNG) and Solomon Islands may provide useful adaptations if more canneries are constructed there and lower tuna catches occur in the west. The Economic Partnership Agreement with the EU is assisting PNG to develop its fish processing operations in the near term by paving the way for exports to Europe in the face of strong competition from canneries elsewhere. The ‘global sourcing provision’ of the agreement is particularly advantageous because it enables PNG to obtain fish from vessels of different nationalities, including those operating outside its EEZ. Maintaining the economic partnership agreement with the EU in the long term is of great importance to PNG. It is also in the strong interest of Solomon Islands to make similar arrangements with the EU.

Other adaptations that may be needed to help maintain continuity in the supply of fish for canneries in PNG and Solomon Islands during El Niño episodes in the short term, and under the projected effects of climate change on tuna in the long term, include: (1) reducing access for distant water fishing nations (DWFNs) to their EEZs to provide more fish for national vessels; (2) requiring DWFNs operating within their EEZs to land a proportion of catches for processing by local canneries; (3) enhancing existing arrangements for their national fleets to fish in the EEZs of other Pacific Island countries and territories (PICTs); and (4) creating additional incentives for tuna caught in other EEZs to be landed in their ports.

Identify ways to add more value to skipjack tuna

Skipjack tuna accounts for >70% of the tuna caught in the EEZs of PICTs (Supplementary Table 1). At present, the great majority of skipjack tuna caught in the Western and Central Pacific Ocean (WCPO) is used for canning. Other countries, e.g., Iceland, have found ways of adding value to fish catches by processing for niche markets and by using 100% of the fish. Given the projected increased demand for fish as the world's population increases to more than 9 billion by 2050 (FAO, 2016), it is reasonable to assume that markets for higher-value products, and markets for more fish products, could be found for skipjack tuna. Increasing the value of skipjack tuna would create the opportunity to increase licence fees, helping PICTs to obtain more government revenue in the short term, and to maintain the present-day contributions of licence fees to economies when abundances of skipjack tuna decline due to climate change.

Continued conservation and management measures for all species of tuna

Addressing the possible overfishing of bigeye tuna in the WCPO by reducing fishing mortality should help rebuild the population to a level that is expected to assist this species adapt to the projected changes to the tropical Pacific Ocean. The benefits of management measures to reduce fishing mortality are not expected to be fully effective for 10–20 years because bigeye tuna is a relatively long-lived species (> 12 years).

Energy efficiency programmes for industrial fleets

Energy audits to identify how to reduce the use of fuel for routine fishing operations, followed by energy efficiency programmes to implement these savings, should increase the economic efficiency of fleets in both the near and long term. These initiatives should assist industrial fleets to cope with fluctuations in oil prices, lower CO_2 emissions and reduce the costs of fishing further afield for vessels from PNG and Solomon Islands supplying national canneries as the distribution of skipjack tuna shifts to the east.

Environmentally-friendly fishing operations

Addressing any effects of existing tuna fishing operations, and those projected to occur as the distribution of tuna moves to the east, on non-target and dependent species should assist PICTs to meet the requirements of certification schemes to promote responsible fishing practices. Finding ways to reduce CO_2 emissions from industrial fishing fleets (outlined above), and from canneries, to ensure that tuna from the region is competitive in carbon labelling schemes should also help maintain access to markets for tuna as global pressure to minimise the carbon footprint of fishing and processing operations increases.

Adaptations for food security and livelihoods (source: Bell et al., 2011, 2017)

Adaptations to minimise the gap

Manage and restore vegetation in catchments

Sustaining coastal fish production around islands depends on good land-management practices to maintain the quality of coastal waters and habitats. A good coverage of vegetation on slopes and wide riparian buffer zones are needed to reduce the transfer of sediments and nutrients to coastal habitats after heavy rainfall. Low vegetation cover due to deforestation and poor farming and land-use practices results in accelerated runoff and erosion, which directly damages coral reef, mangrove and seagrass habitats through increased turbidity, sedimentation and nutrient loads. Maintaining and restoring catchment vegetation is required to protect these important fish habitats in the near term, and should also help reduce future damage from the effects of projected increases in rainfall (Supplementary Figure 2).

Avoid (and reverse) degradation of coastal fish habitats

The key measures needed to safeguard coastal habitats from present-day stresses are: 1) maintaining water quality by controlling pollution from sewage, chemicals (including fertiliser and pesticides) and waste; 2) eliminating activities that damage the three-dimensional structure of coral habitats, such as destructive fishing practices, extraction of coral for building materials, careless anchoring of boats and poorly-designed coastal infrastructure and tourist facilities; and 3) prohibiting activities that threaten the health and extent of mangrove and seagrass habitats (e.g., timber harvesting, damaging fishing practices, dredging). These measures should help maintain coastal fish habitats in the near term. They are also expected to help make coral reefs, mangroves and seagrasses more resilient to the various stressors associated with climate change in the future.

Provide for landward migration of coastal fish habitats

Allowing the inundation of low-lying land adjacent to mangrove forests will provide opportunities for these fish habitats and their associated biota to migrate landward. Where existing road infrastructure blocks the inundation of low-lying land suitable for colonisation by mangroves, channels and bridges should be constructed to allow for inundation. Planting young trees in such places can also help fast-track establishment of new mangrove habitat if necessary. The near-term costs of this adaptation – loss of some uses of undeveloped, low-lying land and expenses associated with raising and planting seedlings – are expected to be balanced by the benefits of maintaining fish habitats in the longer term and the protection that mangroves provide to coastal areas.

Sustain production of coastal demersal fish and invertebrates

Strengthening community-based ecosystem approaches founded on primary fisheries management will help keep production of demersal fish and invertebrates within sustainable bounds where governments and communities lack resources for regular monitoring of catches and analysis of stock status. Primary fisheries management recognises the need to use simple harvest controls, such as size limits, closed seasons and areas, gear restrictions and protection of spawning aggregations. Although this precautionary approach places limits on the harvest of demersal fish and invertebrates in the near term, and will have to be applied even more conservatively due to the uncertainty of climate change, it is still expected to help minimise the gap between the fish needed by rapidly growing populations and coastal fisheries production. Over the longer term, it should also help to explicitly address the impacts of climate change by building the resilience and replenishment potential of stocks. Where resources are available for monitoring and in-depth data analysis, consideration can be given to investments that would permit less conservative catch levels that nonetheless maintain a resilient spawning biomass.

Maximise the efficiency of spatial management

Ensuring that areas dedicated to help protect sufficient spawning biomass for regular replenishment of coastal fish stocks and conserve biodiversity are designed to take account of the ecology of target fish species, e.g., sequential use of different habitats with ontogeny, the dependence of these fish species on structurally complex habitats, and spatial variation in vulnerability of fish stocks to sustained and ongoing climate change. It is particularly important to identify mosaics of coral reef, mangrove and seagrass habitats likely to persist as the climate changes so that the connectivity among habitats needed for successful recruitment of juvenile fish and invertebrates is maintained, and to provide migration corridors as well as a diverse range of feeding areas for adult demersal fish.

Diversify catches of coastal demersal fish

Shifts in the local structure of fish assemblages are expected to occur due to changes in distributions of species, and in response to alterations in the structure of coral reefs and other coastal habitats. Transferring effort away from those species projected to be first and worst affected by climate impacts to species expected to increase in local abundance (or to be more resilient to environmental change), and targeting species with greater rates of production, should help to reduce the rate of decline in the overall catch of demersal fish. However, caution will be needed to limit harvests of fish species with important ecological functions, or species that have an inherent vulnerability to overfishing. Herbivorous fish are a prime example. These species are fundamental to the resilience of coral reef ecosystems because they remove algae, thereby facilitating recovery of corals in the aftermath of major disturbances. Foregoing some of the catch of herbivorous fish reduces potential harvests but will help maximise resilience of reef ecosystems, including the productivity of other coral reef fish.

Adaptations to fill the gap

Transfer coastal fishing effort from demersal fish to tuna

The rich tuna resources of WCPO provide PICTs with the opportunity to fill the gap between the fish needed for good nutrition and sustainable harvests of demersal fish. There are few if any concerns for human health associated with this adaptation; skipjack and yellowfin tuna from the Pacific Island region can be consumed up to 16 and 12 times per month, respectively, without exceeding the limits on methylmercury intake recommended by the US Environmental Protection Agency (Bell et al., 2017).

The most practical way of empowering small-scale fishers to catch more tuna and other large pelagic fish in nearshore waters is to increase the number of fish aggregating devices (FADs) anchored within a few kilometres of the coast, and improve the safety and success of small-scale fishing operations around FADs. This is a prime win-win adaptation for small-scale fisheries in the Pacific Islands region because it will increase access to fish in the near term, and set the stage for communities to continue to fill the gap as it gets progressively larger due to population growth and continued degradation of coral reefs caused by more frequent bleaching and ocean acidification.

The projected declines in biomass of skipjack and yellowfin tuna for PICTs in the western WCPO are not expected to have unduly negative implications for the use of anchored, nearshore FADs for food security. The large present-day industrial catches of tuna in PNG, Federated States of Micronesia and Solomon Islands (Supplementary Table 1) suggest that skipjack and yellowfin tuna should still be plentiful enough to justify investments in nearshore FADs as an efficient adaptation response to declining demersal fisheries and increasing human populations. However, over time, a greater proportion of the tuna catch will need to be allocated to small-scale fishers, underscoring the need to improve the monitoring of artisanal and subsistence tuna fisheries and to include these catches in stock assessments.

Expand fisheries for small pelagic species

The relatively high resilience to fishing of small pelagic fish (mackerel, anchovies, pilchards, sardines, scads and fusiliers), which to date have been exploited only lightly in the region, provides another potential way to increase the catch of small-scale fishers in the near term. This is particularly true in Melanesia, where coastal waters are relatively nutrient-rich due to runoff from high islands and seasonal coastal upwelling (especially in PNG), and often support a higher biomass of these species than locations in the central and eastern WCPO. Regardless of the relatively high resilience of small pelagic fish to harvesting, development of any new fisheries based on such species should implement primary fisheries management to maintain production within sustainable bounds, particularly given the role of such species in ecosystem function and energy transfer.

The outlook for harvesting small pelagic fish in the longer term is less certain and likely to be site specific. Projected decreases in primary productivity due to increased stratification associated with higher sea surface temperature, or the effects of changes in the velocity of ocean currents on formation of eddies that bring nutrient-rich waters into the photic zone, may cause abundance of small pelagic fish to decline in some areas. Conversely, greater projected rainfall in tropical Melanesia may further increase runoff and production of small pelagic fish in some coastal waters.

Extend the storage time of fish catches

Training communities, particularly women, in how to improve traditional methods for smoke curing, salting and drying large catches of tuna and small pelagic fish will enable households to store fish for those times when conditions are not suitable for fishing. In large island nations, such as PNG, it could also create better opportunities to trade seafood products with inland communities without access to fish. Improved post-harvest methods will increase the amount of fish product available for food and reduce wastage in the near term due to better efficiency. It should also assist communities in locations where climate change is projected to increase variability in fish supply.

Development of successful methods for improving the shelf life of tuna caught around FADs will also involve raising awareness of the conditions that cause histamine poisoning in tuna, also known as scombrotoxin[1]. Where there is no access to ice, the duration of trips made by small-scale fishers intending to sell tuna fresh will need to be limited.

Increase access to small tuna and bycatch offloaded by industrial fleets

Promoting better handling of small-sized tuna on board industrial vessels and the sale, storage and distribution of small-sized tuna and bycatch landed at Pacific ports should meet most of the shortfall in the fish needed for good nutrition for rapidly-growing urban populations in the region in the short and long term. However, care may be needed to release small tuna and bycatch purchased from industrial vessels onto the market in ways that do not undermine the livelihoods of local small-scale commercial fishers.

Expand aquaculture of Nile tilapia and milkfish

The simple, proven technology for farming species like tilapia and milkfish is expected to help meet the growing demand for fish in some locations in the short term, and is likely to be favoured by the projected increases in rainfall and temperatures. Availability of suitable feeds is likely to be one of the major limiting factors, however, the following practices to increase feed efficiency should help reduce any shortfall in feed supply: allocation of fishmeal from tuna processing plants in the region to production of aquaculture feeds; use of undesirable introduced and invasive freshwater fish species in PNG to produce fish feeds at the village level; replacing fishmeal with suitable local

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[1] http://www.foodsafetywatch.org/factsheets/scombrotoxin-histamine/

alternative sources of protein; and promoting Best Management Practice for feeding of farmed fish

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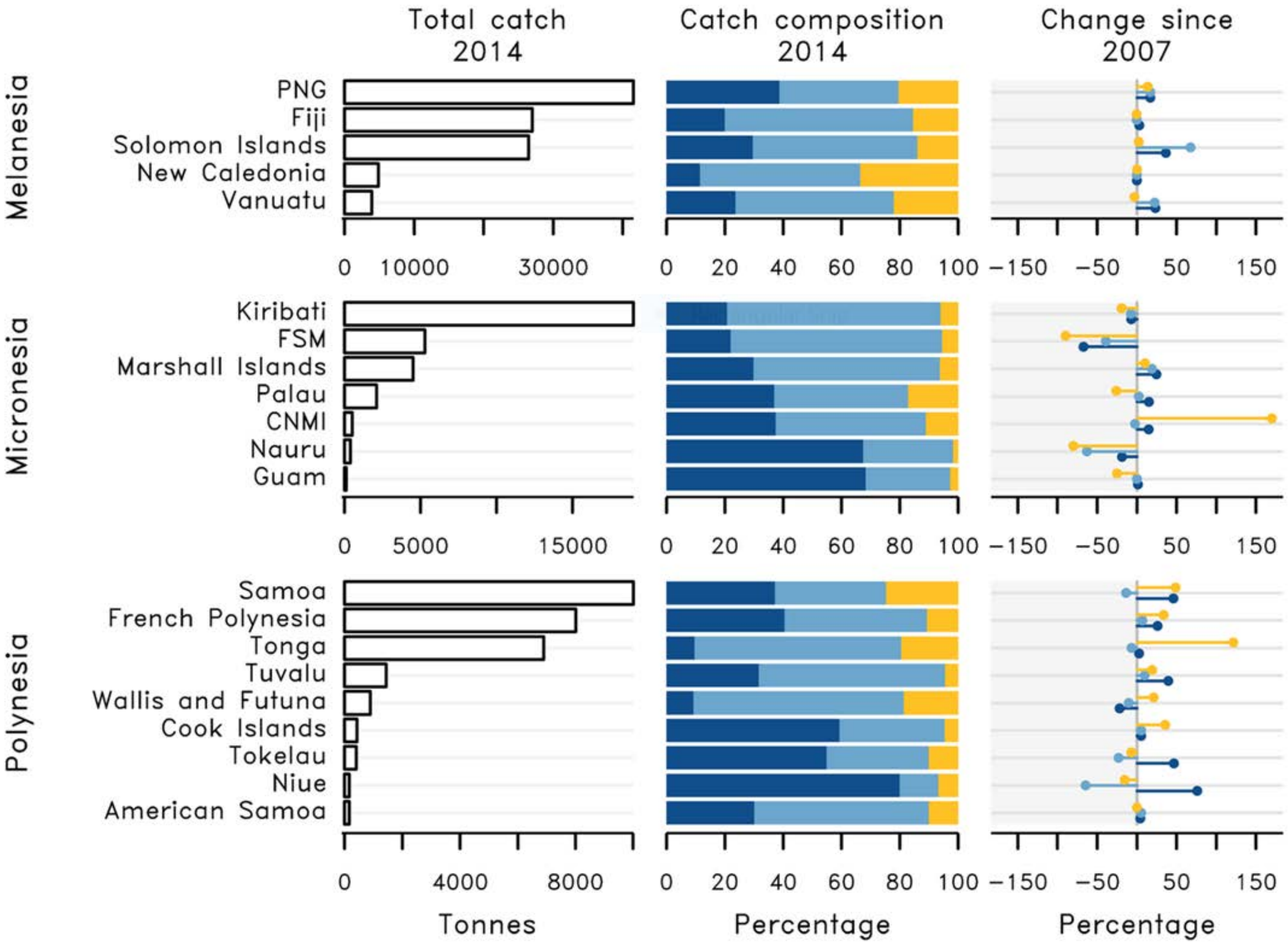
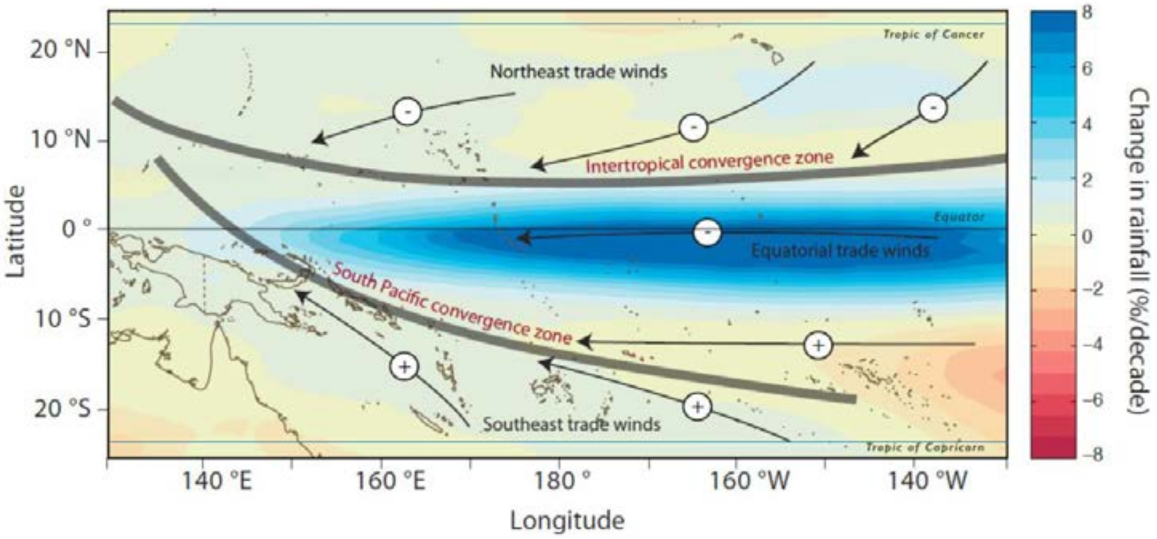
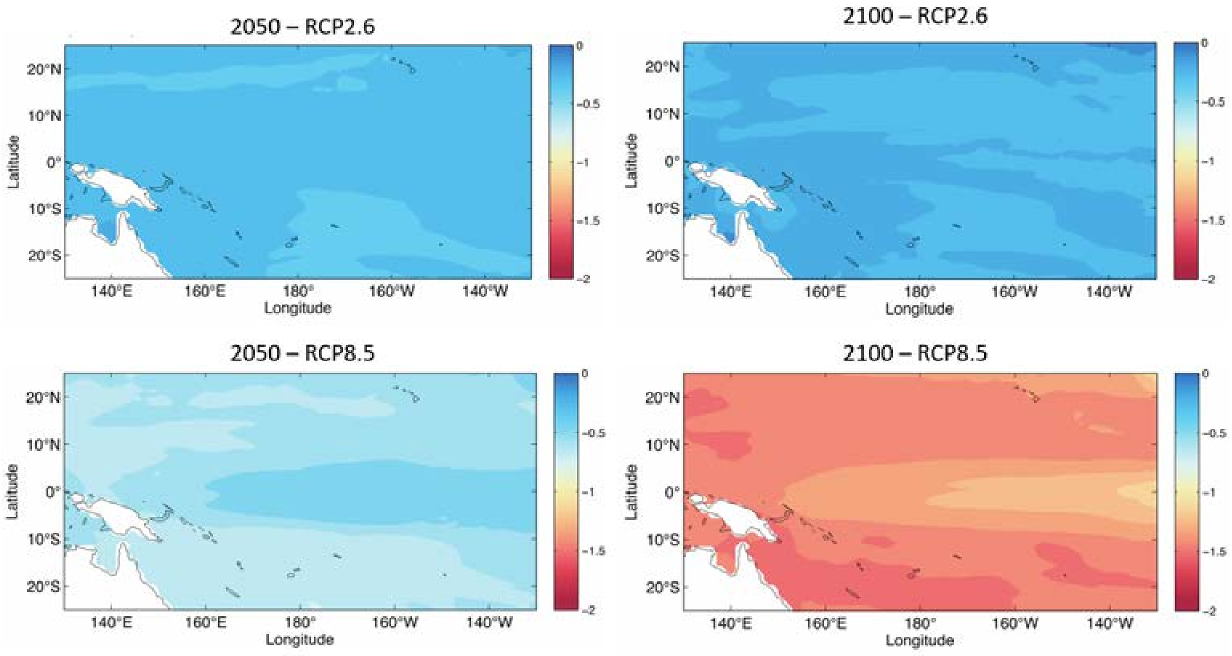
Supplementary Figure 1. Total coastal fisheries catch (Mt) for Pacific Island countries and territories (PICTs) in 2014 (left), together with the estimated percentage of demersal fish (🟦), nearshore pelagic fish (🟦) and all invertebrates (🟨) comprising the total catch in 2014 (centre) and the percentage change in each catch component since 2007 (right). PNG = Papua New Guinea; FSM = Federated States of Micronesia; CNMI = Commonwealth of the Northern Mariana Islands (source: Bell et al., 2017).



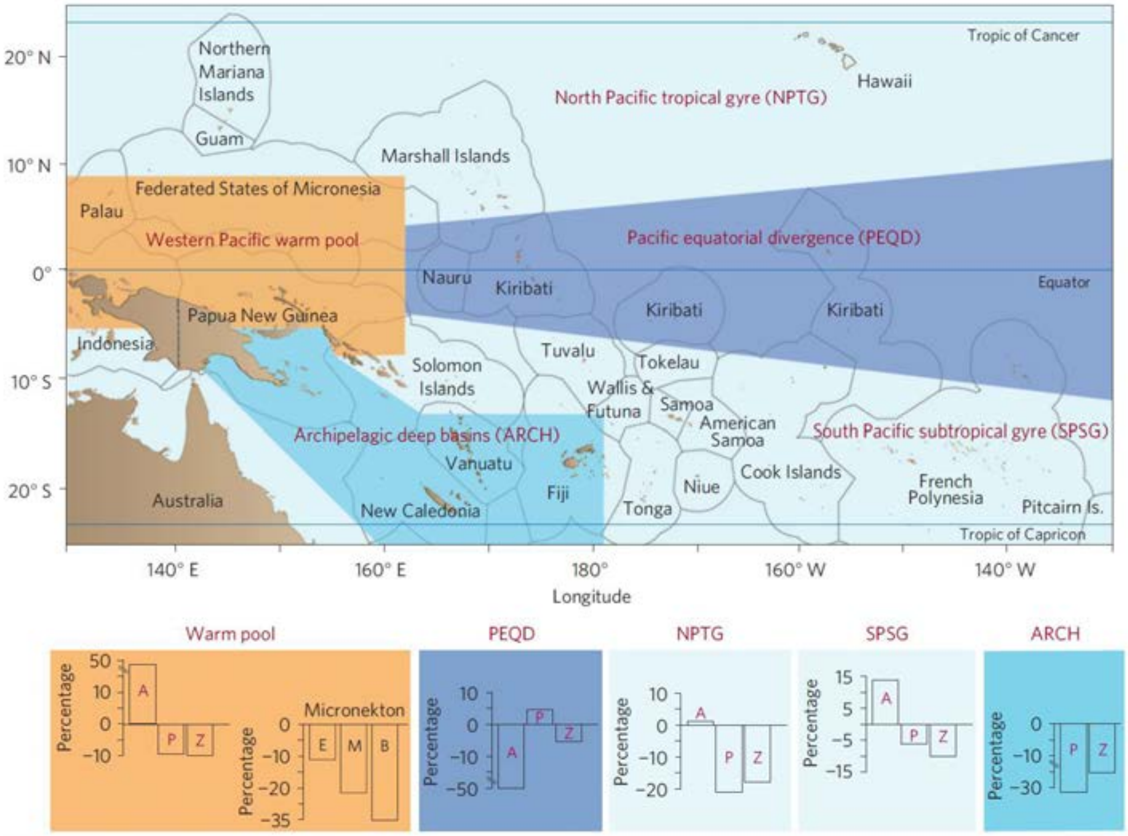
Supplementary Figure 2. Projected changes to rainfall and trade winds for the western and central tropical Pacific under a high emissions scenario (analogous to RCP8.5) between 1980–2000 and 2080–2100. The locations of the two convergence zones are shown as solid lines; '+' and '-' indicate increases and decreases in wind speeds (source: Bell et al., 2013).



Supplementary Figure 3. Projected changes in aragonite saturation (Ω) in the Pacific Island region by 2050 (2045–2055) and 2100 (2090–2100) relative to 2000-2010 (with Ω = 3.9-4.0) under the RCP2.6 and RCP8.5 emissions scenarios.



Supplementary Figure 4. Projected changes in area (A), net primary production (P) and zooplankton biomass (Z) for the five ecological provinces of the tropical Pacific Ocean between 2000–2010 and 2090–2100 under a high emissions scenario. The area of ARCH does not change by definition. Changes in epipelagic (E), mesopelagic (M) and bathypelagic (B) micronekton in the warm pool are also shown (source: Bell et al., 2013).



Supplementary Table 1. Average total catch (Mt) by all fishing methods for all tuna species, and for each species (skipjack, yellowfin, and bigeye tuna and South Pacific albacore), caught between 2012 and 2016 from: the entire Western and Central Pacific Ocean (WCPO); the combined exclusive economic zones (EEZs) of Pacific Island countries and territories (PICTs); and the combined EEZs of the eight countries that are the Parties to the Nauru Agreement (PNA). The average catch (Mt) taken from the EEZ of each PNA member country is also shown.

Species of tuna	Year	WCPO	PICTs	PNA	Parties to the Nauru Agreement							
					PNG	Kiribati	Solomon Islands	FSM	Nauru	Tuvalu	Marshall Islands	Palau
All species	2012	2,666,866	1,673,291	1,588,645	586,102	556,169	97,687	189,327	33,126	51,011	71,319	3,904
	2013	2,687,549	1,569,711	1,505,585	592,004	297,092	130,829	217,195	46,349	163,608	55,092	3,415
	2014	2,849,025	1,730,787	1,655,220	339,172	720,558	89,705	142,002	85,248	177,022	96,609	4,903
	2015	2,648,677	1,432,333	1,322,560	190,754	643,422	132,946	169,139	36,415	67,243	81,192	1,448
	2016	2,719,926	1,536,649	1,474,610	316,278	434,651	179,200	205,551	93,685	131,816	107,143	6,285
	Average	**2,714,409**	**1,588,554**	**1,509,324**	**404,862**	**530,378**	**126,073**	**184,643**	**58,965**	**118,140**	**82,271**	**3,991**
Skipjack	2012	1,758,633	1,197,864	1,163,890	425,613	399,477	58,934	156,846	23,183	39,330	59,999	509
	2013	1,843,541	1,154,008	1,131,744	427,196	224,223	82,666	187,183	35,685	129,084	45,405	301
	2014	1,982,021	1,283,337	1,246,771	224,170	573,944	37,805	112,403	67,386	145,732	84,427	903
	2015	1,811,474	1,033,366	966,640	108,461	525,372	76,714	108,656	24,532	50,017	72,703	185
	2016	1,812,502	1,075,620	1,058,728	196,876	340,018	101,867	167,101	74,006	89,127	87,256	2,477
	Average	**1,841,634**	**1,148,839**	**1,113,555**	**276,463**	**412,607**	**71,597**	**146,438**	**44,958**	**90,658**	**69,958**	**875**

Yellowfin	2012	606,640	351,783	339,622	144,347	122,458	26,899	23,750	4,460	8,304	8,167	1,238
	2013	554,153	297,925	288,523	147,349	45,050	33,491	23,262	6,498	26,157	5,924	793
	2014	589,936	324,527	312,466	104,827	106,993	33,455	21,409	11,669	23,530	8,124	2,460
	2015	584,259	293,474	279,853	73,062	84,910	39,406	52,403	8,911	14,694	5,869	598
	2016	657,941	359,181	346,502	110,035	70,676	67,022	30,409	14,020	38,247	13,429	2,664
	Average	**598,586**	**325,378**	**313,393**	**115,924**	**86,017**	**40,055**	**30,247**	**9,112**	**22,186**	**8,303**	**1,551**
Bigeye	2012	162,719	81,389	73,507	15,220	32,994	3,724	8,563	5,264	3,361	2,235	2,146
	2013	154,227	76,418	72,445	17,196	26,977	4,809	6,646	3,964	8,351	2,255	2,248
	2014	157,560	83,378	79,293	9,851	38,368	4,265	7,920	6,023	7,759	3,569	1,538
	2015	141,051	65,730	61,682	8,850	30,603	6,015	7,965	2,892	2,533	2,169	654
	2016	149,713	64,256	59,662	9,256	21,266	5,133	7,980	5,520	4,443	4,,927	1,139
	Average	**153,054**	**74,234**	**69,318**	**12,075**	**30,042**	**4,789**	**7,815**	**4,733**	**5,289**	**3,031**	**1,545**
South Pacific albacore	2012	138,874	42,255	11,625	923	1,240	8,130	168	219	15	917	12
	2013	135,629	41,360	12,8,,72	263	842	9,863	104	202	16	1,508	73
	2014	119,508	39,545	16,6,,90	323	1,253	14,181	271	170	1	489	2
	2015	111,893	39,763	14,3,,85	380	2,536	10,811	116	80	0	451	11
	2016	99,770	37,592	9,718	111	2,692	5,178	61	140	0	1,531	5
	Average	**121,135**	**40,103**	**13,058**	**400**	**1,713**	**9,633**	**144**	**162**	**6**	**979**	**21**

Supplementary Table 2. Examples of arrangements for management, monitoring and supporting science for industrial tuna fishing in the Western and Central Pacific Ocean performed by the Pacific Islands Forum Fisheries Agency (FFA), the Parties to the Nauru Agreement (PNA), the Western and Central Pacific Fisheries Commission (WCPFC) and the Pacific Community (SPC).

Arrangement	Responsible agency
Management plans and action	
Regional Tuna Fisheries Management and Development Strategy – a regional agreement on a set of shared principles for the management and development of tuna fisheries by FFA member countries	FFA
Implementation of effort quotas, and other sub-regionally agreed management measures for tuna by Parties to the Nauru Agreement (PNA) on vessels fishing within their EEZs	PNA
National tuna fishery management and development plans, incorporating regionally agreed standards; domestication of fisheries operating in their zones, and mechanisms to implement ecosystem approaches to fisheries	FFA
Definition of a Western Tropical Pacific Insular Area (WTPIA) that could form part of the emerging South Pacific Regional Fisheries Management Convention area	FFA
Monitoring, Control and Surveillance	
Agreed policies for the detection and deterrence of illegal, unregulated and unreported fishing, based on the Pacific Islands Regional Fishery Observer Programme, the Regional Vessel Monitoring System, the Regional Register of Fishing Vessels and the Niue Treaty for cooperation in fisheries surveillance and information sharing	FFA
Science	
Regular scientific assessments of the status of tuna stocks and their supporting ecosystem, and occasional scientific assessments of non-tuna fisheries	SPC
Tuna tagging programme	SPC

Supplementary Table 3. The average projected year for the onset of annual severe bleaching (ASB) for coral reefs on the Great Barrier Reef in Australia, and for reefs in Pacific Island countries and territories, under the RCP8.5 emissions scenario. The range of years for the projected timing in the onset of ASB for all reef areas within the country or territory, and standard deviation around the average, are also shown (adapted from van Hooidonk et al., 2016). Blue shading indicates countries/territories projected to experience annual severe bleaching before 2040. Note the projected delay in ASB for higher-latitude reefs relative to reefs closer to the equator.

Country/Territory	**Reef area (km^2)**	**Average year of ASB onset**	**Range across reef area (years)**	**Standard deviation**
Australia (GBR & Coral Sea)	47,910*	2050	64	8.82
Australia (Torres Strait)	2,976	2043	7	1.94
American Samoa	368	2039	9	1.64
Cook Islands	667	2044	15	3.99
FSM	15,074	2038	12	1.46
Fiji	10,000	2044	41	4.04
French Polynesia	15,126	2047	25	4.44
Guam	238	2037	12	2.20
Kiribati	4,320	2041	14	3.50
Marshall Islands	13,930	2040	6	1.50
Nauru	7	2035	0	0
Niue	56	2047	19	6.36
CNMI	250	2037	12	2.20
New Caledonia	35,925	2044	22	3.39
Papua New Guinea	22,200	2040	50	5.90
Palau	2,496	2038	11	2.41
Pitcairn Islands	48	2059	13	2.99
Samoa	466	2038	9	1.80
Solomon Islands	8,535	2040	44	2.81
Tokelau	204	2039	4	0.82
Tonga	5,811	2045	22	2.51
Tuvalu	3,175	2039	9	1.87
Vanuatu	1,244	2043	21	2.97
Wallis & Futuna	932	2038	10	1.45

*Estimated area calculated from Ceccarelli et al. (2013). FSM = Federated States of Micronesia, CNMI = Commonwealth of the Northern Mariana Islands

Supplementary Table 4. Projected percentage changes in biomass of skipjack, yellowfin and bigeye tuna and South Pacific albacore in 2050 and 2100, relative to 2001–2010, in the exclusive economic zones of Pacific Island countries and territories (PICTs) due to the effects of climate change alone under the RCP8.5 emissions scenario (CC) and the combined effects of climate change and fishing effort 1.5 times greater than for the period 2001–2010 (+F). Projections are derived from the SEAPODYM model (Lehodey et al., 2015, 2017; Senina et al., 2016). CNMI = Commonwealth of Northern Mariana Islands; FSM = Federated States of Micronesia.

PICT	**Skipjack**				**Yellowfin**				**Bigeye**				**Albacore**			
	2050		**2100**		**2050**		**2100**		**2050**		**2100**		**2050**		**2100**	
	CC	**+F**	**CC**	**+F**	**CC**	**+F**	**CC**	**+F**	**CC**	**+F**	**CC**	**+F**	**CC**	**+F**	**CC**	**+F**
West of 170ºE																
CNMI	65	65	19	20	0	-2	-8	9	-14	-36	-58	-74	-	-	-	-
FSM	-35	-42	-68	-71	-26	-38	-45	-41	-23	-44	-62	-76	-	-	-	-
Guam	3	2	-25	-25	-18	-23	-31	-19	-19	-40	-59	-74	-	-	-	-
Marshall Islands	-33	-38	-48	-49	-21	-28	-36	-31	-27	-45	-63	-75	-	-	-	-
Nauru	-24	-37	-75	-80	-27	-40	-52	-54	-35	-55	-73	-82	-15	-26	-34	-41
New Caledonia	26	20	104	103	-13	-18	-16	14	-17	-35	-51	-63	-21	-29	-27	-33
Palau	-29	-35	-68	-72	-17	-27	-38	-29	-20	-43	-65	-79	-	-	-	-
Papua New Guinea	-41	-50	-73	-74	-31	-47	-49	-47	-29	-49	-65	-76	-14	-26	-37	-45
Solomon Islands	-12	-20	-26	-26	-19	-30	-31	-20	-23	-44	-60	-73	-18	-29	-31	-38
Vanuatu	38	30	171	171	-9	-15	-11	14	-17	-37	-52	-66	-23	-32	-34	-39

East of 170ºE																
American Samoa	42	38	75	68	6	3	11	25	-18	-36	-53	-69	-26	-34	-32	-36
Cook Islands	-18	-21	3	-3	8	5	19	31	-18	-36	-53	-69	-26	-33	-28	-32
Fiji	25	19	58	54	-5	-9	-9	10	-18	-36	-55	-67	-24	-32	-31	-36
French Polynesia	68	60	110	90	25	22	55	65	-9	-29	-48	-65	-31	-35	-28	-30
Kiribati	-7	-13	-41	-46	-10	-15	-23	-18	-27	-45	-65	-78	-24	-33	-35	-40
Niue	35	31	55	49	6	3	9	24	-14	-32	-49	-65	-25	-32	-32	-35
Pitcairn Islands	128	115	186	155	42	36	90	97	4	-20	-22	-55	-32	-35	-23	-25
Samoa	40	34	63	55	3	0	5	20	-19	-37	-55	-70	-26	-34	-32	-36
Tokelau	-44	-46	-53	-56	-7	-10	-12	-2	-28	-44	-64	-76	-19	-27	-24	-28
Tonga	21	17	31	26	0	-3	-2	15	-15	-33	-52	-66	-25	-33	-29	-33
Tuvalu	-31	-35	-57	-61	-13	-20	-27	-20	-30	-47	-67	-78	-18	-27	-27	-33
Wallis and Futuna	26	20	27	21	-2	-6	-4	10	-21	-39	-58	-71	-25	-33	-31	-36

Supplementary Table 5. Total, rural and urban populations for Pacific Island countries and territories (PICTs) in 2013, and population projections for 2020 and 2035 (Source: Pacific Community).

PICT	**2013**			**2020**			**2035**		
	Rural	**Urban**	**Total**	**Rural**	**Urban**	**Total**	**Rural**	**Urban**	**Total**
Melanesia	**7,475,000**	**1,917,100**	**9,392,100**	**8,433,300**	**2,404,400**	**10,837,700**	**9,946,200**	**4,202,100**	**14,148,300**
Fiji	386,600	472,500	859,100	365,500	521,700	887,200	314,600	648,000	962,600
New Caledonia	86,400	172,500	258,900	86,100	195,400	281,500	78,500	244,000	322,500
Papua New Guinea	6,319,100	1,079,400	7,398,500	7,210,400	1,424,800	8,635,200	8,645,900	2,800,100	11,446,000
Solomon Islands	489,800	121,000	610,800	557,800	166,600	724,400	674,900	342,100	1,017,000
Vanuatu	193,000	71,600	264,600	213,400	95,900	309,300	232,200	167,800	400,000
Micronesia	**162,600**	**362,200**	**524,800**	**159,500**	**411,200**	**570,700**	**144,300**	**497,000**	**641,300**
FSM	79,000	23,900	102,900	76,000	25,500	101,500	64,400	32,600	97,000
Guam	8,600	166,300	174,900	8,500	189,100	197,600	7,900	212,500	220,400
Kiribati	50,300	58,500	108,800	51,500	74,100	125,600	51,400	111,500	162,900
Marshall Islands	17,000	37,200	54,200	16,100	39,700	55,800	14,300	47,500	61,800
Nauru		10,500	10,500		11,700	11,700		14,700	14,700
CNMI	2,400	53,200	55,600	2,200	57,800	60,000	2,000	63,900	65,900
Palau	5,200	12,500	17,700	5,100	13,200	18,300	4,200	14,300	18,500
Polynesia	**369,900**	**279,600**	**649,500**	**358,300**	**302,400**	**660,700**	**331,400**	**392,300**	**723,700**
American Samoa	3,600	52,900	56,500	3,000	55,500	58,500	2,700	63,400	66,100

Cook Islands	3,700	11,400	15,100	3,300	12,300	15,600	2,600	13,600	16,200
French Polynesia	125,400	136,000	261,400	125,100	145,700	270,800	115,100	185,700	300,800
Niue	900	600	1,500	700	600	1,300	500	700	1,200
Samoa	141,900	45,500	187,400	135,900	50,500	186,400	125,900	73,400	199,300
Tokelau	1,200		1,200	1,100		1,100	1,000		1,000
Tonga	75,900	27,400	103,300	71,800	30,900	102,700	66,000	45,400	111,400
Tuvalu	5,300	5,700	11,000	5,400	6,800	12,200	5,500	10,100	15,600
Wallis & Futuna	12,100		12,100	11,900		11,900	12,100		12,100
Total	**8,007,500**	**2,558,800**	**10,566,300**	**8,951,100**	**3,117,900**	**12,069,000**	**10,421,900**	**5,091,400**	**15,513,300**

FSM = Federated States of Micronesia; CNMI = Commonwealth of Northern Mariana Islands

Supplementary Table 6. Projected percentage changes in biomass of skipjack tuna in 2025, relative to 2001–2010, in the exclusive economic zones of Pacific Island countries and territories (PICTs) due to climate change under the RCP8.5 emissions scenario. Projections are also shown for the combined effects of climate change and fishing effort 1.5 times greater than for the period 2001–2010. Projections are derived from the SEAPODYM model (Senina et al., 2016).

PICT	**Virgin biomass**	**Fishing effort x 1.5**
West of 170ºE		
CNMI	8	1
FSM	5	-26
Guam	-15	-25
Marshall Islands	-14	-28
Nauru	15	-17
New Caledonia	13	3
Palau	-10	-24
Papua New Guinea	-6	-38
Solomon Islands	0	-26
Vanuatu	7	-5
East of 170ºE		
American Samoa	25	19
Cook Islands	-23	-25
Fiji	8	0
French Polynesia	48	41
Kiribati	13	1
Niue	24	20
Pitcairn Islands	62	51
Samoa	27	20
Tokelau	-43	-46
Tonga	14	9
Tuvalu	-31	-40
Wallis and Futuna	16	8

CNMI = Commonwealth of Northern Mariana Islands; FSM = Federated States of Micronesia

Supplementary Table 7. Examples of the questions that need to be answered to reduce uncertainty about the vulnerability of national plans for fisheries to climate change, and to optimise adaptations. The rationale for each question is also provided (based on supplementary information for Bell et al., 2013).

Question	Rationale
What is the spatial stock structure of skipjack, yellowfin and bigeye tuna and South Pacific albacore across the tropical Pacific Ocean? (At present, each species is currently managed as a panmictic stock for the Western and Central Pacific Ocean (WCPO).	Preliminary investigations suggest that there may be multiple stocks of yellowfin tuna and bigeye tuna in the WCPO. Knowledge about the spatial structure of each tuna species will improve stock assessments and may have implications for co-operative management arrangements. This information is also needed to improve projections for the responses of tuna resources to climate change. Ultimately, to identify the most appropriate adaptations for industrial tuna fisheries, it will be important to model the predicted responses of each self-replenishing tuna population to the physical, chemical and biological changes projected to occur to the WCPO.
How will additional nutrients delivered to Papua New Guinea's (PNG) coastal waters by increased flows from major rivers change fisheries production?	PNG is the focus here because that is where the bulk of the region's population lives. This question integrates the effects of changes in surface climate, projected to result in substantial increases in the flow of major rivers, with coastal ecological processes likely to affect the productivity of both coastal fisheries and tuna within the large archipelagic waters of PNG.
Will the Equatorial Undercurrent (EUC) transport additional iron to the Pacific equatorial upwelling to reduce iron-limitation of primary production and enhance fisheries?	Phytoplankton growth in the nutrient-rich waters of the Pacific equatorial upwelling (PEQD province in Supplementary Fig. 5) is presently limited by the supply of iron. The prospect that iron from the shelf of PNG may be entrained to a greater extent by increases in the strength of the New Guinea Coastal Undercurrent that feeds the EUC, resulting in increased primary productivity in PEQD, has potential to increase fisheries production and alter the expected effects of climate change on tuna and planktivorous reef fish.
Could decreases in strength of the South Equatorial Counter Current exacerbate declines in coral reef fisheries by reducing larval dispersal and stock replenishment?	Although there is now evidence for limited larval dispersal by many coral reef fish, replenishment of populations affected by substantial local coral bleaching or the combined effects of local overfishing and environmental change is likely to depend to a significant extent on sporadic larval dispersal from distant reefs. Understanding the scope for potential reduction in such dispersal will assist managers to gauge any increased vulnerability of coral reef fish and manage appropriately.
What are the ecological linkages between coral reef, seagrass and mangrove habitats, and what contributions do fish and shellfish associated with mangroves and seagrasses make to coastal fisheries?	Coastal fisheries in the region are based on more than coral reefs. Little is known about the linkages between coral reef, seagrass and mangrove habitats in the life cycles of fish and shellfish species caught by coastal fishers, the importance of the juxtaposition of these habitats in overall fisheries production, and the productivity of stand-alone areas of mangroves and seagrasses. Research is needed to answer these questions, identify the contributions of fish and shellfish associated with mangroves and seagrasses to food security and maximise the resilience of these contributions.

Will coral reefs degraded by climate change increase the incidence of ciguatera fish poisoning, further reducing availability of coral reef fish for food security?	The toxic dinoflagellate microalgae, *Gambierdiscus* spp, that form the basis of ciguatera fish poisoning (through biotransformation of the toxin from the algae in the bodies of the herbivorous species which eat them into ciguatoxins, and through accumulation of these ciguatoxins in the muscles and organs of large carnivorous fish) grow on two main substrata – dead coral and the surfaces of macroalgae. As both dead coral and macroalgae are expected to increase as a result of climate change, there is the risk that the abundance of *Gambierdiscus* spp, and the incidence of ciguatera fish poisoning, may increase. However, interactions are expected with sea surface temperature (SST) because the distribution of the dinoflagellates is influenced by SST.
How should communities be assisted to remove any blockages to expanding the use of nearshore FADs and pond aquaculture to improve access to fish for food security?	Nearshore FADs and pond aquaculture are priority 'win-win' adaptations to climate change. The technology is proven, simple and capable of significantly increasing access to fish. However, just because the technology works, there is no guarantee that communities will adopt it. Communities need to be assisted to understand the potential food security benefits that can be delivered by FADs and pond aquaculture, and to remove any socio-economic impediments to the uptake of these methods where tuna and tilapia may not already be a recognised part of the diet.