Green Climate Fund Regional Tuna Programme:

Feasibility Study

Chapter 2

Climate change vulnerability assessment

Prepared by the Pacific Community and Conservation International on behalf of 14 Pacific Island countries for submission to the Green Climate Fund

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Annex 2-C of the Funding Proposal "Adapting tuna-dependent Pacific Island communities and economies to climate change"

Chapter 2: Climate change vulnerability assessment

Contents

2.1 General introduction

In general terms, this chapter applies the recommended end-to-end, 'climate-to-fish-to-fisheries-to-socioeconomic impact' approach to assess the vulnerability of fisheries resources, and the Pacific Island communities and economies that depend on these resources, to climate change.[1,2]

In broad terms, this approach involves examining how the biophysical features of the ocean will be altered by the progressive accumulation of greenhouse gases (GHG) in the atmosphere; the ways in which the habitats that support coastal fisheries and the food webs that support tuna are likely to respond to the changes in the ocean; the subsequent effects on the productivity of coastal fisheries and distribution of tuna; and, finally, the flow-on effects on the communities that depend on coastal fisheries resources for food security and the economies that are underpinned by the industrial tuna fisheries.

More specifically, this approach involves assembling the following information.

1. The coupled nature of surface climate and the tropical Pacific Ocean.
2. Projected changes to these two over-arching features of the region under representative high and moderate/low greenhouse gas emission scenarios.
3. The nature of the habitats supporting coastal fish species (mainly coral reefs, but also mangroves and seagrasses) and the food webs supporting tuna, and the projected changes to these ecosystems due to alterations to the atmosphere-ocean.
4. Projected changes to the productivity of coastal fisheries due to the indirect effects of alterations to coastal fish habitats, and the direct effects of changes to the ocean.
5. The implications of changes in the productivity of coastal fisheries for the food security of Pacific Island communities.
6. The projected indirect effects of changes to ocean food webs and the direct effects of changes to the physical and biogeochemical nature of the ocean on the distribution and abundance of tuna, and the catches of tuna made by industrial fishing fleets.
7. The consequences of changes to industrial tuna catches for Pacific Island economies.

The huge area over which the Pacific Island countries are located, and over which the tuna resources that underpin Pacific Island economies are distributed (Chapter 1), mean that it was not appropriate to present information on the climate context and vulnerability for each of the 14 countries participating in the Regional Tuna Programme (hereafter 'Programme'). Instead, this vulnerability assessment documents the impacts of climate change on the ecosystems and key coastal and oceanic (tuna) fish resources underpinning fisheries production common to the participating countries. This is due to the regional nature of the Programme and the similarity of the projected effects of increased GHG emissions across much of the Western and Central Pacific Ocean (WCPO). Country-level information is, however, provided where possible and relevant, including for the vulnerability of national communities and economies.

This chapter has drawn on a suite of existing and commissioned studies that collectively provide the information required for the end-to-end vulnerability assessment, and the climate context for the Programme (**Error! Reference source not found.**). These studies were undertaken variously during the timeframes for the 4th, 5th and 6th Intergovernmental Panel on Climate Change (IPCC) assessment reports. Despite the variation in the timeframes of the sources used, the information is presented in a comparable way throughout the chapter (guided by **Appendix 1-A)** to assess vulnerability of fisheries-dependent communities and economies across the region to the projected changes in key features of surface climate and the tropical Pacific Ocean due to high and moderate/low GHG emissions scenarios.

The volume of information available to inform this assessment was substantial. This chapter attempts to distil the key points required to apply the end-to-end approach to assessing the vulnerability of the fisheries-dependent communities and economies in the 14 participating countries. Additional relevant supporting information is provided in appendices.

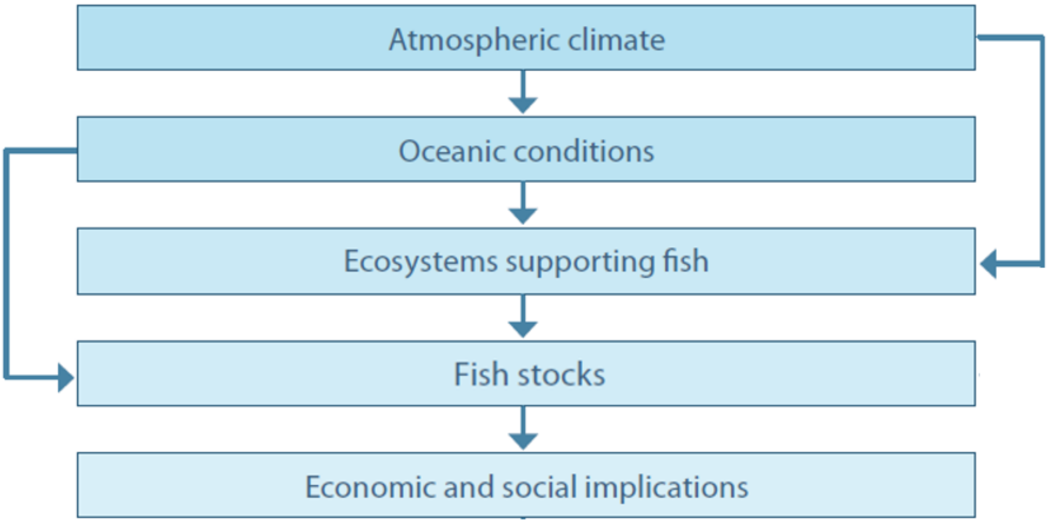


Figure 0.1 The end-to-end approach used to assess the vulnerability of fisheries-dependent communities and economies to climate change.

2.2 Key findings

2.2.1 Climate rationale

The assessments documented in this chapter show that fisheries-dependent communities and economies in 14 Pacific Island countries face severe risks due to the impacts of increasing GHG emissions on the region's linked ocean-atmosphere ecosystems. These impacts are expected to occur in two major forms. The first is through the degradation of coral reefs, which have traditionally provided much of the animal-based protein required for domestic food security across the region.[3] The second major impact is on the redistribution of tuna supporting the industrial fisheries that many Pacific Island countries depend on for revenue to fund basic services for their citizens. The socio-economic benefits derived by the 14 Pacific Island countries participating in the Programme are summarised in Figure 00.2. The substantial direct and indirect effects that GHG emissions are having on the production of coastal fisheries (especially coral reef fish) and tuna in the Pacific Island region are described in detail. These effects are also summarized in the IPCC Sixth Assessment Report,[4] the IPCC Special Report on 1.5°C[5] and the IPCC Special Report on the Oceans and Cryosphere.[6]

The degradation of coral reefs is driven largely by the increasing sea surface temperature (SST) and pH declines, resulting in less structurally-complex coral reef habitats.[7] The reduced capacity of degraded coral reefs to support fish, combined with the direct effects of ocean warming and acidification on the growth, reproduction and survival of coral reef fish,[8] are highly likely to cause substantial decreases in coastal fisheries production in the Pacific Island region. These effects are projected to occur as early as 2030 under continued high GHG emissions, and result in losses of fish production among the participating countries of 7–65% under a moderate emissions scenario (SSP2-4.5), and 10–73% under a high emissions scenario (SSP5-8.5), by 2050.

Ocean warming is also affecting the distribution of the region's rich tuna resources. In the WCPO, the abundant skipjack tuna is caught most easily at the convergence of the two tropical ecological provinces − the western Pacific Warm Pool and the Pacific equatorial divergence. This convergence zone is already known to shift by up to 4,000 km due to climatic variability driven by the El Niño Southern Oscillation (ENSO) events. Preliminary modelling confirms that tuna in equatorial areas are likely to shift progressively to the east as the Warm Pool expands due to ocean warming, and to a lesser extent into subtropical waters.[9] The resulting redistribution of tuna resources is predicted to reduce the average annual combined tuna catch from the exclusive economic zones (EEZs) of tuna-dependent Pacific Island countries in equatorial waters by 20% (range 10%−30%) by 2050 under a high emission scenario (RCP8.5), compared to the annual average catch.

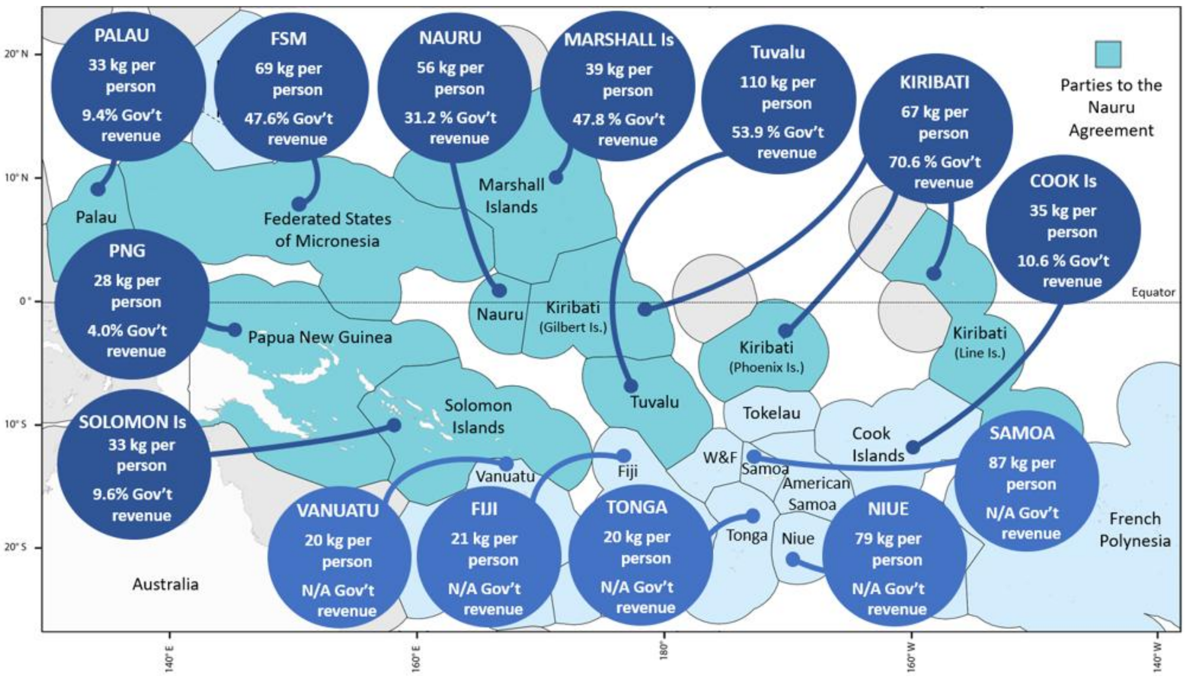


Figure 00.2. Annual average national fish consumption per capita (kg), and the average percentage contribution of tuna-fishing access fees to (non-aid) government revenue (2015−2018)[10,11]

2.2.2 Food security impacts

The implications for the food security of Pacific Island people are profound. Across the region, annual national fish consumption per capita ranges from 20–110 kg, i.e., up to five times the global average, and fish traditionally caught from coral reefs and other coastal habitats by small-scale fisheries provide 50–90% of dietary animal protein for coastal communities.[12] By 2030, population growth and the negative effects of climate change on coral reef fish production will create a gap in the supply of fish needed for good nutrition of Pacific Island people. The rich tuna resources of the region are the most practical choice for filling this gap.[13]

The large tuna resources of the region are not overfished nor subject to overfishing[14] due to exemplary management by Pacific Island countries, and no problems are anticipated in using tuna to provide 25% of all fish needed for local food security across the region. Indeed, only 6% of the total annual tuna catch from the Pacific Island region will be needed to fill the gap in fish supply by 2035.[15] Although the distribution of tuna is projected to shift eastward, national waters are still expected to hold large volumes of fish, capable of supporting the additional small-scale fisheries needed to contribute to national food security. Furthermore, apart from imports, which are often of poor nutritional quality, there are few if any alternative, affordable sources of high-quality animal protein produced in the region. This is due to the limited potential for agriculture, horticulture, animal husbandry and aquaculture in many of the island nations.[16]

Because tuna usually occur some distance from the coast, communities will need additional support to catch and distribute them. To make tuna a cornerstone of national food systems, urgent action is required to: (i) empower coastal communities to catch more tuna efficiently and safely; and (ii) ensure that the supply of tuna for urban communities, delivered by industrial fishing vessels, is not disrupted as fleets fish and tranship their catch further to the east.

2.2.3 Economic impacts

Pacific Island countries have already done much to sustain the economic benefits they receive from tuna.[17] Regrettably, climate change poses a serious threat to this notable achievement.

In brief, the tuna-dependent Pacific Island countries have established a fisheries management system that is proving to be robust in accommodating the effects of ENSO and climate change on the distribution of tuna within their combined EEZs. This mechanism – the Parties to the Nauru Agreement (PNA) Vessel Day Scheme (VDS) – enables the eight participating countries[18] to share the economic benefits from tuna resources equitably, regardless of where the tuna are caught within their combined jurisdictions.[19] The VDS is widely recognized as a world-leading, climate-smart fisheries management framework.[20] However, the VDS is currently unable to secure all the present-day benefits that PNA members receive from tuna as the fish move progressively from their combined EEZs into high-seas areas,[21] leaving these countries highly vulnerable.[22]

Climate-driven redistribution of tuna threatens to undermine the economies of the PNA member countries and Cook Islands, which obtain an average of 32% (range = 4–70%) of their total (non-aid) government revenue from tuna-fishing access fees (Figure 2.2).[23] By 2050 under RCP8.5, the redistribution of tuna is projected to reduce the total fishing access fees for these nine countries by an average of ~USD 90 million (range USD 40−USD 140 million) per year at today's prices.[24] For several of these countries, the projected loss of fishing access fees is estimated to reduce total (non-aid) government revenue by 6−13% per year (range 2−9% to 11−18%).[25]

This significant reduction in government finance will have direct impacts on vulnerable populations in these countries, with fewer resources available for health, education, disaster preparedness and post-disaster recovery. Tuna redistribution could also affect employment across the region, where tuna fishing and processing has created ~25,000 jobs.[26]

2.2.4 Summary of vulnerabilities and necessary adaptations

The information assembled in this chapter identifies the vulnerability of the 14 Pacific Island countries participating in the Programme, which range from low-moderate to very high (Table 2.1). It also identifies that the adaptations proposed under Components A and B of the Programme must be designed to be both regional and national in scope. The adaptations need to be of regional significance because tuna are migratory fish species shared by Pacific Island countries. Therefore, reliable information is needed on how tuna resources will respond to climate change and move across national jurisdictions, and from EEZs to high-sea areas. This will empower all participating countries to identify the most appropriate adaptations and implement them with confidence.

The scope of adaptations must also be relevant at the national level because the vulnerabilities to food insecurity, and the adaptations required to increase access to tuna for food security, need to be customised for each country, due to varying food security contexts and the wide differences in population size and location of Pacific Island nations. The food security adaptations centre around increasing access to tuna and associated pelagic fish species in nearshore waters through the deployment of anchored fish aggregating devices (FADs), and leveraging increased utilisation of tuna and bycatch transhipped or unloaded in Pacific Island ports by industrial tuna fleets.

The priority adaptation for the tuna-dependent economies involves empowering them to negotiate for the right to retain access to the tuna resources that have historically occurred within their combined EEZs when the tuna are redistributed to the high seas.[27] For the subtropical countries (Fiji, Niue, Samoa, Tonga and Vanuatu), preliminary modelling indicates that the more modest tuna resources that occur in their EEZs could increase.[28] For these economies, adaptations centre on capitalising on any significant opportunities. To implement effective adaptations for both categories of Pacific Island economies, more reliable information on the timing and extent of possible tuna redistribution is essential.

Table 00.1. Summary of the vulnerabilities of the 14 Pacific Island countries eligible for support from the Green Climate Fund with respect to shortages of coral reef fish for food security, and continued contribution of fishing access fees paid by industrial tuna fleets to government revenue.[29]

Pacific Island country	Vulnerability to shortages of coral reef fish per capita	Vulnerability to loss of government revenue	Comments on vulnerability of national economies to climate-driven redistribution of tuna by 2050
Cook Is	**Low-moderate**	**Low**	Preliminary modelling indicates that annual losses of total non-aid government revenue due to climate-driven redistribution of tuna under continued high GHG emissions could be limited to **<1%** in Cook Islands in 2050. However, improved modelling is needed to reduce uncertainty associated with this projection.
Fiji	**Low-moderate**	N/A	There could be an increase in tuna biomass in Fiji's EEZ due to climate-driven tuna redistribution under continued high GHG emissions by 2050, according to preliminary modelling. However, improved modelling is needed to reduce uncertainty and assess the cost:benefit of adaptations to capitalize on this possibility.
FSM	**Low-moderate**	**Moderate**	Preliminary modelling indicates that FSM could lose **~6%** of total non-aid government revenue per year by 2050 due to climate-driven redistribution of tuna under continued high GHG emissions. However, improved modelling is needed to reduce uncertainty associated with this projection.
Kiribati	**Moderate**	**Moderate**	Preliminary modelling indicates that Kiribati could lose **~6%** of total non-aid government revenue per year by 2050 due to climate-driven redistribution of tuna under continued high GHG emissions. However, improved modelling is needed to reduce uncertainty associated with this projection.
Marshall Is	**Low-moderate**	Low	Preliminary modelling indicates that annual losses of total non-aid government revenue due to climate-driven redistribution of tuna

			under continued high GHG emissions could be limited to **<1%** in Marshall Islands in 2050. However, improved modelling is needed to reduce uncertainty associated with this projection.
Nauru	**Very High**	**Moderate-high**	Preliminary modelling indicates that Nauru could lose **~7%** of total non-aid government revenue per year by 2050 due to climate-driven redistribution of tuna under continued high GHG emissions. However, improved modelling is needed to reduce uncertainty associated with this projection.
Niue	**Low-moderate**	N/A	There could be an increase in tuna biomass in Niue's EEZ due to climate-driven tuna redistribution under continued high GHG emissions by 2050 according to preliminary modelling. However, improved modelling is needed to reduce uncertainty and assess the cost:benefit of adaptations to capitalise on this possibility.
Palau	**Low-moderate**	**Low**	Preliminary modelling indicates that annual losses of total non-aid government revenue due to climate-driven redistribution of tuna under continued high GHG emissions could be limited to **<1%** in Palau in 2050. However, improved modelling is needed to reduce uncertainty associated with this projection.
PNG	**High**	**Low**	Preliminary modelling indicates that PNG could lose **>1%** of total non-aid government revenue per year by 2050 due to climate-driven redistribution of tuna under continued high GHG emissions. However, improved modelling is needed to reduce uncertainty associated with this projection.
Samoa	**Moderate-high**	N/A	There could be an increase in tuna biomass in Samoa's EEZ due to climate-driven tuna redistribution under continued high GHG emissions by 2050, according to preliminary modelling. However, improved modelling is needed to reduce uncertainty and assess the cost:benefit of adaptations to capitalize on this possibility.
Solomon Is	**Moderate-high**	**Low-moderate**	Preliminary modelling indicates that Solomon Islands could lose **~3%** of total non-aid government revenue per year by 2050 due to climate-driven redistribution of tuna under continued high GHG emissions. However, improved modelling is needed to reduce uncertainty associated with this projection.
Tonga	**Low-moderate**	N/A	There could be an increase in tuna biomass in Tonga's EEZ due to climate-driven tuna redistribution under continued high GHG emissions by 2050, according to preliminary modelling. However, improved modelling is needed to reduce uncertainty and assess the cost:benefit of adaptations to capitalize on this possibility.
Tuvalu	**Low-moderate**	**High**	Preliminary modelling indicates that Tuvalu could lose **~13%** of total non-aid government revenue per year by 2050 due to climate-driven redistribution of tuna under continued high GHG emissions. However, improved modelling is needed to reduce uncertainty associated with this projection.
Vanuatu	**Very high**	N/A	There could be an increase in tuna biomass in Vanuatu's EEZ due to climate-driven tuna redistribution under continued high GHG emissions by 2050, according to preliminary modelling. However,

			improved modelling is needed to reduce uncertainty and assess the cost:benefit of adaptations to capitalize on this possibility.

2.2.5 Contributions to regional resilience

The Programme supports the following goals of the *Framework for Resilient Development in the Pacific: An integrated approach to address climate change and disaster risk management* (FRDP),[30] endorsed by Pacific Island Leaders: (i) strengthened adaptation and risk reduction to enhance resilience to climate change, including managing risks caused by climate change within social and economic development planning processes; and (ii) strengthened preparedness, response and recovery to natural disasters caused by climate change. The Programme will also build resilience to climate change by supporting the following important management frameworks, strategies and resolutions for the fisheries sector in the region:

- the Western and Central Pacific Fisheries Commission (WCPFC) Resolution on Aspirations of Small Island Developing States and Territories (Resolution 2008-01);[31]
- the *Regional Roadmap for Sustainable Pacific Fisheries*,[32] designed to improve sustainability of tuna resources, add value to tuna catches, increase employment, and provide better access to tuna for food security, as well as building resilience of coastal habitats (by progressively shifting fishing effort from coral reefs to tuna);
- *A New Song for Coastal Fisheries – Pathways for Change,*[33] an innovative regional approach to maintain the benefits of small-scale fisheries in the face of declining coastal ecosystems and associated fish stocks;
- the Parties to the Nauru Agreement (PNA) Vessel Day Scheme that supplies 95% of tuna caught in the region; and
- the Forum Fisheries Agency's (FFA) Climate Change Strategy, adopted by the Forum Fisheries Committee in August 2023 to bring additional focus to the implications of climate change to the industrial tuna fisheries administered by FFA member countries.

In addition, the Programme will assist many Pacific Island countries to implement their Nationally Determined Contributions (NDCs) because 10 of the 14 participating countries have included the need for adaptations to the effects of climate change on the ocean and coastal marine habitats in their NDCs.[34]

2.3 Coupled surface climate-tropical Pacific Ocean and projected changes

Projected future changes to surface climate and atmospheric conditions due to continued GHG emissions are expected to have profound impacts on many features of the tropical Pacific Ocean including sea surface temperature (SST), eddies, availability of nutrients, dissolved oxygen, pH, currents, wave height and speed, sea level and coastal processes (see **Appendix 2-B** for detailed descriptions of these features). Some of the most relevant observed and projected impacts on the coupled features of surface climate and the tropical Pacific Ocean are summarised below. Additional information about these impacts is available in **Appendix 2-C**.

The surface temperature of the WCPO region has increased by more than 0.7 °C since 1900.[35] Projections based on a suite of global climate models from the Climate Model Intercomparison Project version 5 (CMIP5) used for IPCC AR5 indicate that, under the highly-ambitious RCP2.6 emissions scenario, increases in average SST in the WCPO will remain below 1°C by 2100 relative to 2000–2010.[36]

However, with increased CO_2 emissions corresponding to the business-as-usual RCP8.5 scenario, SST is expected to increase by 2.5°C to 3.5°C by 2100, and to rise most rapidly in equatorial waters. This long-term warming is expected to cause more extreme marine heat waves, resulting in much higher temperatures over short periods.[37] The warming ocean, and higher projected rainfall, are expected to increase stratification of the water column, reducing the supply of nutrient-rich water to the surface mixed layer.[38,39]

Globally, sea level has risen about 20 cm since the industrial revolution.[40] Continued warming of the ocean to a depth of several hundred metres, together with melting of glaciers and ice sheets, is expected to cause sea level to rise by 0.4 m by the end of the century under RCP2.6, and by more than 0.6 m under RCP8.5.[41] With the possibility of more rapid melting of the ice-sheets (not well accounted for in climate models), sea-level rise could be considerably greater, exacerbating the effects of storm surges on coastal populations and fish habitats.

Increasing rates of ocean acidification in the WCPO through absorption of atmospheric CO_2[42] are reducing the aragonite saturation state, the main form of calcium carbonate used by corals and other marine organisms to build hard skeletons and shells.

Since the industrial revolution, ocean acidification has reduced the pH of the upper water column by 0.1,[43] and the aragonite saturation level to 3.9.[44] Aragonite saturation levels greater than four are optimal for calcifying organisms, saturation levels between 4.0 and 3.0 are marginal to very marginal for calcification, and below 3.0 complex coral reef systems do not occur.[45] Strong mitigation of CO_2 emissions (RCP2.6), is expected to maintain aragonite levels at approximately 3.5, providing conditions adequate for some coral growth. In contrast, under RCP8.5 it is very likely that aragonite levels in the WCPO will drop below 3.0 between 2050 and 2100, causing serious degradation of coral reefs.[46]

The CMIP5 simulations indicate that winds and ocean circulation in the region will also change significantly. The northeast and equatorial trade winds are projected to weaken, whereas the southeast trade winds are expected to intensify. The South Equatorial Current and the associated New Guinea Coastal Undercurrent are projected to increase, whereas the velocities of the South Equatorial Counter Current and the North Equatorial Counter Current are expected to decrease.[47,48] In turn, changes in ocean circulation are expected to alter the location and strength of warm (cold) eddies that reduce (enhance) delivery of nutrient-rich water to the photic zone.[49]

The projected changes in the key features of surface climate and the tropical Pacific Ocean are listed in Table 2.2.

2.4 Habitats supporting fish in the Pacific Island region

The main habitats that support coastal fish species in the 14 Pacific Island countries participating in the Programme include coral reefs, seagrass meadows and mangrove forests. These habitats often form a connected mosaic, with mangroves typically located along the shore and seagrass meadows and coral reefs extending away from the coast.[50] Collectively, these habitats are important for coastal fisheries due to their role in providing food, shelter and nursery areas for juvenile fish and invertebrates, as well as cover and feeding grounds for adult demersal fish and invertebrate species that move among habitats during different life history stages.[51] The connectivity between this mosaic of habitats sustains a high diversity of commonly-harvested species targeted by Pacific communities for food and income.[52]

Table 0.2. Projected changes to key features of the tropical Pacific Ocean from the suite of CMIP5 models by 2050 (2045–2055) and 2100 (2090–2100), relative to 2000–2010, for the RCP2.6 and RCP8.5 emissions scenarios. All changes are expressed as the multi-model inter-quartile range, except for aragonite and pH, which are the multi-model median changes.[53]

Ocean variable	Multi-model median 2000–2010	RCP2.6		RCP8.5	
		2050	2100	2050	2100
Sea surface temperature (SST)[1]	27.4 °C	+0.4–0.8	+0.3–0.8	+0.9–1.3	+2.3–3.3
pH[1]	8.07	-0.06	-0.05	-0.12	-0.31
Aragonite[1,]	3.9	-0.32	-0.35	-0.63	-1.43
Maximum Warm Pool SST, warmest 10% region	29.4 °C	+0.4–0.8	+0.3–0.8	+0.9–1.3	+2.0–3.1
Warm pool edge, defined by 29 °C isotherm (longitude)	170°	180.8–191°	179.5–193.3°	187–205.3°	213.3°–EM[2]
Sea-level rise	0 metres	+0.28–0.31	+0.4–0.44	+0.36–0.41	+0.6 - –0.66
Westward wind stress 2 °S–2 °N, 130 °E–230 °W (10-4 Nm-2)	-32.6	-0.6– +3.3	0– +4.2	-0.3– +4.5	-2.1– +7.5

1= Averaged over full domain 25°S to 25°N, 130°E to 130°W; 2 = EM: eastern margin of Pacific basin

Collectively, the 14 participating countries have ~74,000 km^2 of coastal habitats, dominated by coral reefs (Table 2.3). These habitats support a high biodiversity of fish species, and species richness decreases from the west to east of the region, with the greatest species richness occurring in Papua New Guinea (PNG) and Solomon Islands, which are also part of the Coral Triangle – the most diverse and biologically complex marine ecosystem in the world.[54] The estimated coastal habitat area for each of the participating countries demonstrates the extent of coral reefs, seagrass meadows and mangrove forests, and the relative importance of the different habitats in supporting coastal fisheries (Table 2.3).

In general, coastal habitats in the Pacific Islands region are in relatively good condition,[55] however, there are many drivers of change and increasing threats to their condition.

Summaries of the extent of each of the main coastal habitats across the region are provided below. Further details are given in **Appendix 2-D**.

.4.1.1 Coral reefs

Coral reefs are the best studied coastal habitat in region, covering over 46,000 km^2 in the 14 participating countries (Table 2.3). An assessment of their status and trends[56] focused on two indicators – live hard coral cover and macroalgae cover. The 440,000 observations since 1987 show that, prior to 1998, average hard coral cover was relatively high and stable between 37.0% and 37.7%. In 2019, this had declined to 31.3%. The impacts of the 1998 El Niño in the Pacific Islands region were evident in a 2.3% decline in average coral cover between 1999 and 2001, and El Niño events in 2015 and 2016 caused considerable coral mortality across the region, which was apparent in the 2.7% decline in average coral cover between 2015 and 2017. The average cover of macroalgae on the other hand remained relatively low (15%) and stable between 1987 and 1999, followed by a progressive increase over the last two decades, peaking at 20.8% in 2018.

2.4.2 Seagrass meadows

The 14 participating countries have extensive seagrass meadows, totalling almost 22,000 km^2 in area (World Conservation Monitoring Centre data), with 16 species found across the region.[57] The greatest area and species diversity is in Melanesia, with PNG having the highest diversity (13 species). Seagrass species diversity progressively decreases eastwards, resulting in only two species occurring in French Polynesia. Seagrass condition in 65% of Pacific Island countries and territories (PICTs) has been assessed based on 57 datasets of meadow extent and ecosystem trends, and was categorised as increasing, decreasing or undetermined[58]. Seagrass meadows are under increasing threats from anthropogenic activities, especially changes in land use, further exacerbated by pressures from climate change.[59] However, in a global context, current evidence suggests that the Pacific Islands region remains a location with relatively low pressures and more resilient seagrass.

2.4.3 Mangrove forests

There are ~6,000 km^2 of mangroves in the region (Global Mangrove Watch), representing ~3.8% of the world's mangrove forests.[60] Some of the largest areas occur in Fiji, PNG, and Solomon Islands. Although several areas of mangroves are diverse and assessed to be in relatively good condition (e.g., in PNG which hosts 43 species), other locations only have small remnant forests due to infrastructure development (e.g., the airport area in Pohnpei, Federated States of Micronesia, which is located on a low-lying mangrove island) and reclamation (e.g., in Fiji, where mangrove forest area is estimated to have declined from 42,462 ha in 1999 to 37,000 ha in 2009, largely due to land reclamation). In many PICTs, mangroves have been observed to migrate landward as a natural response to rising sea level. In cases where this natural landward migration is constrained by topography or the presence of seawalls and other man-made structures, mangrove areas reduce over time. Based on these observations, continued sea-level rise and other climate change impacts pose an ongoing threat to mangrove forests.[61]

2.5 Projected changes to coastal habitats

Coastal habitats in the Pacific Islands region have evolved to survive within a specific range of prevailing climatic conditions – the coping range.[62] Any changes in these conditions can be expected to have impacts on these habitats and, in turn, the fisheries resources and human communities they support.
An extensive body of research has shown that coral reefs are highly vulnerable to ocean warming and acidification,[63] [64] but also to damage from more intense cyclones and storms, and increased sedimentation and nutrient loads stemming from increased runoff due higher rainfall and increased land use (deforestation and agriculture). There is now widespread recognition that increasing SST is causing coral bleaching and mass mortality more frequently around the world, including on reefs in the Pacific Islands region, driving changes in the structure and function of coral reef fish assemblages.[65,66] Increases in global warming above 1.5 °C are expected to result in net erosion of coral reefs throughout the tropics.[67] [68] A global assessment found that thermal bleaching is expected to become an annual event spanning Pacific reefs under a high emissions scenario by ca. 2040.[69] A summary of the key assessment of the vulnerability of coral reefs to ocean warming (and the implications for the services they provide) in the three IPCC reports cited above is provided in **Appendix 2-D.**

Table 2.3 Estimated area (km²) of coastal habitats in 2022 in each Pacific Island country participating in the GCF Programme. Data sources: WRI – World Resources Institute; WCMC – World Conservation Monitoring Centre [UNEP]; GMW – Global Mangrove Watch. FSM = Federated States of Micronesia; PNG = Papua New Guinea. Blank cells indicate that the habitat does not occur in the country.

Country	Estimated habitat area (km²)		
	Coral reef (WRI data)	Seagrass meadow (WCMC data)	Mangrove forest (GMW data)
Cook Islands	530.8		<0.1
FSM	4,957.0	1,594.6	87.9
Fiji	6,741.7	1,745.6	488.1
Kiribati	3,061.2	499.6	1.5
Marshall Islands	3,581.0	529.3	0.3
Nauru	15.4		
Niue	44.7		
Palau	972.3	732.2	56.9
PNG	14,686.6	9,347.4	4,524.7
Samoa	404.2	988.7	2.3
Solomon Islands	6,790.6	1,261.7	526.5
Tonga	1,670.4	3,703.4	10.4
Tuvalu	1,238.2	-	0.1
Vanuatu	1,813.0	1,244.7	15.8
Total	**46,506.9**	**21,647.1**	**5,714.7**

Ocean acidification also affects corals, reducing calcification rates, impacting growth, and making coral reefs more susceptible to damage.[70] Ocean acidification is expected to slow the rate of reef accretion and enhance erosion over the coming decades. For example, optimal coral calcification rates occur at 2–3 °C below the bleaching temperature threshold.[71] But when corals bleach, calcification is suppressed because photosynthetic products from zooxanthellae are essential for the calcification process and their expulsion from corals reduces these products. Similarly, corals exposed to nutrients, turbidity, sedimentation or pathogens are more susceptible to thermal stress, or less able to survive and recover from bleaching or other acute disturbances.[72] In more acidic seawater, coral reefs are expected to be more susceptible to other pressures, such as eutrophication, coral disease, storms and bleaching.[73]

The effects of climate change are exacerbating the degradation of seagrass meadows caused by several local impacts, including sand extraction, deforestation and catchment agriculture, coastal development and poor water quality.[74] Changes in nutrient dynamics and light penetration in coastal waters due to flood events impact seagrass growth and reproduction, as does the combined stresses of light and temperature.[75] Elevated nutrients and sediments that increase epiphytic algal growth and turbidity also reduce light needed by seagrasses, reducing their productivity and area.[76] Tropical seagrasses are also heavily influenced by weather patterns, including flood and cyclone events that have the potential to physically damage meadows, particularly in shallow areas. Elevated CO_2 concentrations are expected to counterbalance some of the impacts described above by increasing the thermal tolerance of the plants and providing some inherent resilience.[77] Seagrass buffers pH decline in seawater and any improved resilience of this habitat may play a wider role in maintaining the coastal mosaic of habitats that support fisheries.

Mangroves are highly exposed to sea-level rise due to their location on the coastal fringe of islands, and any decline in mangroves can be expected to exacerbate extreme high tide flooding, storm surge and shoreline erosion from more intense storms and cyclones.[78] Mangroves have the ability to adapt to projected sea-level rise if sediment accretion is fast enough and landward barriers, such as roads, retaining walls and buildings, do not constrain landward migration. Higher atmospheric CO_2 concentrations and greater rainfall in some sub-regions could enhance the potential for mangroves to expand landward by increasing their productivity.[79] Ultimately, the pace of sea-level rise under high emissions is expected to be greater than the ability of mangroves to migrate, particularly if landward migration is constrained by structures.[80]

Drought, sea level change, and MHW events can also cause significant mangrove dieback, and changes in rainfall and river flow can affect coastal wetland and mangrove fish and invertebrate species, particularly recruitment success, growth, and catchability.[81] In addition, more intense storms will impact mangrove forests through the physical processes of erosion, burial, wind throw and lightning strikes. Projected changes in rainfall, particularly the amplification of the seasonal cycle, has implications for mangrove growth, depending on whether the rainfall changes coincide with the peak mangrove growing season. [82]

2.5.1 Projected changes in habitat area

Technical Study 1 identified the area of each coastal habitat expected to experience degradation, based on the percentage of the existing area considered to have a 'very high' or 'high' vulnerability. The projected vulnerable areas of each habitat in each country (where it occurs) under the SSP5-8.5 and SSP2-4.5 emission scenarios by 2050 are given in Table 2.4.

Table 2.4 Total percentage area of each coastal habitat type assessed as having a 'very high' or 'high' vulnerability under the SSP2-4.5 and SSP5-8.5 emission scenarios by 2050 in each of the participating countries. These values represent the estimated percentage decline in area for each habitat type due to climate change. Blank cells indicate the country does not have that coastal habitat type.

Country	Coral reef		Mangrove		Seagrass	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
Cook Islands	5.37	6.09			0	0
FSM	1.01	1.15	4.80	5.43	56.51	64.00
Fiji	11.83	13.40	17.52	19.84	4.59	5.19
Kiribati	13.77	15.59	9.29	10.53	0	0
Marshall Islands	1.90	2.15	6.62	7.50	0	0
Nauru	44.15	50.00			0	0
Niue	16.56	18.75			0	0
Palau	0	0	2.01	2.27	0	0
Papua New Guinea	15.14	17.15	20.74	23.49	14.51	16.43
Samoa	77.60	87.88	36.19	40.98	88.30	100.00
Solomon Islands	9.11	10.32	3.53	4.00	0	0
Tonga	24.65	27.91	0	0	0	0

Tuvalu	0	0			0	0
Vanuatu	23.26	26.35	20.27	22.95	0	0

2.6 Habitats supporting tuna

This section reviews observed changes to the bio-physical features of the tropical Pacific Ocean and those that are projected to occur.[83]

Habitats supporting tuna occur across the vast area of the WCPO. Although much of this open ocean domain is relatively unproductive, it supports the largest tuna fisheries in the world (Chapter 1). The production of the four species of tuna, and other large pelagic fish, is underpinned by food webs based not only on the photosynthetic primary production of phytoplankton in the surface photic zone, but also by bacteria and detritus (also called 'marine snow'), derived from phytoplankton and dead animal remains.
Most of this primary production occurs where nutrients, such as nitrogen, phosphorus and silicon, are transported to surface waters from the deeper layers of the ocean by physical processes.[84] The energy produced through primary production moves through a 'trophic pyramid' via various zooplankton (such as copepods and larval fish), macro-zooplankton (including jellyfish and salps) and micronekton (such as squid, shrimp and small fish), to sustain tuna and other large pelagic fish (Figure 2.3).

The transfer of energy between each level in the trophic pyramid is generally only about 10% because: (i) there are energy losses through respiration and excretion at each stage; and (ii) the consumers in the next trophic level do not assimilate all available organic matter.[85] The various levels of the food web also contribute to the oceanic carbon sink by transferring carbon from the upper layers to the ocean depths through sinking of dead particles and the capture of prey from the photic zone by vertically migrating zooplankton and micronekton.

This process, referred to as the 'biological carbon pump', helps reduce the concentrations of CO_2 in the atmosphere.[86,87] The availability of the nutrients that underpin the food web for tuna, together with suitable water temperatures and dissolved oxygen levels, determine the distribution and abundance of tuna and other large oceanic fish across the WCPO.[88,89,90] Therefore, the responses of phytoplankton, zooplankton and micronekton to changes in the ocean processes that deliver nutrients to the photic zone, and to changes in the physical and chemical properties of the ocean projected to occur as a result of global warming and ocean acidification, are expected to affect all life stages of tuna and other large oceanic fish species.

All production of phytoplankton at the base of food webs for tuna and other large pelagic fish occurs in the photic zone, where there is sufficient light for photosynthesis. This primary production uses nutrients regenerated within the photic zone and 'new' nutrients transferred there from deeper water. Details of the regenerated and new nutrients made available for the primary production at the base of food webs are provided in **Appendix 2-E**.

Although primary production by phytoplankton is based on the uptake of inorganic compounds, all other parts of the food web rely on ingesting organic matter, a process known as 'heterotrophy'. This organic matter is consumed in solution by bacteria but is in the form of 'particles' when consumed by zooplankton and micronekton. The biomass of 'heterotrophic' organisms depends on the amount of organic matter produced by phytoplankton, either as dissolved compounds released by excretion or in a particulate form resulting from NPP. In general terms, therefore, the abundance and diversity of species in the food web of open ocean ecosystems relies primarily on the level of phytoplankton production.

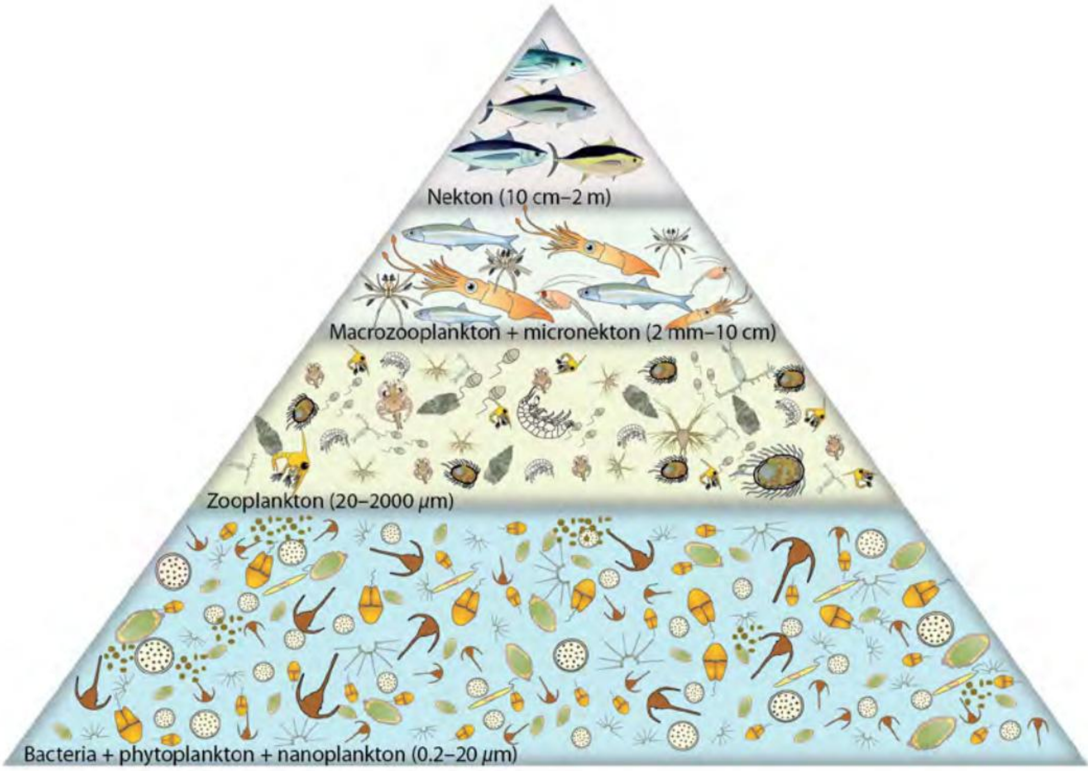


Figure 00.3 Generalized trophic pyramid for the tropical Pacific Ocean. The base of the food web consists of bacteria, small phytoplankton and protists (nanozooplankton), 0.2–20 μm in size. These organisms are ingested by zooplankton, such as crustaceans, molluscs or tuna larvae, up to a size of 2000 μm. In turn, zooplankton are consumed by macrozooplankton, such as jellyfish, and micronekton, such as squid, shrimp and small fish. Micronekton and, to a lesser extent, macrozooplankton are the prey for tuna and other large pelagic fish at the top of the pyramid (see **Appendix 2-E** for size ranges of these organisms).[91]

Observations have shown that production of small phytoplankton and bacteria are similar and that the production of phytoplankton is supplemented by production based on the contributions of heterotrophic bacteria and detritus (non-living particles). This resulted in the concept of the 'microbial loop,[92] which was originally pictured as a parallel model of trophic structure to the classical food web.[93] It is now recognized that the classical and microbial food webs are linked through processes of coagulation and the formation of 'marine snow', i.e. particles rich in microbes available to mesozooplankton grazers (Figure 2.4).[94]

The zooplankton that graze on phytoplankton and 'marine snow', and the micronekton that consume zooplankton are not distributed evenly in the water column. The main factors that determine their distribution are their swimming ability and the location of the nutrients supporting the phytoplankton on which they depend. Zooplankton and micronekton migrate towards the surface at dusk and to deeper water at dawn in search of food and to avoid predators.

This results in different biomasses of zooplankton and micronekton within the water column during the day and night. The larger the organisms, the greater the migrations, so that diel variations in the abundance of micronekton in the photic zone are greater than those of the zooplankton.[95] There is also a relationship between the minimum depth of the nutrient-rich water below the surface, i.e. the 'nutricline' associated with the thermocline,[96] and phytoplankton production and mesozooplankton biomass. For example, in the tropical western Pacific, both the production of phytoplankton and the biomass of mesozooplankton increase as the depth of the nutricline decreases (Figure 2.5). The proportion of mesozooplankton occurring within the first 100 m of the water column also increases as the nutricline depth decreases because there is greater new primary production when the nutricline is shallow. In addition, the depth of the nutricline also affects the diel vertical migrations of mesozooplankton (Figure 2.5). When the nutricline is deep, causing more oligotrophic conditions in surface waters, the vertical night-time movements of mesozooplankton increase, indicating that coupling between mesozooplankton and surface phytoplankton biomass is reduced in such places. Finally, the percentage contribution of small zooplankton (microzooplankton) is greater in oligotrophic areas, where the nutricline is deep.[97]

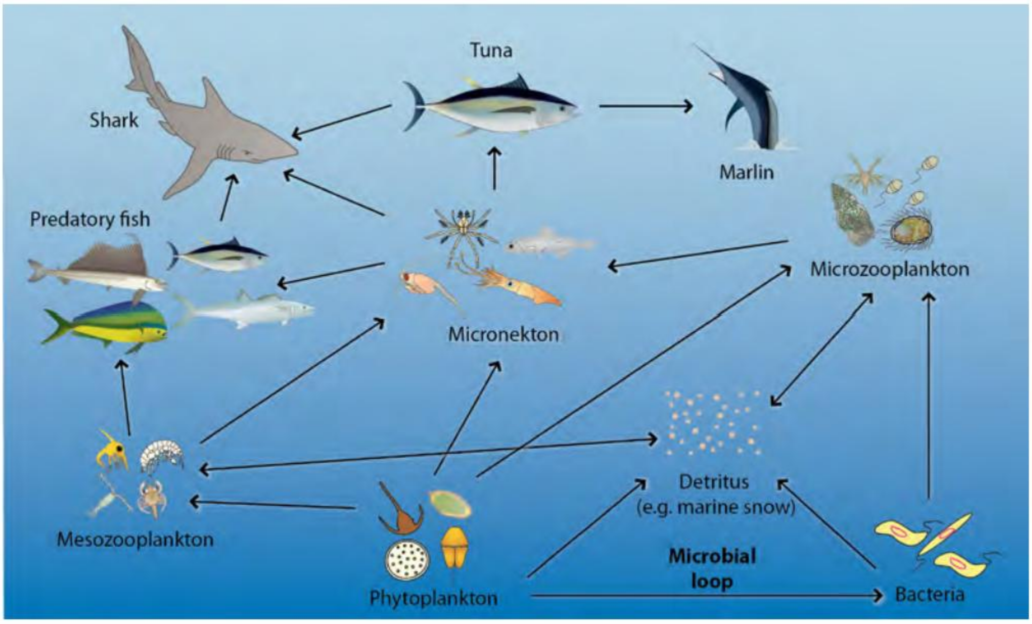


Figure 00.4 Generalised food web supporting tuna and other large pelagic fish. Note that in the lower levels of the food web, the classical and microbial pathways are linked through formation of 'marine snow' and other detritus.

The opposite is true for the larger mesozooplankton (500–2000 µm) (Figure 2.5). The deep and dark ocean below the photic zone follows different rules.[98] Deep currents may have different directions to those at the surface, and vertical hydrological gradients are generally weaker, making exchanges easier between water masses. Nevertheless, the photic zone and deep ocean ecosystems are inter-related – organisms living at depth need to get their energy from the photic layer by vertical migrations, or by heterotrophic processes based on sinking particles, or from other organisms of the deep ocean. Even so, non-migrating species living below the photic zone at all times represent more than half of the micronekton biomass.[99]

The most important part of oceanic food webs from a fisheries perspective – the link between micronekton and tuna – is still quite poorly understood. Several studies on the feeding ecology of tuna[100,101,102,103] have shown that their diets consist mainly of small fish, squid and crustaceans. The proportions of these three categories of micronekton vary within and between tuna species, and among life history stages, regions, time of the year and the depth preferences of the fish.[104,105,106,107]

2.6.1 Ecological provinces in the WCPO

The processes described above occur to different extents within the WCPO depending on location. These locations have been described as 'ecological provinces'. The five ecological provinces in the Pacific Island area of the tropical Pacific Ocean are: the Pacific Equatorial Divergence (PEQD), the Western Pacific Warm Pool (Warm Pool), the North Pacific Tropical Gyre (NPTG), the South Pacific Subtropical Gyre (SPSG) and the Archipelagic Deep Basins (ARCH) (Figure 2.6). The borders of these provinces are generally defined by convergence zones of surface currents, and each province has a specific wind regime and vertical hydrological structure.

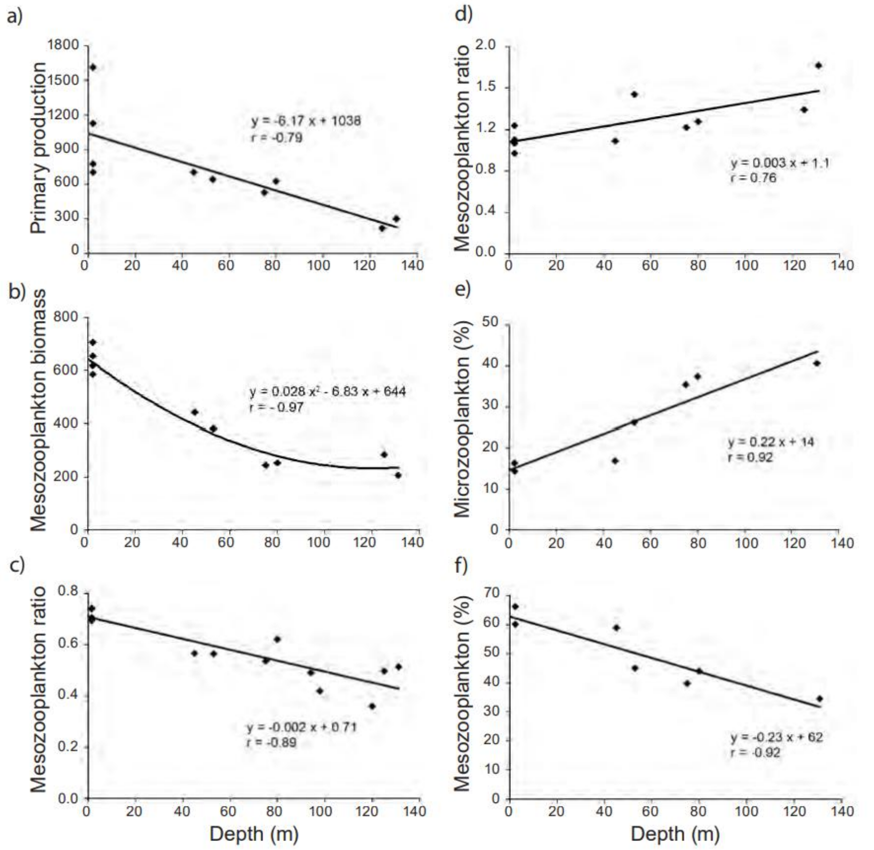


Figure 00.5 Depth of nutricline and mesoplankton features. The relationships between minimum depth of the nutricline (defined as NO_3 = 0.1 µM) and (a) primary production (mg C per m^2 per day); (b) mesozooplankton biomass (0–200 m, mg C per m^2); (c) vertical distribution of mesozooplankton (0–100 m: 0–500 m ratio); (d) diel variation in biomass of mesozooplankton within the upper 200 m of the water column (night:day ratio); (e) microzooplankton (35–200 µm) as a percentage of total zooplankton biomass; and (f) large mesozooplankton (500–2000 µm) as a percentage of total zooplankton biomass, in the WCPO. Data are from 7-day long time-series stations in the tropical Pacific.[108]

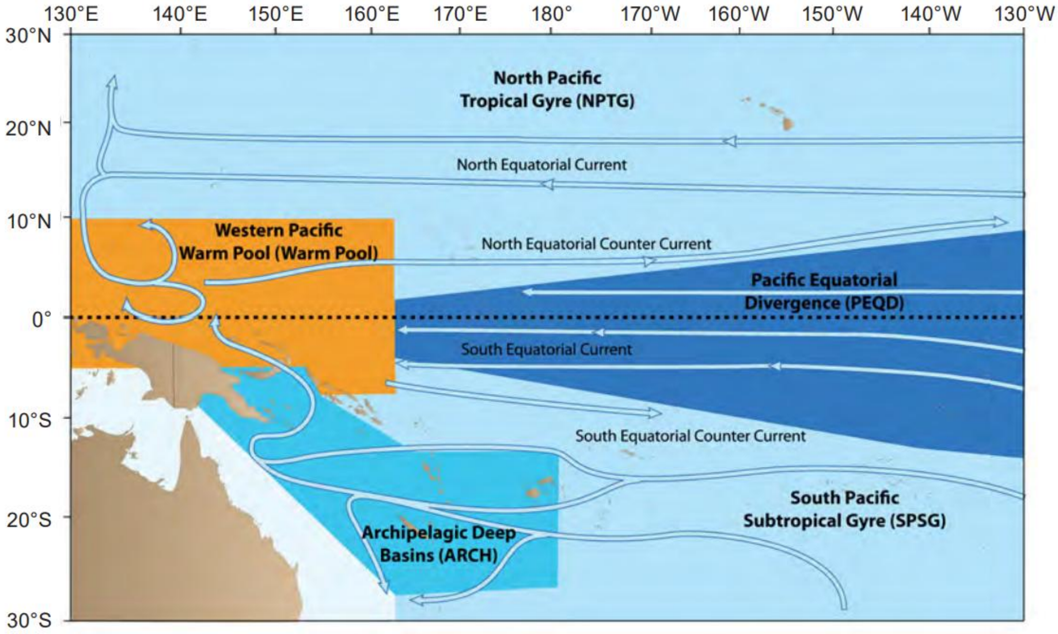


Figure 00.6 The five ecological provinces of the tropical Pacific Ocean [109] together with the major ocean currents of the region.

The locations of the PEDP and the Warm Pool can change dramatically from year to year, depending on the prevailing ENSO conditions, which alter the extent of upwelling in the eastern and central equatorial Pacific Ocean and the nitrate concentrations of the surface waters.[110] The ARCH is characterised by the occurrence of many archipelagos and seamounts. It is a patchwork of processes, on a variety of spatial scales, with varied vertical structures, driven by the way the landmasses divert surface currents and create eddies.[111] This province also receives nutrients due to runoff from the high islands located there.

The vertical hydrological structure and associated physical processes of each province have a profound effect on the phytoplankton productivity available to supply the base of the food web. In particular, the features of each province mediate access to the new nutrients needed for primary production. Although regenerated nutrients also contribute to the growth of phytoplankton, the amount of new production is determined by inputs of nutrients from deep water to the photic zone and varies among provinces, in line with the well-known correlation between primary production and the depth of the nutricline.[112] The biophysical features of each province are described below.

2.6.1.1 Pacific Equatorial Divergence

The Pacific Equatorial Divergence (PEQD) is generated by the effects of the earth's rotation (Coriolis force) on the South Equatorial Current (SEC) in the two hemispheres.[113] As a result of this divergence, there is significant upwelling of new nutrients from below the photic zone, creating the richest surface waters in the tropical Pacific Ocean.

The waters of PEQD are characterized by higher salinity, higher nutrient concentrations and phytoplankton abundance (chlorophyll a). These nutrient-rich waters span much of the equatorial Pacific Ocean and drift polewards before submerging at the convergence with the North Equatorial Counter Current (NECC) (ca. 5°N) and the South Equatorial Counter Current (SECC) (ca. 6°S–8°S) (Figure 2.7).

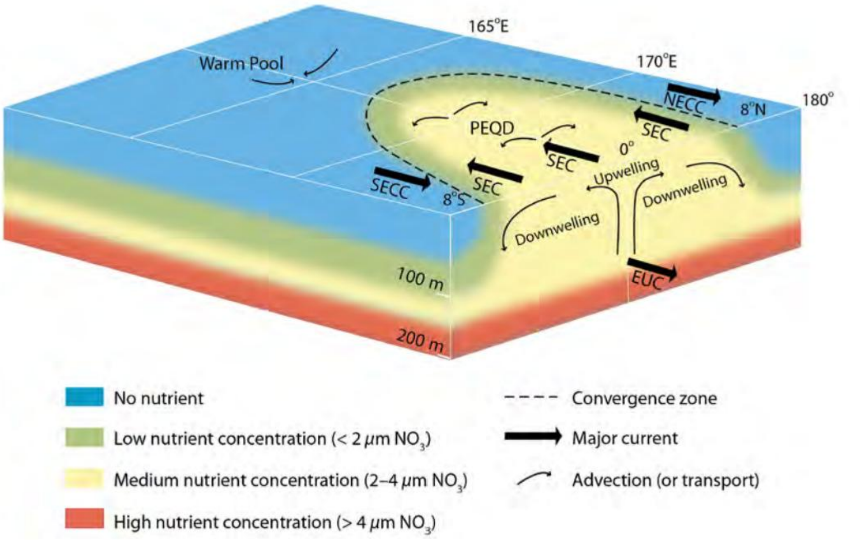


Figure 00.7 Upwelling in Pacific Equatorial Divergence (PEQD) province. Nutrient-rich waters are brought to the surface from the Equatorial Undercurrent (EUC) and carried to the north and south by upwelling. Eventually, they plunge at the convergences between the South Equatorial Current (SEC) and South Equatorial Counter Current (SECC), and with the SEC and the North Equatorial Counter Current (NECC). The SEC also carries the upwelled waters to the west until they converge with the Warm Pool, at a salinity front, a region with distinct concentrations of dissolved carbon dioxide, nutrients and phytoplankton. Based on satellite images and data from the EBENE cruise along 180° in 1996.[114]

At these convergences, particulate organic matter sinks and is remineralized, leading to low levels of dissolved oxygen. Ironically, although the macronutrients (nitrate, SRP and silicate) available in PEQD exceed those needed for prolific growth of phytoplankton, primary production in this province is limited by low concentrations of iron. The iron in PEQD is derived from Papua New Guinea and is delivered by the eastward flowing New Guinea Coastal Undercurrent,[115] and the Equatorial Undercurrent (EUC), and possibly from thermal vents and atmospheric dust.[116] However, the quantities are insufficient to enable all the macronutrients in PEQD to be used by phytoplankton. Consequently, PEQD acts like a buffer; regardless of the level of macronutrients, phytoplankton biomass remains relatively constant because the large reservoir of nutrients enables primary productivity to continue for several months, if nutrients inputs are temporarily reduced for climate-related reasons.[117,118]

The surface waters of PEQD drift to the west until they converge with the Warm Pool (Figure 2.7). The border between PEQD and the Warm Pool is marked by a clear 'front' in salinity, pCO_2, chlorophyll a and zooplankton.[119] The convergence zone between PEQD and the Warm Pool changes due to variation in the strength and longitudinal extension of the SEC between seasons and among years, in response to ENSO events.[120] During strong La Niña episodes, the front reaches the far western side of the equatorial Pacific, causing a great reduction in the size of the Warm Pool. During El Niño events, the front moves to the east and may reach the Galapagos Islands, causing PEQD to disappear.[121] Such fluctuations of the surface area of PEQD and the Warm Pool can be seen by ocean colour imagery[122] and predicted from climatic indices, such as the Southern Oscillation Index (SOI).[123]

2.6.1.2 Western Pacific Warm Pool

In contrast to PEQD, the surface waters of the Warm Pool have a significantly lower salinity due to high rainfall,[124] and are nutrient-depleted because there is no upwelling in this province. The thermocline in the Warm Pool is relatively deep (~ 80 m) under average climatic conditions, being located close to the lower limit of the photic zone. The thermocline has a strong temperature gradient, which forms a considerable barrier to the transfer of nutrients to the surface layer.[125] This situation changes markedly during El Niño episodes, when there is a shoaling of the thermocline to a depth of ~ 40 m. When this occurs, there is an increase in primary production, stimulated by the supply of more new nutrients to the photic zone below the thermocline. Despite the fact that the Warm Pool is low in nutrients, the greatest catches of skipjack and yellowfin tuna are often made in this part of the region.[126]

2.6.1.3 North Pacific Tropical Gyre and South Pacific Subtropical Gyre

On both sides of the equatorial band, the large atmospheric anticyclones in the northern and southern subtropical Pacific generate oceanic gyres. The provinces covered by these large gyres are known as the North Pacific Tropical Gyre (NPTG) (also known as the North Pacific Subtropical Gyre) and the South Pacific Subtropical Gyre (SPSG). They are characterized by a very deep but weak thermocline, which allows some nutrient inputs to the photic zone from deep water through mixing and diffusion. However, during summer, a strong and shallower (40–60 m) thermocline is superimposed on the main thermocline, due to the increase in solar radiation, creating a barrier to nutrient inputs.[127] This leads to lower primary production in the upper photic zone in summer compared with the rest of the year.[128]

2.6.1.4 Archipelagic deep basins

This province is characterized by many islands and shallow seamounts which alternate with oceanic basins.[129], where availability of nutrients from runoff can be significant in the vicinity of high islands. In addition, current regimes are more complex due to the way islands, archipelagos or seamounts divert oceanic circulation through a range of mesoscale processes, including upwelling or downwelling, cyclonic or anticyclonic eddies in the lee of the islands, frontal zones and an increase of amplitude in internal waves.[130] The result is that ARCH is a mosaic of surface waters with different characteristics, in contrast to the other provinces, which are generally dominated by more stable large-scale processes.

2.6.2 Differences in structure and variability of food webs among ecological provinces

The structure of food webs for tuna differs among the five ecological provinces based on their biophysical attributes. These differences are illustrated in Figure 2.8. Some simple comparisons help to highlight the main differences. The ratio of phytoplankton biomass to mesozooplankton biomass is an indicator of the complexity of a food web; food webs based on large phytoplankton supported by 'new' nutrients have fewer trophic links because the herbivores that feed on this phytoplankton are larger. There is a direct link, or only one intermediate trophic link, between phytoplankton and mesozooplankton. As a result, the ratio between the biomass of phytoplankton and zooplankton is rather low. This ratio varies from 4.1 in PEQD, to 7.4 in the Warm Pool and to 9.7 for the gyres, indicating the existence of more trophic links between phytoplankton and mesozooplankton in the oligotrophic ecosystems (Warm Pool and gyres) than in PEQD. The ratio varies greatly within ARCH. In short, a greater biomass of phytoplankton is needed for a given mesozooplankton biomass in oligotrophic systems.[131]

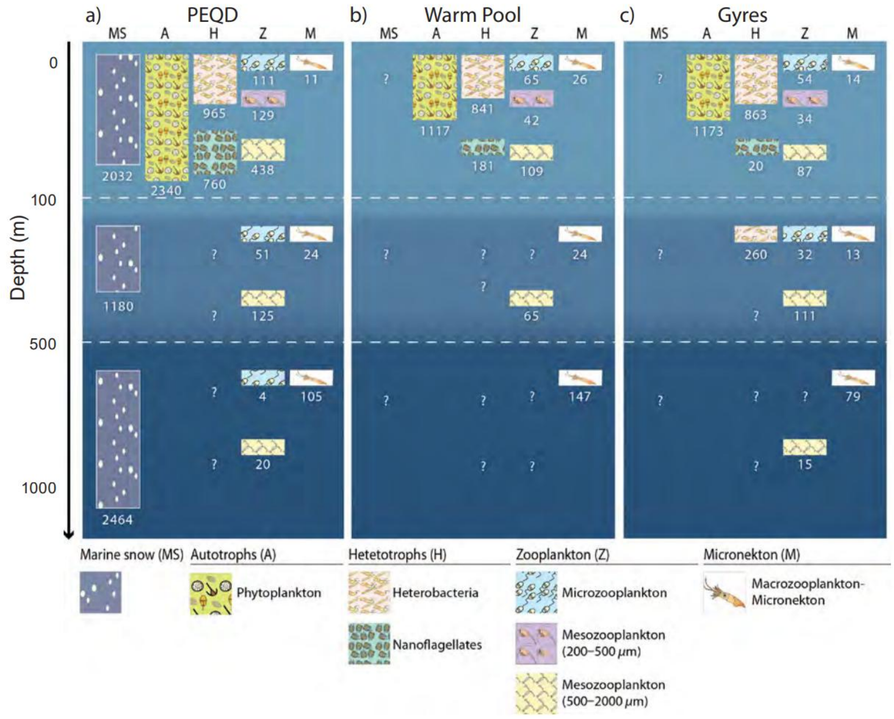


Figure 00.8 Structure of the food webs in: (a) the Pacific Equatorial Divergence province (PEQD) along the equator; (b) the Warm Pool along the equator; and (c) the North Pacific Tropical Gyre and South Pacific Subtropical Gyre. Boxes and the figure below them indicate the mean daily biomass of the different components of the ecosystem (in mg carbon per m²), i.e., taking diel vertical migrations into account. The mesozooplankton biomass below the photic zone (100 m) refers to the sum of the two size fractions (200–500 and 500–2000 µm). ? = no data available.[132]

Comparisons between the deep and surface layers also help to distinguish the food webs from different provinces. For example, the biomass of mesozooplankton down to a depth of 1000 m in PEQD is 3.3 times greater than in the gyres, and the biomass of micronekton is 1.9 times greater. The reason is that most of the mesozooplankton is closely linked to the photic zone in PEQD, whereas part of the micronekton lives permanently at a depth of 500 to 1000 m and depends on different trophic pathways. Thus, only 16% of the micronekton biomass within the depth range 0 to 1000 m is in the photic zone at night in PEQD,[133] whereas 40% occurs there in the gyres,[134] 44% in ARCH[135] and 50% in the Warm Pool.[136]

The taxonomic composition of micronekton is relatively consistent among provinces and includes fish, squid and carid, sergestid, penaeid and euphausiid shrimps. However, the ratio between micronekton biomass and mesozooplankton differs considerably among provinces, based partly on variation in the complexity of their food webs and the amount of micronekton and mesozooplankton derived from a given biomass of phytoplankton.[137]Additional information on the structure and variability of food webs among provinces is given in Appendix 2-F.

2.6.3 Projected changes to the ecological provinces supporting tuna

2.6.3.1 Biophysical features

The projected effects of climate change on the surface areas of provinces under a high (A2) and low (B1) emission scenario (Appendix 2-A) show three main trends.[138] First, there is expected be a reduction of the area of PEQD as its western border is displaced eastward. A reduction of 20–27% in surface area is expected by 2035, with the western edge of the province moving from 180° to 170°W. A 30% shrinkage of the province is projected to occur under B1 and a 50% decrease under A2 by 2100, with the western edge lying between 160°W and 150°W (Figure 2.9, Table 2.5). Second, there is projected to be a corresponding increase in the area of the Warm Pool, which is expected to expand by 18–21% in 2035 and by 26% and 48% under B1 and A2, respectively, by 2100 (Figure 2.9, Table 2.5). Third, the gyres are expected to expand towards the poles and to the west (Figure 2.9, Table 2.5). This expansion is likely to be greater for SPSG, where the oligotrophic waters are expected to increase by 4–7% in 2035, and up to 14% for the A2 scenario by 2100 (Figure 2.9, Table 2.5). No change in the area of ARCH is expected, by definition.

For all provinces, the average mixed layer depth (MLD) is projected to decrease by <10% for both scenarios in 2035 and 2100 except for PEQD (Table 2.5). The decreases in MLD in the Warm Pool are expected to have little effect on the supply of nutrients to the photic zone due to the strong gradient of the thermocline there. However, for the gyres, a decreasing MLD is expected to reduce nutrient inputs into the photic zone, because the gradient gets stronger as it usually occurs during summer. In PEQD, the greater decreases in MLD projected to occur by 2100 (Table 2.5) are not expected to affect primary production because nitrate concentrations there, due to upwelling, are still likely to exceed levels at which the supply of iron presently limits the growth of phytoplankton.[139]

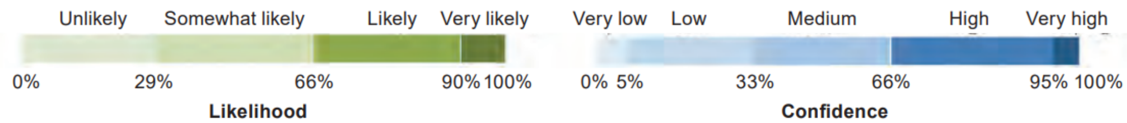
The modelling showed ubiquitous warming of the region (Table 2.5), which is expected to increase stratification and inhibit the supply of nutrients to the surface in oligotrophic provinces. Although the greatest warming is projected to occur in the non-upwelling areas of the equatorial Pacific, the enhanced warming of the equatorial region in general is expected to reduce the upwelling of deep, nutrient-rich water, contributing to the contraction of PEQD. This contraction is most pronounced in the A2 scenario (Figure 2.9**Figure 00.9** Projected changes in surface areas of the five ecological provinces in the tropical Pacific Ocean under the B1 and A2 emissions scenarios for 2035 and 2100, relative to present conditions) and helps explain why NPP is expected to decrease across the entire equatorial Pacific by 2100 under high emissions of CO_2.[140] Dissolved oxygen (O_2) is projected to decrease by up to 26% in PEQD to a depth of 300 m by 2100 under the A2 scenario, and increase by 7–8% in NPTG by 2100 under the B1 and A2 scenarios (Table 2.5). Elsewhere, changes to O_2 at 300 m are minor and, in all provinces except PEQD, percentage saturation of O_2 is expected to be 50–75%. In PEQD, however, it is projected to drop to 22–28%.

Few differences in the effects of ocean acidification are expected among provinces measured using Omega aragonite (Ω aragonite).[141] Depending on the emissions scenario, the projected decrease of Ω aragonite ranges between 8% and 35% (Table 2.5), which corresponds to a diminution in calcification rates of 2–9% for corals.[142] For pelagic organisms like haptophytes, the response to ocean acidification is less clear[143,144] with responses ranging from increased growth and calcification[145] to moderate decrease in growth and calcification.

Table 0.5 Projected effects of the B1 and A2 emissions scenarios for 2035 and 2100 on the main physical, chemical and biological features of the five ecological provinces in the tropical Pacific Ocean (based on the IPSL/PISCES model). Values are percentage changes relative to present values (2000–2010). Numbers in brackets refer to actual projected changes in SST (°C); actual projected MLD (m); actual projected percentage saturation of O_2 at a depth of 300 m; and actual projected aragonite saturation state (Ω, no unit). Likelihood and confidence values for each projection can be estimated for each cell in the table by combining the likelihood values for scenarios and the confidence values for features of the province.[146]

Province	Year	Scenario	Feature of Province						
			Area	SST	MLD	O_2	Ω aragonite	NPP	ZooBiomass
PEQD	2035	B1	-20	+1 (0.3)	-5 (24)	-8 (26)	-10 (3.43)	0	-2
		A2	-27	+2 (0.5)	-9 (24)	-12 (26)	-9 (3.51)	0	-2
	2100	B1	-30	+3 (0.9)	-12 (23)	-5 (28)	-15 (3.24)	+2	-3
		A2	-50	+6 (1.6)	-26 (19)	-26 (22)	-35 (2.49)	+4	-6
Warm Pool	2035	B1	+18	+1 (0.4)	+3 (32)	0 (50)	-8 (3.82)	-7	-6
		A2	+21	+2 (0.5)	-5 (27)	-2 (49)	-10 (3.74)	-5	-3
	2100	B1	+26	+4 (1.2)	0 (30)	0 (50)	-17 (3.46)	-9	-9
		A2	+48	+7 (2.3)	-5 (29)	-2 (49)	-33 (2.79)	-9	-10
NPTG	2035	B1	+1	+1 (0.0)	-2 (37)	+1 (61)	-8 (3.57)	-3	-3
		A2	+1	+1 (0.4)	-3 (36)	+3 (60)	-11 (3.66)	-5	-4
	2100	B1	+1	+5 (1.3)	-1 (37)	+7 (63)	-18 (3.27)	-11	-10
		A2	+1	+9 (2.4)	-3 (36)	+8 (64)	-33 (2.66)	-22	-18
SPSG	2035	B1	+4	+2 (0.5)	0 (40)	-2 (66)	-8 (3.69)	-3	-3
		A2	+7	+2 (0.5)	-5 (38)	-4 (65)	-11 (3.60)	-5	-4
	2100	B1	+7	+4 (1.1)	0 (40)	-2 (66)	-18 (3.32)	-3	-5
		A2	+14	+8 (2.1)	-6 (39)	-4 (64)	-34 (2.65)	-6	-10
ARCH	2035	B1	0	+2 (0.5)	-3 (38)	-1 (75)	-9 (3.77)	-5	-5
		A2	0	+2 (0.5)	-3 (37)	-3 (74)	-12 (3.69)	-8	-6
	2100	B1	0	+5 (1.3)	-7 (36)	-1 (75)	-18 (3.38)	-20	-17
		A2	0	+9 (2.4)	-9 (35)	-1 (75)	-35 (2.70)	-33	-26

Area = surface area of the province; SST = sea surface temperature; MLD = mixed layer depth; O_2 = dissolved oxygen at a depth of 300 m; Ω aragonite = Omega aragonite; NPP = net primary production; ZooBiomass = zooplankton biomass; PEQD = Pacific Equatorial Divergence; Warm Pool = Western Pacific Warm Pool; NPTG = North Pacific Tropical Gyre; SPSG = South Pacific Subtropical Gyre; ARCH = Archipelagic Deep Basins.



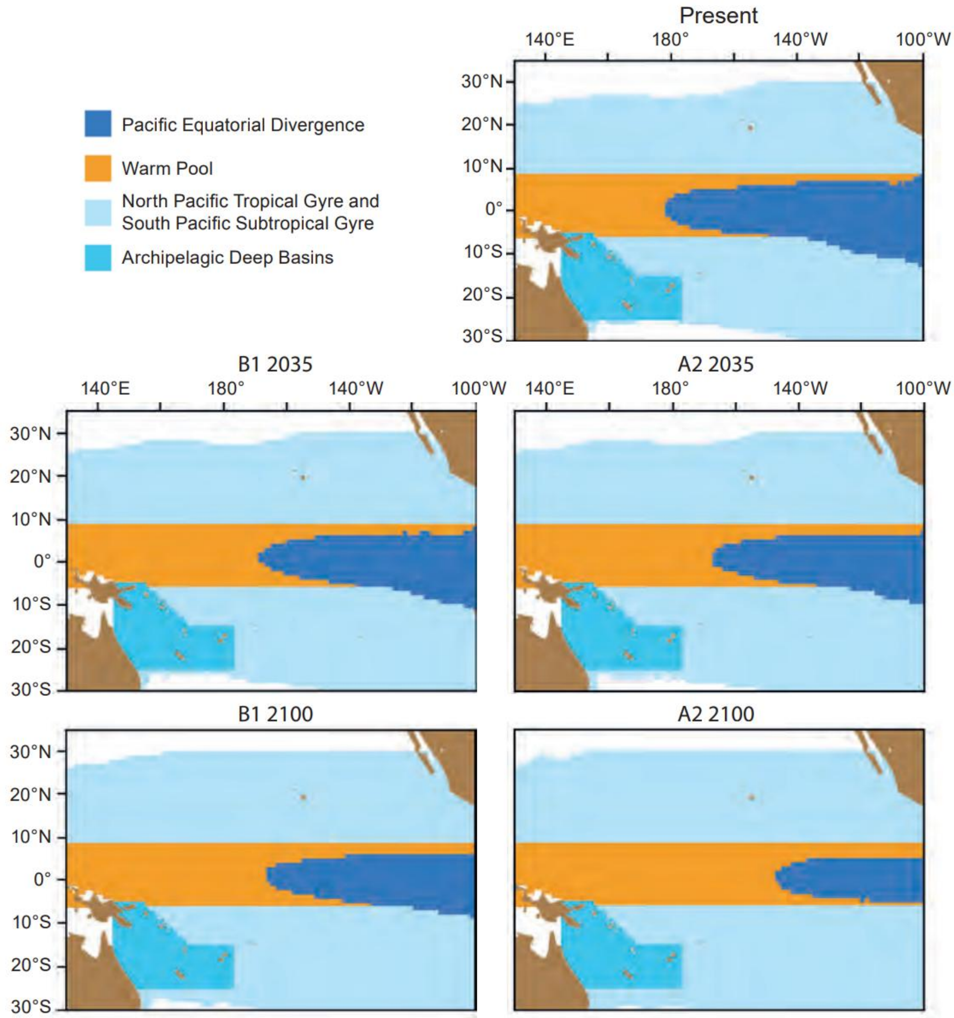


Figure 00.9 Projected changes in surface areas of the five ecological provinces in the tropical Pacific Ocean under the B1 and A2 emissions scenarios for 2035 and 2100, relative to present conditions.

2.6.3.2 Food webs

The vulnerability of food webs for tuna and other large pelagic fish in each province was evaluated during SPC's initial assessment of the vulnerability of tropical Pacific fisheries and aquaculture to climate change using the framework recommended by the Intergovernmental Panel for Climate Change.[147,148] This framework is based on: (i) changes in the key physical and chemical features of the environment; (ii) the sensitivity of all levels in the food web to this exposure; (iii) the potential impact of this exposure and sensitivity; and (iv) the capacity of the organisms to adapt to these changes and reduce the potential impact.[149] The vulnerability of food webs in each province to changes in water temperature, mixed layer depth, nutrient inputs to the photic zone, solar and ultraviolet radiation, dissolved oxygen and ocean acidification based on the IPCC framework and the modelling described in Chapter 4 of SPC's vulnerability assessment.[150] The vulnerability of the food web in each province to increased GHG emissions is summarised below and described in more detail in **Appendix 2-F**.

The food web in PEQD is expected to have a moderate vulnerability to the increases in GHG emissions in 2035, and a high vulnerability by 2100 (Table 2.6). This is due mainly to substantial decreases (20–50%) in the size of this important province (Table 2.6), and its relocation further east. Changes to net primary production (NPP) and the biomass of zooplankton in the food webs for tuna themselves within the more limited PEQD are expected to be slight (Table 2.6).[151]

The possible implications for tuna include an overall reduction in the quantity of forage previously available in PEQD, and relocation of the main feeding area for tuna (the convergence zone between PEQD and the Warm Pool) further to the east. Similar changes already occur regularly due to El Niño events, and the effects of projected changes to PEQD can be expected to mimic those due to ENSO closely.[152]

The food web in the Warm Pool is also expected to have a moderate vulnerability under the B1 and A2 scenarios in 2035, and a high vulnerability in 2100 (Table 2.6). This is also driven mainly by the substantial projected changes to its surface area (Table 2.6), which resemble the effects of El Niño on this province. However, an important difference is that, whereas the nutricline in the Warm Pool becomes shallower during El Niño episodes and increases nutrient supply to the photic zone and NPP, the projections under global warming show a deepening of the nutricline. Such deepening is expected to lead to reductions of up to ~ 10% in NPP (integrated throughout the water column) and zooplankton biomass by 2100 in the Warm Pool (Table 2.6).[153]

The projected reduction in NPP in the Warm Pool is a possible threat to the production of tuna because it presents a markedly different situation than the one that presently appears to operate towards the end of an El Niño event, when the increased NPP from a shoaling of the nutricline appears to trigger the movement of tuna westwards.[154] Taken together, the projected reduction in the area of PEQD, and the expansion of the nutrient-poor Warm Pool, will result in a more oligotrophic equatorial Pacific Ocean.[155]

The food web in SPSG is expected to have a low vulnerability in 2035 due to the limited expansion in area and decreased NPP and zooplankton biomass projected to occur by that time (Table 2.6). However, continuation of these trends will result in the vulnerability increasing to low-moderate by 2100 (Table 2.6).[156]

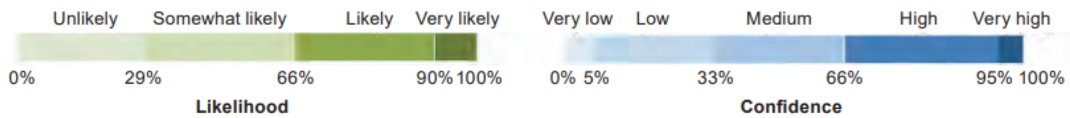
The vulnerability of the food webs in NPTG is considered to be low in 2035 (Table 2.6) due to negligible changes in surface area and only modest changes in NPP and zooplankton biomass. However, vulnerability is expected to be moderate by 2100 under both the B1 and A2 scenarios because NPP is projected to decrease by 11–22% and the biomass of zooplankton is expected to decline by 10–18%. In both gyres, the biophysical modelling indicates that the projected decreases in NPP and zooplankton biomass are expected to be concentrated at the poleward extremes of these provinces.

In ARCH, the main effects of global warming are projected to decrease the availability of nutrients through variations in the depth of the mixed layer and the incursion of more oligotrophic water from SPSG. As a result of these limited changes, the food web for tuna in ARCH is expected to have a low vulnerability in 2035 under both the B1 and A2 emissions scenarios (Table 2.6). By 2100, ARCH is expected to have a moderate vulnerability because NPP and the biomass of zooplankton are projected to decline due to greater expansion of nutrient-poor water from SPSG.

Table 00.6 Integrated vulnerability assessments for each of the five ecological provinces in the tropical Pacific Ocean for 2035 and 2100 for the B1 and A2 scenarios combined[157]

Province	Year	Vulnerability	Projected changes
PEQD	2035	Moderate	Decrease in surface area of 20–27% as western boundary of PEQD moves eastwards from 180° to 170°W. Minor (2%) reduction in zooplankton biomass. No direct effect of higher SST, and lower O_2 and pH, on biomass or composition of plankton.
	2100	High	Decreases in surface area of 30–50% and movement of boundary to 160–150°W. A 2–4% increase in NPP and 3–6% decrease in biomass of zooplankton. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.
Warm Pool	2035	Moderate	Increase in surface area eastwards by 18–21%, with a 5–7% reduction in NPP and 3–6% decrease in biomass of zooplankton throughout the water column. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.
	2100	High	Increase in surface area eastwards by 26–48%, with a 9% reduction in NPP and 9–10% decrease in biomass of zooplankton throughout the water column. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.
NPTG	2035	Low	Surface area increases limited to 1% as the province extends to the north. NPP decreases by 3–5% and zooplankton biomass declines by 3 to 4%. No direct effect of higher SST and O_2, or lower pH, on biomass or species composition of plankton.
	2100	Moderate	Increase in surface area stabilises at an increase of 1% but NPP decreases greatly (11–22%) and biomass of zooplankton declines by 10–18%. No direct effect of higher SST and O_2, or lower pH, on biomass or species composition of plankton.
SPSG	2035	Low	Surface area increases by 3–7%. NPP decreases by 4–5% and biomass of zooplankton declines by 3–4%. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.
	2100	Low-Moderate	Surface area increases by 7–14% and extends poleward, with a 3–6% reduction in NPP and 5–10% decrease in biomass of zooplankton due to deepening of the thermocline. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.
ARCH	2035	Low	No change in surface area. A reduction in NPP of 5–8% and a 5–6% decrease in biomass of zooplankton due to deepening of the thermocline. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.
	2100	Moderate	No change in surface area. Greater (20–33%) reduction in NPP and a 17–26% decrease in biomass of zooplankton due to deepening of the thermocline. No direct effect of higher SST, and lower O_2 and pH, on biomass or species composition of plankton.

SST = sea surface temperature; O_2 = dissolved oxygen percentage saturation at 300 m; PEQD = Pacific Equatorial Divergence; Warm Pool = Western Pacific Warm Pool; NPTG = North Pacific Tropical Gyre; SPSG = South Pacific Subtropical Gyre; ARCH = Archipelagic Deep Basins.



2.7 Vulnerability of communities to declines in coastal fisheries production

The importance of assessing the vulnerability of coastal communities to the projected effects of changes to coastal fish habitats and the tropical Pacific Ocean is the linked to the extraordinary dependence that Pacific Island people have traditionally had on fish for food security (Chapter 1, Section 6.2). Across the region, annual national fish consumption per capita ranges up to five times the global average, and fish traditionally caught from coral reefs and other coastal habitats by small-scale fisheries provide 50–90% of dietary animal protein for coastal communities.[158]

Plans have been put in place to maintain the important contribution of fish to nutrition across the region, including through the food security goals of the *Regional Roadmap for Sustainable Pacific Fisheries*.[159] Challenges facing these plans include 1) the effects of rapid human population growth on the amount of fish available per person from sustainable coastal fisheries, which has created a gap in the supply of fish needed for good nutrition in many of the participating countries, and 2) climate-driven degradation of coastal fish habitats and changes to the tropical Pacific Ocean, which are projected to reduce the productivity of coastal fisheries, exacerbating the gap in fish supply.

The projected impacts of climate change on the coastal fisheries production that has underpinned food security in all participating countries for generations were assessed using methods that combined the indirect and direct effects of GHG emissions on fish assemblages in coastal waters. Indirect effects refer to the expected impact of coastal fish habitats degraded by climate change (Section 2.4) on the recruitment, growth and survival of associated fish and invertebrate species. The direct effects refer to the changes in fish production expected to occur through alterations to the tropical Pacific Ocean (Section 2.3) that affect the physiology of animals, and therefore also influence the recruitment, growth and survival of coastal fish and invertebrate species. Details of the indirect and direct effects of increased GHG emissions on the production of coastal fisheries species are provided in **Appendix 2-G.**

Assessments of the impacts of climate change on coastal fisheries production were made for a high emissions scenario in 2030 approximating SSP5-8.5, and for the moderate SSP2-4.5 and high SSP5-8.5 emissions scenarios in 2050. These methods used for these assessments are described in detail in **Technical Study 1**. For 2030, the assessment was based on the use of expert opinion, as done for SPC's initial vulnerability assessment,[160] rather than using modelling due to the greater levels of uncertainty associated with model projections over such a relatively short timeframe. For 2050, the assessment encompassed evaluating the effects of the two emission scenarios on 1) the habitats supporting coastal fisheries; 2) the biomass of coastal fisheries species; and 3) the catch of coastal fisheries species available for human consumption using the suite of models from the Fisheries and Marine Ecosystem Model Intercomparison Project, FishMIP.[161]

To estimate the gap in fish supply recommended for good nutrition of the target communities in each country, the projected coastal fish catch in each of the 14 countries in 2030 under a high emissions scenario, and in 2050 under both emission scenarios, was converted to fish availability per capita in kg/person per year. This was done by dividing the total projected catch under each emissions scenario by the predicted coastal population in 2030 and 2050, calculated using the percentage of the total population living within 5 km of the coast[162] and applying it to the 2030 and 2050 national population estimates.[163] The availability of fish per capita was then compared with the minimum annual consumption rate (kg) of fish per person needed to provide the protein required for good nutrition in each country from **Technical Study 2** to estimate the shortfall/surplus of coastal fish available to meet the dietary requirements of the population in 2030 and 2050 under the respective emission scenarios.

2.7.1 Vulnerability of contribution of coastal fish to food security by 2030

The expected availability of coastal fisheries production for domestic consumption in each of the 14 countries participating in the GCF Programme in 2030 is summarised in Table 2.7.

Table 2.7 Estimated availability of coastal fisheries catch in 2030 under an SSP5-8.5 equivalent emissions scenario for each Pacific Island country participating in the Programme. This analysis combines the expected effects of increased GHG emissions on the three categories of coastal fisheries. The percentage contribution of each category to total estimated catch in 2030 is also provided (source: Technical Study 1).

Country	Projected catch (tonnes) in 2030						
	Demersal fish[1]	%	Nearshore pelagic fish[2]	%	Invertebrates[3]	%	Total coastal fisheries
Melanesia							
Fiji	16,839	64	5,270	20	4,180	16	26,289
PNG	14,012	40	13,760	39	7,420	21	35,192
Solomon Is	8,613	48	5,750	32	3,575	20	17,938
Vanuatu	1,669	50	753	23	885	27	3,307
Micronesia							
FSM	6,070	49	3,560	29	2,750	22	12,380
Kiribati	14,547	72	4,250	21	1,375	7	20,172
Marshall Is	2,332	64	1,080	29	253	7	3,665
Nauru	299	47	310	49	30	5	639
Palau	917	44	680	33	485	23	2,082
Polynesia							
Cook Is	141	36	240	61	14	4	395
Niue	60	40	75	51	13	9	148
Samoa	4,264	50	2,550	30	1,655	20	8,469
Tonga	5,061	80	650	10	605	10	6,316
Tuvalu	808	68	326	27	52	4	1,186
Total	**75,633**	**55**	**39,254**	**28**	**23,292**	**17**	**138,179**

1.Calculated as estimated catch in 2007, reduced by 3.5% (mid-range of projected 2% to 5% decrease by 2035 relative to 2000–2010 under a high emissions scenario); 2. No change to estimated catch in 2007 because even though there may be some decreases in NSP catch by 2030 relative to 2007, the estimated tuna biomass in the exclusive economic zone of each country is expected to be high enough to maintain catches at 2007 levels; 3. No change to estimated catch in 2007 because catch is dominated by intertidal and shallow subtidal species expected be affected negligibly by a high emissions scenario by 2035.

The gap/surplus in fish supply required for good nutrition of the national population in each participating country by 2030 under continued high GHG emissions, is summarised in Table 2.8.

On the basis of the analysis summarised in Table 2.8, eight of the participating countries fall into the category where coastal fisheries production by 2030 will not have the capacity to provide the fish needed for good nutrition of the national population. The remaining six countries have a surplus of fish capable of providing the recommended protein intake in principal but in all cases these countries face severe problems in economically distributing enough of the coastal fisheries catch from its source to meet dietary requirements in areas with relatively high population density. Thus, these six countries fall into the same category as the other eight countries with respect to priority adaptations – increasing access to tuna through the use of FADs (Technical Study 3) and improving the supply of tuna and bycatch from the transhipping and unloading activities of industrial fishing operations (where these activities occur) (Technical Study 5) are needed to increase fish supply.

Table 2.8 Gap/surplus in fish supply (kg whole weight) required to provide the national population in each participating country (except Papua New Guinea) with 50% of their recommended intake of dietary protein in 2030.

Country	National population 2030	Coastal fish catch per year (t) 2030	Coastal fish catch per capita per year (kg) 2030	Canned fish per capita converted to whole weight (kg)[1]	Total fish available per capita per year (kg)	Fish needed for nutrition per capita per year (kg)[2]	Gap in fish supply per capita per year (kg)[3]
Melanesia							
Fiji	920,980	26,289	29	13	42	65	- 23
PNG[4]	2,273,165	35,192	15	3	18	52	- 34
Solomon Is	892,093	17,938	20	6	26	52	- 26
Vanuatu	363,200	3,307	9	9	18	57	- 39
Micronesia							
FSM	106,507	12,380	116	4	120	63	+ 57
Kiribati	138,935	20,172	145	5	150	65	+ 85
Marshall Is	53,983	3,665	68	9	77	60	+ 17
Nauru	12,588	639.15	51	2	53	67	- 14
Palau	17,930	2,082	116	7	123	68	+ 55
Polynesia							
Cook Is	15,889	394.89	25	4	29	82	- 53
Niue	1,393	147.83	106	14	120	80	+ 40
Samoa	209,369	8,469	40	13	53	70	- 17
Tonga	97,257	6,316	65	4	69	73	- 4
Tuvalu	11,250	1,186	105	6	111	68	+ 43

1.From Technical Study 2 (Table 6), and Bell et al. (2019)[164] converted to whole fish weight.; 2. From Technical Study 2 (Table 17); 3. Note that countries with (+) have a surplus of fish in principal but see Table 9 in Annex 23 for explanations about why these countries have requested FADs under the GCF Programme; 4. Population within 5 km of the coast only.

2.7.2 Vulnerability of contribution of coastal fish to food security by 2050

2.7.2.1 Projected changes in habitat area

The results for the modelling of projected changes in the areas of coastal fish habitats for the two emissions scenarios in 2050 were spatially variable among and within the 14 Pacific Island countries participating in the Programme (Table 2.9).

Table 2.9 Total percentage area of each coastal habitat type assessed as having a 'very high' or 'high' vulnerability under the SSP2-4.5 and SSP5-8.5 emission scenarios by 2050 in each of the Pacific Island countries participating in the GCF Regional Tuna Programme. These values represent the estimated percentage decline in area for each habitat type due to climate change. Blank cells indicate the country does not have that coastal habitat type (source: Technical Study 1).

Country	Coral reef		Seagrass		Mangrove	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
Cook Islands	5.37	6.09				
FSM	1.01	1.15	56.51	64.00	4.80	5.43
Fiji	11.83	13.40	4.59	5.19	17.52	19.84
Kiribati	13.77	15.59	0	0	9.29	10.53
Marshall Islands	1.90	2.15	0	0	6.62	7.50
Nauru	44.15	50.00	0	0		
Niue	16.56	18.75	0	0		
Palau	0	0	0	0	2.01	2.27
Papua New Guinea	15.14	17.15	14.51	16.43	20.74	23.49
Samoa	77.60	87.88	88.30	100.00	36.19	40.98
Solomon Islands	9.11	10.32	0	0	3.53	4.00
Tonga	24.65	27.91	0	0	0	0
Tuvalu	0	0	0	0		
Vanuatu	23.26	26.35	0	0	20.27	22.95

The reduction in coral reef area is largely driven by increasing SST and pH declines, with well-documented impacts on hard corals due to thermal bleaching and acidification undermining reef structure.[165] Although the mechanisms for seagrass sensitivity to thermal stress are poorly understood, it is believed that thermal risk is a combination of: (1) exposure of shallow-water seagrasses to marine heatwaves (MHW) events, and (2) shifts in the photosynthesis/respiration balance (i.e., increases in SST and air temperature results in increased respiration, driving increased stress and declines.[166] Mangrove vulnerability is driven by increasing air temperatures, sea-level rise, and anthropogenic threats such as catchment activity (deforestation and agriculture) and pollution.

2.7.2.2 Projected changes in fish biomass

The indirect and direct impacts of climate change are projected to result in declines in coastal fish biomass in most of the 14 Pacific Island countries participating in the Programme by 2050 (Figure 2.10), relative to a reference period of 2010–2020[167]. The largest declines in biomass under both emissions scenarios are projected to be in those countries closest to the equator and in the western Pacific region, expanding to higher latitudes and in an easterly direction. There is, however, a considerable range in the projected biomass of coastal fish stocks in each of the countries under both the SSP2-4.5 and SSP5-8.5 emissions scenarios (Table 2.10).

Table 2.10 The average (median), upper and lower values across the model ensemble of projected percentage change in coastal fisheries biomass for each country participating in the GCF Programme by 2050 under SSP2-4.5 and SSP5-8.5 emissions scenarios. Averages calculated using median (or upper or lower) value of the ensemble for the 20-year period around 2050 (2041–2060).

Country	Projected change in biomass (%)					
	SSP2-4.5			SSP5-8.5		
	Average	Lower	Upper	Average	Lower	Upper
Melanesia						
Fiji	-0.8	-22.6	+13.3	-2.5	-29.1	+13.7
Papua New Guinea	-18.0	-49.8	-2.1	-24.0	-55.5	-2.6
Solomon Islands	-15.8	-43.3	-1.8	-18.1	-52.6	-0.5
Vanuatu	-2.2	-23.8	+10.4	-2.8	-30.9	+12.8
Micronesia						
FSM	-18.4	-47.6	-1.0	-24.2	-51.1	-1.3
Kiribati – Gilbert Islands	-6.4	-25.9	+4.9	-9.0	-32.3	+9.5
Kiribati – Line Islands	-6.2	-16.9	+7.7	-9.5	-23.4	+11.1
Kiribati – Phoenix Islands	-7.0	-19.7	+3.6	-10.4	-25.8	+6.7
Marshall Islands	-9.9	-38.8	+3.0	-14.5	-42.8	+1.8
Nauru	-10.7	-33.8	+1.8	-13.4	-40.4	+4.4
Palau	-19.9	-43.9	-2.3	-28.4	-48.0	-2.9
Polynesia						
Cook Islands	-6.8	-21.7	+2.7	-11.0	-25.2	+2.3
Niue	-2.6	-25.8	+27.2	-3.9	-29.7	+31.5
Samoa	-9.9	-31.0	+0.8	-12.3	-35.9	+0.8
Tonga	-0.5	-23.4	+19.0	-4.7	-27.3	+16.1
Tuvalu	-15.7	-33.3	-0.6	-19.1	-42.5	+2.7

The reason for the wide range of projections for each country is that the range of models used for this analysis vary in their assumptions. The wide range of projections suggests that exceptions to a general decline by 2050 may be possible in some countries. It also highlights the level of uncertainty in modelling outputs. In the face of the uncertainties associated with the modelling, a practical approach to interpreting the projections in Table 2.10 is to regard the upper estimate as the "best case" scenario, the average as the "most plausible" and the lowest estimate as the "worst case" scenario.

Technical Study 1 and Appendix 2-H provide further detail about the causes and implications of the uncertainty associated with the suite of models used for the 2050 projections, together with illustrations of the variability in coastal fish biomass projections from the ensemble of models within and among countries participating in the Programme, and future trends in relative percentage median change in coastal fish biomass for each country from the modelling.

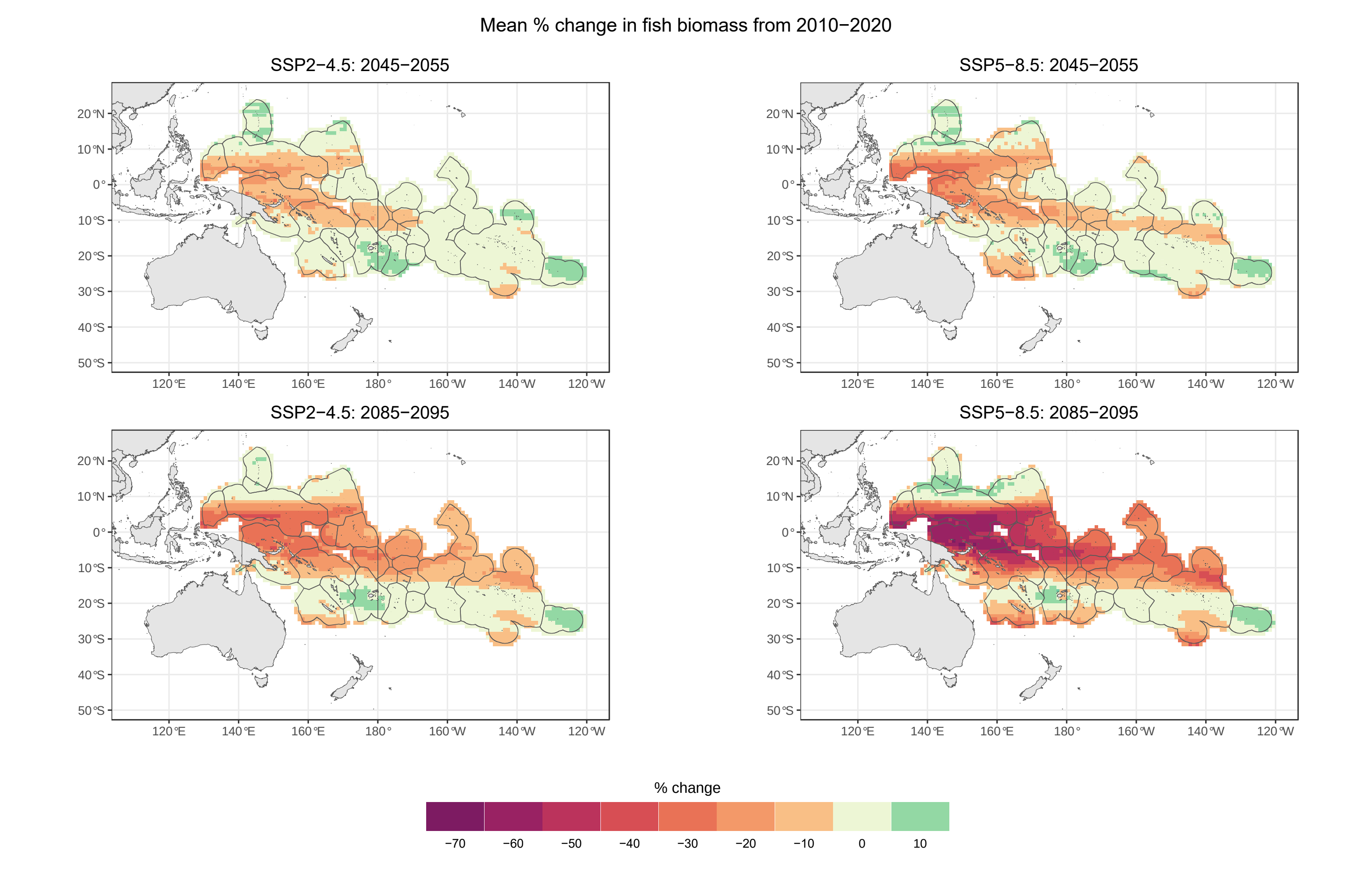


Figure 2.10 Projected relative (%) change in coastal fisheries biomass across the Pacific Island region for 2050 (2045-2055) and 2090 (2085-2095) under the SSP2-4.5 and SSP5-8.5 emission scenarios relative to 2010-2020. Black lines represent the exclusive economic zones of Pacific Island countries and territories. Source: Technical Study 1.

2.7.2.3 Projected changes in coastal fish catch

When the effects of projected changes in coastal habitat area are combined with the effects of the projected decreases in coastal fish biomass, it is evident that catches of coastal fisheries resources are highly likely to decline across the region under both emission scenarios by 2050 (Table 2.11). The decreases in projected coastal fisheries production are substantial even under SSP2-4.5, where they range from 7-65% by 2050 among the countries, increasing to 10-73% for SSP5-8.5 (Table 2.11). It should be noted that there is also considerable uncertainty associated with these projections, given that they incorporate the uncertainty associated with the projected changes in fish biomass (**Appendix 2-H**), and in the estimates of the areas of coastal habitat. The various assumptions, caveats and uncertainties in associated with this analysis are provided in **Technical Study 1**, Appendix 1-D.

2.7.2.4 Gaps in coastal fish supply driven by climate change

The projected effects of climate change on coastal fisheries catch ultimately affects the food security for Pacific Island communities. The extent of this impact depends on several variables, and this analysis explores whether protein derived from coastal fisheries resources is likely to meet consumption needs under different climate change scenarios in the 14 Pacific Island countries participating in the Programme.

Populations in the participating countries[168] have historically been largely subsistence-based with food security heavily dependent on coastal fish species for protein.[169] [170]Consequently, this analysis is focused on the contribution of coastal fisheries resources to the recommended consumption of dietary protein needed for good nutrition (**Technical Study 2**), much of which still comes from subsistence fishing.

The future availability of coastal fisheries resources for each Pacific Island country is based on the projected changes in catch, relative to the coastal fish catch in 2021[171] (Table 2.11). For the analysis of the contribution of coastal fisheries resources to the recommended consumption of dietary protein needed for good nutrition, the data on future projected catches have been converted to a per capita basis. Assuming that future fisheries will be managed in a similar way to current practices, the amount of fish available per person will decline in all 14 participating countries under SSP2-4.5 and SSP5.8.5 (Table 2.12).

Analysis of the combined effects of reduced catch due to increased GHG emissions, and changes in population size within 5 km of the coast (Table 2.12), to identify the future gap (or surplus) in the supply of coastal fish per capita relative to the fish supply recommended for good nutrition by WHO and SPC (see Table 17 in **Technical Study 2**) is provided in Table 2.13. This analysis shows that nine countries will have a gap in recommended fish availability by 2050 under both SSP2-4.5 and SSP5-8.5. Five countries will retain a surplus in fish supply by 2050. However, as mentioned in Section 3.5.1, most of these countries face severe problems in distributing fish from remote coral reefs to population centres and will also require the adaptation described in Technical Studies 3 and 5 to improve the supply of fish for their urban communities.

Table 2.11 Projected change (percentage) in habitat area, average biomass of coastal fish species, and coastal fish catch by 2050 under SSP2-4.5 and SSP5-8.5 emissions scenarios for each Pacific Island country participating in the Programme. Projected habitat changes in 2050 were based on expected declines in coral reef and seagrass areas combined, except for PNG which also included mangrove area declines. Projected change in catch is relative to the recorded coastal fisheries catch from each country in 2021.[172] See Technical Study 1 (Appendices B and C) for further details. Source: Welch et al. (forthcoming).[173]

Country	Projected change in coastal habitats (%) 2050		Projected change in coastal fish biomass (%) 2050		Baseline catch (tonnes) 2021	Projected change in annual catch (%) 2050	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5		SSP2-4.5	SSP5-8.5
Melanesia							
Fiji	-13.0	-14.7	-0.8	-2.5	30,100	-13.7	-16.9
PNG	-16.9	-19.1	-18.0	-24.0	46,000	-31.8	-38.5
Solomon Is	-8.2	-9.3	-15.8	-18.1	30,000	-22.7	-25.8
Vanuatu	-22.0	-25.0	-2.2	-2.8	4,400	-23.8	-27.0
Micronesia							
FSM	-1.9	-2.2	-18.4	-24.2	5,000	-20.0	-25.9
Kiribati–Gilbert Is	-1.67	-1.89	-6.4	-9.0	17,204	-7.9	-10.7
Kiribati–Line Is	-62.4	-70.67	-6.2	-9.5	1,790	-64.7	-73.4
Kiribati–Phoenix Is	0	0	-7.0	-10.4	7	-7.0	-10.4
Marshall Is	-2.5	-2.8	-9.9	-14.5	4,200	-12.2	-17.0
Nauru	-44.2	-50.0	-10.7	-13.4	240	-50.1	-56.7
Palau	-0.9	-1.0	-19.9	-28.4	2,400	-20.6	-29.1
Polynesia							
Cook Is	-5.4	-6.1	-6.8	-11.0	430	-11.8	-16.4
Niue	-16.6	-18.8	-2.6	-3.9	169	-18.8	-21.9
Samoa	-48.2	-54.6	-9.9	-12.3	11,000	-53.3	-60.2
Tonga	-7.7	-8.7	-0.5	-4.7	7,000	-8.1	-13.0
Tuvalu	0	0	-15.7	-19.1	1,500	-15.7	-19.1

Table 2.12 Per capita availability of coastal fish in kg (whole weight) per person per year in 2021 for the population living within 5 km of the coast for 14 Pacific Island countries. Also shown at the projected changes in fish availability per capita per year under the SSP5-8.5 emissions scenario in 2030, and under the SSP2-4.5 and SSP5-8.5 emissions scenarios in 2050. FSM = Federated States of Micronesia; PNG = Papua New Guinea.

Country	2021			2050 SSP2-4.5			2050 SSP5-8.5		
	Population within 5 km of coast [1]	Coastal fish catch (tonnes) [2]	Fish per capita (kg) [3]	Population within 5 km of coast [1]	Coastal fish catch (tonnes) [4]	Fish per capita (kg) [3]	Population within 5 km of coast [1]	Coastal fish catch (tonnes) [4]	Fish per capita (kg) [3]
Cook Is	15,526	430	28	15,786	379	24	15,786	359	23
Fiji	682,783	30,100	44	720,731	25,976	36	720,731	25,013	35
FSM	105,757	5,000	47	98,668	4,000	41	98,668	3,705	38
Kiribati	120,740	19,000	157	181,852	16,397	90	181,852	15,846	87
Marshall Is	54,516	4,200	77	52,461	3,688	70	52,461	3,486	66
Nauru	11,835	240	20	14,425	120	8	14,425	104	7
Niue	1,283	169	132	1,139	137	121	1,139	132	116
Palau	17,960	2,400	134	16,439	1,906	116	16,439	1,702	104
PNG	1,915,831	46,000	24	3,169,670	31,372	10	3,169,670	28,290	9
Samoa	193,855	11,000	57	224,510	5,137	23	224,510	4,378	20
Solomon Is	662,511	30,000	45	1,213,589	23,190	19	1,213,589	22,260	18
Tonga	99,526	7,000	70	93,311	6,433	69	93,311	6,090	65
Tuvalu	10,673	1,500	141	11,830	1,265	107	11,830	1,214	103
Vanuatu	283,213	4,400	16	477,620	3,353	7	477,620	3,212	7

1.Based on Andrew N.L. et al. (2019) Coastal proximity of populations in 22 Pacific Island Countries and Territories. PLoS One, 14 (9); 2. As estimated by Gillett and Fong (2023); 3. Whole fish (not just edible portion); 4. Projected catch from Table 2.1

Table 2.13 The gap (-) or surplus (+) in fish supply (whole weight) by 2050 relative to recommended consumption of fish per capita per year in the 14 Pacific Island countries participating in the GCF Programme expected to occur under SSP2-4.5 and SSP5-8.5. FSM = Federated States of Micronesia; PNG = Papua New Guinea.

Country	SSP2-4.5			SSP5-8.5		
	Recommended consumption per capita per year (kg) [1]	Fish available per capita (kg) [2]	Gap or surplus per capita (kg) [2]	Recommended consumption per capita per year (kg) [1]	Fish available per capita (kg) [2]	Gap or surplus per capita (kg) [2]
Cook Is	83	24	-59	83	23	-60
Fiji	67	36	-31	67	35	-32
FSM	65	41	-24	65	38	-27
Kiribati	67	90	+23	67	87	+20
Marshall Is	62	70	+8	62	66	+4
Nauru	67	8	-59	67	7	-60
Niue	78	121	+43	78	116	+38
Palau	68	116	+48	68	104	+36
PNG	53	10	-43	53	9	-44
Samoa	70	23	-47	70	20	-50
Solomon Is	53	19	-34	53	18	-35
Tonga	75	69	-6	75	65	-10
Tuvalu	70	107	+37	70	103	+33
Vanuatu	58	7	-51	58	7	-51

1. From Table 17 in Technical Study 2, based on proportion of men, women and children in the population, their average body weights, the fact that fish is ~23% protein, 60% recovery of edible flesh per kg, and WHO/SPC recommendations that fish provides 50% of the protein intake of 0.7 g per kg of body weight per day. Values are kg of whole fish; 2. Whole fish (not just edible portion) availability from Table 2.12.

2.8 Overview and recommendations

2.8.1 Vulnerability of coastal fisheries production and fish supply for local consumption

The vulnerability assessment undertaken for Component A of the Programme, based on consideration of the indirect and direct effects of climate change, shows that although there is spatial variability among and within participating countries, climate change has a high likelihood of causing declines in coastal habitats, coastal fisheries biomass and catches of coastal fisheries resources into the future. Although the impacts are expected to be modest by 2030 under SSP5-8.5, the assessment shows clearly that impacts will continue and accelerate, and that projected declines in coastal fisheries production are likely to be significant in many of the participating countries by 2050, even under SSP2-4.5.

The projections to 2050 highlight the potential for progressive, deleterious impacts of reduced coastal fisheries productivity on food security and livelihoods. Furthermore, significant inter-annual variability in the projected changes in fish catch coupled with the projected increase in episodic events, such as those due to marine heat waves, suggests that some of the climate-driven changes in coastal fisheries production could be sudden (Appendix 2-H). The overall impact of changes to the contributions that coastal fisheries make to food security and livelihoods will depend on the effectiveness of adaptations to maintain the capacity for coastal areas to sustain demersal fish and invertebrates.

Although progress has been made since SPC's initial assessment of the vulnerability of tropical Pacific fisheries and aquaculture in 2011, including development of relevant regional supporting policies and strengthening of community-based coastal resource management, effective measures to sustain coastal resources remain limited. The strong likelihood is that continued declines in coastal fish catch will widen the gap that is already occurring between the fish required for good nutrition of coastal communities and sustainable fish harvests from coral reefs and other coastal habitats driven by rapid population growth in many of the participating countries. Climate change will exacerbate the gap in fish supply, which provides a powerful incentive for the participating countries to improve the sustainability of coastal fisheries to minimise the gap. This can be done by 1) maintaining sufficient spawning biomass to replenish stocks regularly, and 2) reducing the impacts of poor land use on coastal habitats. Both actions will maximise the autonomous capacity of coastal fish and invertebrate species to adapt to the indirect and direct effects of climate change.

Even so, many of the participating countries will face a major challenge to maintain the traditional levels of per capita fish consumption due to the combined effects of population growth and climate change, particularly by 2050 under both SSP2-4.5 and SSP5-8.5. Progressive expansion of Outputs and Activities within Component A of the Funding Proposal will lay the foundation for the participating countries to make significant advances in addressing this important challenge.

2.8.2 Recommendations

Several recommended adaptations have already been made about how to minimise loss of coastal fisheries production during climate change, and how to fill the gap in fish supply by increasing access to tuna to supply the protein needed for national food security.

[174] Those recommendations have been reinforced by the analysis of the minimum per capita dietary protein intake required for good nutrition of rapidly-growing Pacific Island populations (**Technical Study 2**), and expanded by this vulnerability analysis to form the basis for the adaptations in Outputs 1 and 2, and the related Activities, in the logframe for the Programme.

These adaptations centre around:

1) assisting the 14 participating countries to strengthen their national programmes to make nearshore fish aggregations devices (FADs) an integral part of the national infrastructure for food security to increase access to tuna and other large pelagic fish for local consumption by coastal communities (**Technical Study 3**)[175];

2) improving the transhipping and unloading systems for tuna and bycatch from industrial fishing operations in Pacific Island ports to increase the availability of these fish for local consumption by urban communities (**Technical Study 5**); and

3) maximising the shelf-life of FAD-caught fish and fish offloaded in regional ports through development of post-harvest methods.

The first of these key adaptations – scaling up the installation of nearshore FADs – does not pose any risks to the sustainable management of tuna resources. It has been estimated that filling the expected gap in fish supply in 2035 completely with tuna would only require 6% of the annual tuna catch from the Pacific Island region (Chapter 1).[176] This level of additional catch is not expected to affect the status of the large tuna resources of the region, which have not been overfished nor subject to overfishing[177] due to exemplary management by Pacific Island countries. However, future analyses indicate that increasing the total tuna catch could affect sustainable management, the need to use tuna to fill the gap in fish supply could be done by re-allocating use of some of the resource presently used to supply international markets to domestic food security, thereby avoiding the need to increase total catch (Chapter 1). Importantly, the effectiveness of nearshore FADs is not expected to be reduced significantly by the projected eastward redistribution of tuna described in Section 2.9 below because national waters are still expected to hold large quantities of tuna capable of supporting the additional small-scale fisheries needed to contribute to national food security.

A wider set of recommendations is provided in **Technical Study 1**, Appendix 1-E). Examples of some of the other recommendations relevant to the key adaptations outlined above are:

- Continued investment in the development and implementation of standardized data collection systems and tools appropriate for measuring the catches of coastal fish species in the participating countries (e.g., IKASAVEA),[178] including for use in monitoring catches made around FADs.

- Active education and awareness-raising among government authorities and communities about (i) the role of coastal habitats in sustaining fisheries resources and the consequences of poor land use and fishing practices on coastal habitats and fish stocks; and (ii) the expected further impacts of climate change of coastal fisheries production and the need to rely on replacing much of the previous coastal fish catch with tuna and other nearshore pelagic fish to maintain the traditional benefits of fish for good nutrition.

- Exploration of the potential for developing fisheries for pelagic fish in the neritic zone (e.g., mackerel, anchovies, pilchards, sardines), where these species occur regularly in coastal waters and associate with FADs.

2.9 Vulnerability of economies to climate-driven tuna redistribution

The importance of assessing the effects of changes to biophysical features of the WCPO on the distribution of the tropical tuna species is linked to the extraordinary socio-economic benefits derived by nine of the countries participating in the Programme from industrial fishing fleets operating in their EEZs (Chapter 1, Section 10)[179].

These extraordinary benefits have been secured mainly through co-operative management of the purse-seine fishery within the combined EEZs of eight of the participating countries under the Parties to the Nauru Agreement (PNA) Vessel Day Scheme (VDS) (Box 2.1). Co-operative management of the purse-seine fishery has enabled tuna-dependent economies to adapt to the profound effects of the El Niño-Southern Oscillation (ENSO) on the extent of the Warm Pool and the associated distribution of the abundant skipjack tuna (Box 2.1) (**Appendix 2-I**). The benefit of this adaptation is that it has stabilised the pre-existing, large, inter-annual variability in the contribution of tuna-fishing access fees to national economies.

The socio-economic importance of tuna has been recognised by Pacific Island Leaders in their *Regional Roadmap for Sustainable Pacific Fisheries.*[180] The *Roadmap's* sustainability goal is being achieved – annual purse-seine catches from the EEZs of the participating countries have deviated little from the 10-year average of 1.4 million tonnes (Table 2.14) In addition, as mentioned above, none of the tuna species caught by purse-seine in the region are overfished or subject to overfishing, due largely to co-operative management by PNA members (Box 2.1) under the auspices of the Western and Central Pacific Fisheries Commission (WCPFC).

However, realisation that climate change will alter the tropical Pacific Ocean, and cause further modifications to ENSO[181] [182] and the Warm Pool and the other ecological provinces (Section 2.6.3), has prompted the regional organisations assisting Pacific Island countries to manage their tuna resources, the Pacific Community (SPC), Pacific Islands Forum Fisheries Agency (FFA) and WCPFC (Chapter 1), to support modelling of the effects of climate change on tuna biomass.[183] The initial modelling, which focused mainly on the EEZs of the countries, projected progressive redistribution of tuna biomass in equatorial waters to the east and, to a more modest extent, to higher latitudes. This modelling demonstrated that, provided tuna biomass remains high within the combined EEZs of PNA participants, the provisions of the VDS (Box 1) are expected to limit the implications of climate-driven tuna redistribution for tuna-dependent economies and the goals of the *Roadmap*.

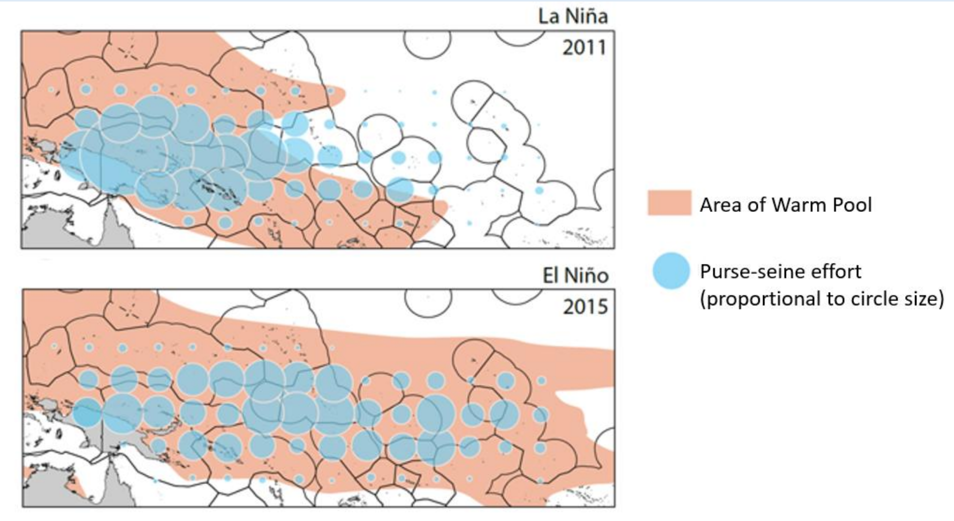
However, as explained in the Funding Proposal, the nine tuna-dependent Pacific Island countries are now concerned that redistribution to the east could lead to decreases in tuna biomass within their EEZs, and increases in high-seas areas, undermining the socio-economic benefits they derive from tuna fishing and the strong management of tropical Pacific tuna resources. The five subtropical countries are also interested to know whether the projections from the preliminary modelling suggesting that the biomass of tuna may increase in their EEZ are likely to eventuate so that they can assess whether to invest in capitalising on such opportunities.

This vulnerability assessment for Component B of the Funding Proposal evaluates the risks to the sustainability of the tuna-dependent economies by summarising recent simulated changes to tuna biomass in their EEZs and in high-seas areas in the WCPO and Eastern Pacific Ocean (EPO) under high (RCP8.5) and moderate (RCP4.5) GHG emissions scenarios by 2050. The results of this modelling are then used to identify the potential implications for future purse-seine catches within the EEZs of the nine countries, and for the vital government revenue flowing to their economies from purse-seine fishing.

Box 2.1. The Parties to the Nauru Agreement (PNA) Vessel Day Scheme[184]

The Pacific Island countries that are the Parties to the Nauru Agreement (PNA) (Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu) have developed a system for jointly managing the purse-seine fishery targeting skipjack tuna within their combined exclusive economic zones (EEZs) called the Vessel Day Scheme (VDS).

The 'cap and trade' VDS sets the total annual purse-seine fishing effort within the combined EEZs of PNA members at ~45,000 fishing days and allocates these days to members based on individual EEZ areas and their past 8–10 years of fishing effort history. The VDS provides a trading mechanism among PNA members, allowing them to respond to the profound effects of the El Niño Southern Oscillation (ENSO) on the Western Pacific Warm Pool and the prime fishing grounds for skipjack tuna. During La Niña events, the best catches of skipjack tuna are made in the west of the region (see top panel in the diagram below), whereas during El Niño events fishing is most efficient up to 4,000 km to the east (see bottom panel). During La Niña events, the VDS enables countries in the west to buy fishing days from members in the east, enabling fleets to keep fishing in the west. The reverse occurs during El Niño events. Therefore, regardless of where the tuna are caught, all PNA members receive access fees every year. In this way, the VDS evens out the previously high inter-annual variability in access fees received by PNA members and helps stabilize government revenue for tuna-dependent economies.



The various provisions of the VDS, i.e., transferability of fishing days among PNA members, 'pooling' of days by groups of members, and 'roaming' of vessels from PNA member countries among their collective EEZs, also provide non-confrontational adaptations to the progressive redistribution of skipjack tuna within the combined EEZs of PNA members due to ocean warming .[185] [186] However, the VDS does not encompass adaptations for climate-driven redistribution of tuna from the EEZs of PNA members to high-seas areas.

Table 2.14 Total annual catch in tonnes (t) for all tuna species, by all fishing methods, from the exclusive economic zones (EEZs) of the nine tuna-dependent economies between 2013 and 2022. The average total tuna catch from the EEZ of each country for the 10-year period is also shown. For Kiribati, data are presented for the total EEZ for the nation, and for each of three separate EEZ areas (in grey) comprising the total EEZ (source: Oceanic Fisheries Programme, Pacific Community).

Country	**Year**										**Average total catch (t)**
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	
Cook Is	16,650	20,310	24,578	13,878	24,048	40,071	35,944	17,125	6,486	12,353	21,144
FSM[1]	220,521	143,951	172,307	200,960	194,802	297,975	172,906	202,857	117,475	238,453	196,221
Kiribati	299,526	744,155	648,783	413,619	386,650	401,710	690,057	356,418	356,408	238,241	453,557
Gilbert Is	(191,165)	(443,047)	(318,802)	(334,893)	(266,157)	(288,642)	(562,579)	(274,921)	(312,180)	(183,917)	(317,630)
Line Is	(31,894)	(63,779)	(189,433)	(32,617)	(30,869)	(35,562)	(72,538)	(36,910)	(24,546)	(29,596)	(54,774)
Phoenix Is	(76,467)	(237,330)	(140,549)	(46,109)	(89,625)	(77,505)	(54,939)	(44,586)	(19,682)	(24,728)	(81,152)
Marshall Is	46,352	88,657	37,845	90,895	33,143	36,453	13,765	47,293	66,431	44,344	50,518
Nauru	163,812	179,776	67,193	115,738	82,316	174,916	105,693	135,819	150,172	79,556	125,499
Palau	3,209	4,995	1,574	6,134	20,599	9,560	6,654	898	1,308	693	5,562
PNG[2]	619,155	345,452	190,766	351,641	392,152	376,702	379,793	481,288	482,065	712,236	433,125
Solomon Is	131,741	88,479	126,373	165,261	171,928	89,868	72,035	109,735	121,892	155,074	123,239
Tuvalu	57,016	99,163	76,931	124,199	57,607	90,160	120,528	89,831	78,596	61,427	85,546
Total	**1,557,981**	**1,714,937**	**1,346,350**	**1,482,324**	**1,363,245**	**1,517,415**	**1,597,374**	**1,441,263**	**1,380,832**	**1,542,377**	**1,494,410**

2.9.1 Methods used to assess climate-driven tuna redistribution

The 'Spatial Ecosystem and Populations Dynamics Model' (SEAPODYM) framework[187] was used to assess how high, RCP8.5 (SSP5-8.5 equivalent), and moderate, RCP4.5 (SSP2-4.5 equivalent), emissions scenarios are likely to affect the distribution of the four tropical tuna species by 2050 (10-year average 2046–2055).

Full details of the modelling approach are provided in **Technical Study 1**, Appendix 1-G. Some of the key features, considerations and implications of the modelling approach are provided below.

- The SEAPODYM framework describes the spatial dynamics of tuna species as well as micronekton biomass distributions at basin and global scales, under the influence of both fishing and environmental effects.
- The model first simulates the prey dynamics[188] (food webs) and then the age-structured population dynamics of tuna with different rules according to life stage.[189] [190]
- Several developments to the framework have occurred in the last few years to improve the modelling of spawning and feeding habitats and behaviours, fishing mortality and model parameter estimations from various datasets of observations, including fishing catch and effort, size frequencies of catches, and tagging data.
- A phase of model parameter optimisation over the historical period 1980–2010 provided reference parameter estimates prior to running the projections.
- To account for uncertainty associated with different Earth System Model projections, forcings from four models were selected (Table 2.15) based on their ability to best capture ENSO-type variability. [191]
- The ensemble of models provides simulations that couple physical and biogeochemical processes with pelagic ecosystem biological and tuna-specific dynamics under moderate (RCP4.5) and high (RCP8.5) emissions scenarios. These simulations are based on the CMIP5 climate model forcings.
- Earth System Model physical and biogeochemical outputs using the latest CMIP6 scenarios cannot yet be used for the tuna simulations. This is due to the inevitable delay associated with processing the model forcings, including a phase of bias correction, that need to be followed by a phase of revision of the tuna models, for which the parameters need to be re-estimated. Nonetheless, the moderate and high emissions scenarios used are equivalent to those generated under CMIP6 for SSP2-4.5 and SSP5-8.5.
- The impacts of climate change on the distributions of the tropical tuna species in the Pacific Ocean are analysed by extracting the mean of tuna biomass for adults and recruits from the four-simulation ensemble for different areas, i.e., the EEZs of Pacific Island countries and international waters (high-seas areas).
- The vulnerability analysis of the four main tuna species exploited in the WCPO was carried out based on a review of potential impacts, the simulation results from the tuna models, and using multidisciplinary expertise.

Table 2.15 Earth System Models used to account for atmospheric forcing uncertainty in the modelling of the projected responses of tuna abundance and distribution to climate change.

Code	CMIP5 model
IPSL	IPSL-CM5A-MR (Institut Pierre Simon Laplace, France)
MIROC	MIROC-ESM (Model for Interdisciplinary Research on Climate, Japan)
MPI	MPI-ESM-MR (Max Planck Institute for Meteorology, Germany)
GFDL	GFDL-ESM2G (Geophysical Fluid Dynamics Laboratory, USA)

2.9.2 Assessing the vulnerability of tuna catches by 2050

Projecting changes to the productivity of the fisheries targeting the four tuna species targeted by industrial fishing fleets requires the definition of fishing scenarios relying on various socio-economic, technical, and political hypotheses, which are extremely challenging to define over the coming few decades. Although there are ongoing initiatives to create such scenarios,[192] this assessment is limited to a preliminary analysis of the possible effects of changes in tuna biomass under RCP8.5 and RCP4.5 by 2050 on purse-seine catches in the EEZs of the nine participating countries with tuna-dependent economies. On a multi-annual average basis, it is assumed that the projected changes to tuna biomass will result in approximately proportional changes in catch.[193]

Because purse-seine catches are comprised of different proportions of skipjack, yellowfin and bigeye tuna, and because each species is projected to have a different response to ocean warming, changes in purse-seine catches under each emissions scenario by 2050 were estimated as the weighted mean responses of all three tuna species combined. These estimates were derived from the average relative abundance of each species in purse-seine catches in the EEZs of each country and the projected percentage change in biomass of each species under each emission scenario.[194]

The weighted average percentage changes in biomass of all tuna species combined were then applied to 10-year average purse-seine catches from the EEZs of the nine countries to estimate the changes in purse-seine catches for these jurisdictions. In the case of Kiribati, which has three separate EEZ areas, the change in catch for each EEZ area was estimated as described above and then amalgamated to produce the overall estimated change in purse-seine catch for the country.

The projected percentage change in total purse-seine catch differs from the percentage change in total tuna biomass due to variation in the relative contributions of the three tuna species to total catch and to total biomass.

2.9.3 Assessing vulnerability of economies to projected changes in catch by 2050

To assess the potential effects of climate-driven redistribution of tuna on the economies of the nine tuna-dependent countries, it was assumed that estimated changes in purse-seine catch within their EEZs due to the climate-driven redistribution of tuna biomass described above would result in a proportional change in access fees earned from purse-seine fishing and associated operations.

To estimate the effects of RCP8.5 and RCP4.5 on the capacity of Pacific Island governments to earn access fees from industrial tuna fishing, and the contributions of these access fees to total government revenue excluding grants (hereafter 'government revenue'), the annual averages of government revenue, tuna-fishing access fees earned by the nine countries, and the average percentage contribution of access fees to their government revenue were used as a baseline. The projected changes in total purse-seine catch in each EEZ for RCP8.5 and RCP4.5 were then applied to the average annual access fees received to estimate the change in value of access fees by 2050 for each emissions scenario. The change in access fees was used to adjust government revenue in 2050 under both emissions scenarios, assuming that the relative contributions of the various sources of government revenue remain the same. For both emissions scenarios, the estimated government revenue and access fees in 2050 were used to calculate the percentage contribution of tuna-fishing access fees to government revenue in 2050. Finally, percentage contributions of average annual access fees to recent government revenue, and projected revenue in 2050 were compared to estimate the potential changes to these contributions under RCP8.5 and RCP4.5 by 2050.

The estimated percentage changes in government revenue for each of the nine tuna-dependent economies do not account for i) management responses; ii) variation in the value of access to particular EEZs and the willingness of fleets to pay for this access due to the effects of changes in tuna biomass on catchability of each species, levels of fishing effort/catch rates, or changes to the price of tuna or cost of landing the tuna; and iii) the impact of tuna redistribution on the degree of control that these countries exert over fisheries targeting tuna. The latter factor is expected to be particularly important. For example, substantial movement of tuna from the EEZs of PNA countries into high-seas areas would be expected to limit the effectiveness of the Vessel Day Scheme[195] by reducing the degree of control over the fishery exerted by PNA members.

Overall, it is important to note that the simple approach used to assess the potential effects of tuna redistribution on government revenue is intended only to provide indicative information on the magnitude of these impacts. To obtain more robust estimates of climate-driven changes in government revenue, significantly more complex bio-economic analyses will be required, beginning with, for example, a fleet-dynamics analysis to investigate the potential response of purse-seine vessels to redistribution of tuna and the flow-on effects on access fees.

2.9.4 Projected redistribution of tuna caught by purse seine fishing by 2050

The projected climate-driven redistribution of the three tuna species caught by purse-seine fishing (skipjack, yellowfin and bigeye tuna) under RCP8.5 by 2050 is shown in Figure 2.11. The expected vulnerabilities of these species to the effects on increased GHG emissions on the tropical Pacific Ocean are summarised in **Appendix 2-J**.

The modelling depicted in Figure 2.11 indicates that total tuna biomass in the combined jurisdictions of the tuna-dependent Pacific Island countries would decrease by an average of ~13% (range = -5% to -20%) (Figure 2.12a), and by up to ~30% in the majority of the individual EEZ areas (see Supplementary Table 5 in **Appendix 2-K**).[196] Conversely, tuna biomass is projected to increase by an average of ~23% (range = 13% to 32%) in the central eastern Pacific Ocean (EPO-C, Figure 2.12a), the high-seas area where most tuna are caught (see Supplementary Table 4 in **Appendix 2-K**). These projected changes in tuna biomass by 2050 generally reflect the contrasting responses of sea surface temperature, primary production and the prey organisms of tuna to RCP8.5 in the WCPO and EPO (see Supplementary Figures 3 and 4 in **Appendix 2-K**).

The projected effects of the moderate RCP4.5 emissions scenario on redistribution of tuna biomass are far less pronounced (Figures 2.11 and 2.12a). Under this scenario, total biomass of tuna in the combined EEZs of the tuna-dependent countries decreases by only an average of 1% (range = -9% to +8%), and decreases occur on average in only three EEZ areas (see Supplementary Table 7 in **Appendix 2-K**). In contrast, the projected effects of RCP4.5 on tuna biomass in high-seas areas are similar to those for RCP8.5, i.e., there is an average increase of ~18% (range = +9% to +32%) in EPO-C (Figure 2.12a). A possible explanation for the significant increases in tuna biomass in high-seas areas under RCP4.5 by 2050 is the stronger response to increased GHG emissions by the food web supporting tuna in the EPO than in the WCPO (see Supplementary Figure 4 in **Appendix 2-K**).

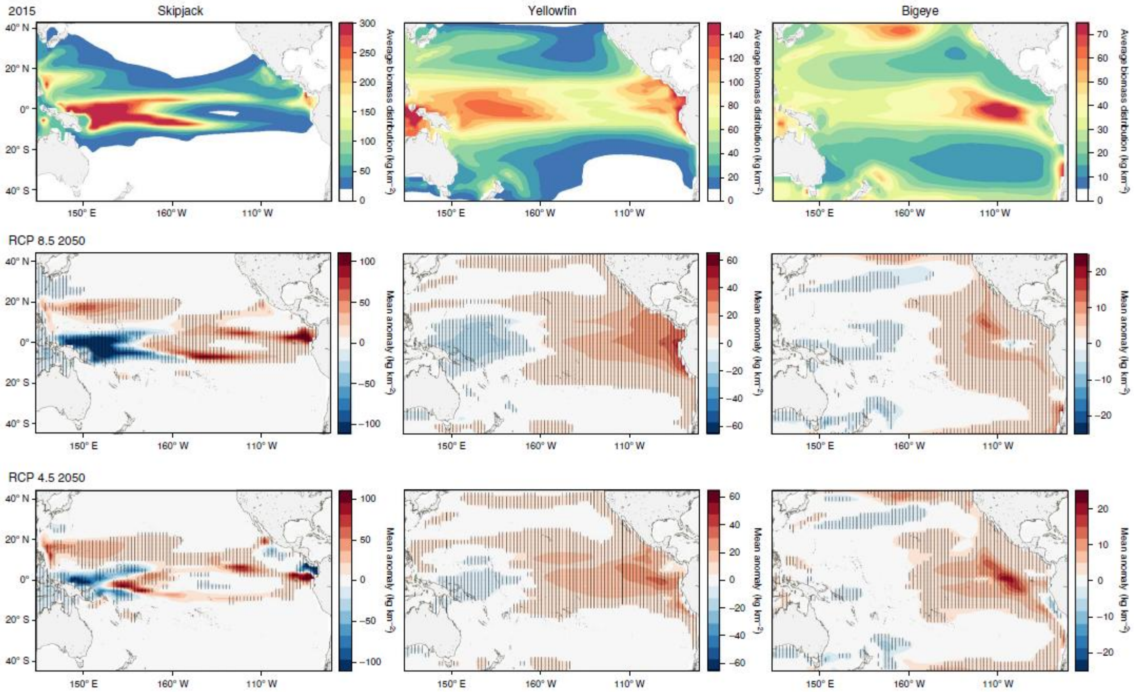


Figure 2.11 Projected effects of climate change on the distributions of the three tuna species caught by purse-seine fishing in the Pacific Ocean. Average biomass distributions (kg km^{-2}) of skipjack, yellowfin and bigeye tuna in the Pacific Ocean basin for 2015 (2011−2020) (top row) and mean anomalies (kg km^{-2}) from the average 2015 biomass distribution of each tuna species projected to occur by 2050 (2044−2053) under two emissions scenarios, RCP 8.5 (middle row) and RCP 4.5 (bottom row). Shading indicates areas where projections from all four ESMs (Section 7) agree in the sign of change, excluding near-zero changes (white zones). (Source: Bell et al. 2021)[197].

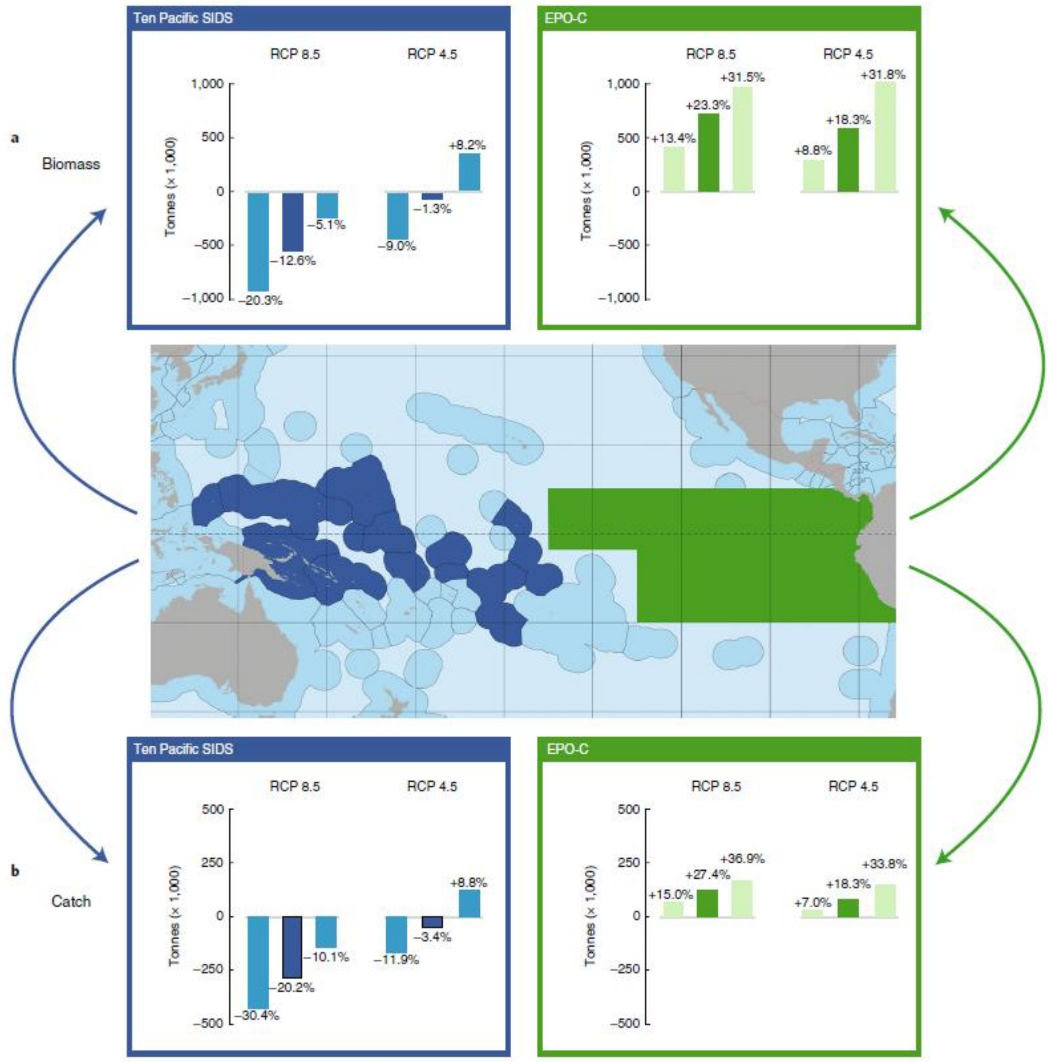


Figure 2.12 Redistribution of tuna biomass and purse-seine catch from the combined EEZs of the tuna-dependent Pacific Island countries to the central eastern Pacific Ocean. **a**, Projected changes in total biomass of skipjack, yellowfin and bigeye tuna in the combined EEZs and EPO-C under the RCP 8.5 and RCP 4.5 emissions scenarios in 2050 relative to the average biomass from these areas in 2009−2018. **b**, Projected changes in total purse-seine catch in the combined EEZs and EPO-C under the RCP 8.5 and RCP 4.5 emissions scenarios in 2050 relative to the average catch from these areas in 2009−2018. The dark column in each histogram represents the average change from the four ESMs. The columns on either side of the average represent the maximum and minimum changes projected by the range of ESMs. Note that the information presented includes data from the territory of Tokelau. (Source: Bell et al. 2021).[198]

2.9.5 Projected changes in purse-seine catches of tuna by 2050

The projected changes in tuna biomass due to increased GHG emissions are expected to affect purse-seine catches of tuna from the EEZs and high-seas areas (Section 2.9.1). By 2050 under RCP8.5, the total purse-seine catch from the combined EEZs of the tuna-dependent countries is estimated to decrease by an average of 20% (range = -30% to -10%), i.e., 284,000 tonnes (range = -428,000 to -

143,000 tonnes), but increase by an average of 27% (range = +15% to +37%), i.e., 125,000 tonnes (range = +69,000 to +169,000 tonnes) in EPO-C (Table 2.16, Figure 2.12b).

The projected changes in purse-seine catch by 2050 under RCP4.5 also follow the patterns in tuna biomass, decreasing by an average of 3% (range = -12% to +9%), i.e., 47,000 tonnes (range = -165,000 to +124,000 tonnes) in the combined EEZs of the tuna-dependent countries, and increasing in EPO-C by an average of 18% (range = +7% to +34%), i.e., 84,000 tonnes (range = +32,000 to +154,000 tonnes) (Table 2.16, Figure 2.12b).

2.9.6 Projected changes in government revenue

The estimated changes in purse-seine catch under RCP8.5 could reduce total annual fishing access fees 20-50earned by the tuna-dependent economies by an average of USD 90 million (range = USD 40–140 million) per year compared to the average annual revenue received between 2015 and 2018 (Table 2.17, see also Supplementary Table 15 in **Appendix 2-K**). Losses in access fees are estimated to occur in all countries under RCP8.5, and reduce total government revenue by an average of up to 13% (range = -8% to -18%) for individual Pacific SIDS, by 2050 (Table 2.17, see also Supplementary Table 15 in **Appendix 2-K**).

Under RCP4.5, the average change in access fees for all tuna-dependent economies represents a loss of USD 12 million (range = -USD 54 million to +USD 48 million) per year (Table 2.17, see also Supplementary Table 16 in **Appendix 2-K**). Due to the more limited loss of access fees under RCP4.5, total government revenue in 2050 is estimated to decrease by an average of 1% or less in only three of the countries (Table 2.17, see also Supplementary Table 16 in **Appendix 2-K**).

The estimates of reduced access fees, and flow-on losses in government revenue, due to climate-driven redistribution of tuna include a number of assumptions (Section 2.9.1) but, overall, are likely to be conservative because they do not account for the control that the PNA members exert in the marketplace. At present, the PNA members command high access fees due to the fact that ~90% of the catch from the purse-seine fishing grounds within the Pacific Island region of the WCPO comes from their combined EEZs. However, if there is significant movement of fish from the EEZs to high-seas areas, the tuna-dependent countries would be unlikely to obtain the same daily rates for fees. Any such effects are also likely to occur to some extent under RCP4.5, which is projected to reduce catches in the combined EEZs of the countries by ~50,000 tonnes, and increase catches in high-seas areas by more than 100,000 tonnes per year (Table 2.16)

Even at conservative levels, the estimated losses in fishing access fees are expected to have significant implications for economic development. They would coincide with the need for increased financial resources and flexibility to adapt to climate change, including sustained government facilitation of community-based initiatives.[199] The projected reductions in tuna biomass and catch are also expected to affect the ability of many of tuna-dependent countries to harmonise the employment, value-adding and food security goals of the *Roadmap* for *Sustainable Pacific Fisheries*, and achieve sustainable development.[200] [201] Some of the participating countries may also need to use to a greater proportion of their tuna resources for local consumption (see Section 2.8), further limiting the scope for earning access fees and potentially reducing the supply of tuna that supports employment in national canneries.

Table 2.16 10-year (2009–2018) average purse-seine tuna catches in tonnes (t) from a) the exclusive economic zones (EEZs) of tuna-dependent Pacific Island countries, and b) high-seas areas (see Supplementary Figure 1 in Appendix 2-K), together with average projected changes to these catches by 2050 in tonnes and percentage terms under the RCP8.5 and RCP4.5 emissions scenarios. Highlighted rows are the three EEZ areas of Kiribati, which have been integrated to produce the total for Kiribati. Note that the information presented includes data from the territory of Tokelau. (Source: Bell et al. 2021)[202].

Area	Average catch (t)	RCP8.5 – 2050			RCP4.5 – 2050		
		Catch (t)	Change (t)	Change (%)	Catch (t)	Change (t)	Change (%)
a) EEZs of tuna-dependent Pacific Island countries							
Cook Islands	11,080	10,640	-440	-4.0	12,065	+985	+ 8.9
FSM	178,587	155,407	-23,180	-13.0	173,773	-4,815	-2.7
Kiribati	396,048	363,520	-32,528	-8.2	423,251	+ 27,202	+6.9
Gilbert Islands	(260,073)	(225,177)	(-34,896)	(-13.4)	(278,023)	(+17,950)	(+6.9)
Phoenix Islands	(94,696)	(92,140)	(-2,557)	(-2.7)	(101,132)	(+6,435)	(+6.8)
Line Islands	(41,279)	(46,203)	(+4,924)	(+11.9)	(44,096)	(+2,817)	(+6.8)
Marshall Islands	37,003	36,728	-275	-0.7	37,778	+ 775	+2.1
Nauru	110,794	86,886	-23,908	-21.6	117,059	+6,266	+5.7
Palau	2,655	2,646	-9	-0.3	2,738	+ 82	+3.1
Papua New Guinea	461,032	308,404	-152,628	-33.1	389,654	-71,378	-15.5
Solomon Islands	116,877	86,399	-30,477	-26.1	106,740	-10,137	-8.7
Tokelau	21,392	17,954	-3,438	-16.1	22,610	+1,218	+ 5.7
Tuvalu	73,080	55,992	-17,088	-23.4	75,589	+2,509	+ 3.4
Total	**1,408,548**	**1,124,577**	**-283,971**	**-20.2**	**1,361,257**	**-47,291**	**-3.4**
b) High-seas areas							
I1	15,330	11,396	-3,934	-25.7	13,541	-1,790	-11.7
I2	23,083	16,413	-6,670	-28.9	20,738	-2,345	-10.2
I3	47	60	+13	+27.8	61	+14	+29.8
I4	21,443	21,773	+ 330	+1.5	22,727	+1,284	+6.0
I5	23,231	28,021	+4,790	+20.6	26,194	+2,963	+12.8
I6	16,211	16,868	+657	+4.1	17,800	+1,589	+9.8
I7	16.7	18	+1.3	+9.0	17	+0.2	+1.3
I8	2.2	3	+0.8	+15.5	3	+ 0.4	+20.2
I9	33.2	41	+7.8	+24.7	36	+3	+8.9
H4	20,893	17,796	-3,097	-14.8	23,308	+2,415	+11.6
H5	46,517	49,502	+2,985	+6.4	48,360	+1,842	+4.0
EPO-N	84,175	100,443	+16,268	+19.3	98,130	+ 13,955	+16.6
EPO-C	457,664	583,082	+125,418	+27.4	541,194	+ 83,530	+18.3
EPO-S	3,293	4,339	+1,046	+31.8	3,747	+ 454	+13.8
Total	**711,939**	**849,755**	**+137,816**	**+19.4**	**815,856**	**+103,917**	**+14.6**

Table 2.18 Average government revenue (excluding grants), tuna-fishing access fees, and the percentage of government revenue derived from access fees, for tuna-dependent Pacific Island economies between 2015–2018, together with estimated changes in purse-seine tuna catch, access fees, and the percentage contribution of access fees to government revenue, by 2050 under the RCP8.5 and RCP4.5 emissions scenarios. See Supplementary Tables 15 and 16 in Appendix 2-K for ranges of estimated percentage changes in access fees and government revenue by 2050. Note that the information presented includes data from the territory of Tokelau. (Source: Bell et al. 2021)[203].

Country	Average 2015–2018			Change by 2050 (RCP8.5)			Change by 2050 (RCP4.5)		
	Gov't revenue (USD million)	Access fees (USD million)	Gov't revenue (%)	Purse-seine tuna catch (%)[1]	Access fees (USD million)	Gov't revenue (%)	Purse-seine tuna catch (%)[1]	Access fees (USD million)	Gov't revenue (%)
Cook Is.	126.1	13.5	10.6	-4.0	-0.5	-0.4	+8.9	+1.2	+1.0
FSM*	150.6	68.4	47.6	-13.0	-8.9	-5.9	-2.7	-1.8	-1.2
Kiribati	181.7	128.3	70.6	-8.2	-10.5	-5.8	+6.9	+8.9	+4.9
Marshall Is.	66.1	31.0	47.8	-0.7	-0.2	-0.3	+2.1	+0.7	+1.0
Nauru	98.6	29.5	31.1	-21.6	-6.4	-6.5	+5.7	+1.7	+1.7
Palau	75.2	7.1	9.4	-0.3	-0.02	-0.03	+3.1	+0.2	+0.3
PNG**	3360.8	134.3	4.0	-33.1	-44.4	-1.3	-15.5	-20.8	-0.6
Solomon Is.	429.0	41.3	9.6	-26.1	-10.8	-2.5	-8.7	-3.6	-0.8
Tokelau	16.0	13.4	84.2	-16.1	-2.1	-13.4	+5.7	+0.8	+4.8
Tuvalu	47.4	25.6	53.9	-23.4	-6.0	-12.6	+3.4	+0.9	+1.9
TOTAL		492.4			-89.9			-12.0	

2.9.7 Projected changes in biomass of South Pacific albacore by 2050

South Pacific albacore is not taken by purse-seine fishing and therefore features most prominently in the five participating countries in subtropical waters where industrial tuna fishing is generally limited to longline fishing (Fiji, Niue, Samoa, Tonga and Vanuatu).

The modelling to date for South Pacific albacore has been limited to the RCP8.5 emissions scenario. Under this scenario, the projected changes in biomass have some similarities to the projections for the other three tuna species in that biomass is expected to increase in the EPO (Figure 2.13) and decrease throughout much of the WCPO. Biomass of South Pacific albacore is expected to decrease in the EEZs of four of the five Pacific Island countries in the subtropical Pacific that benefit mainly from this species; the exception is Tonga (Table 2.19). The particular vulnerabilities of South Pacific albacore to the projected changes in ocean variables by 2050 are summarised in **Appendix 2-J**.

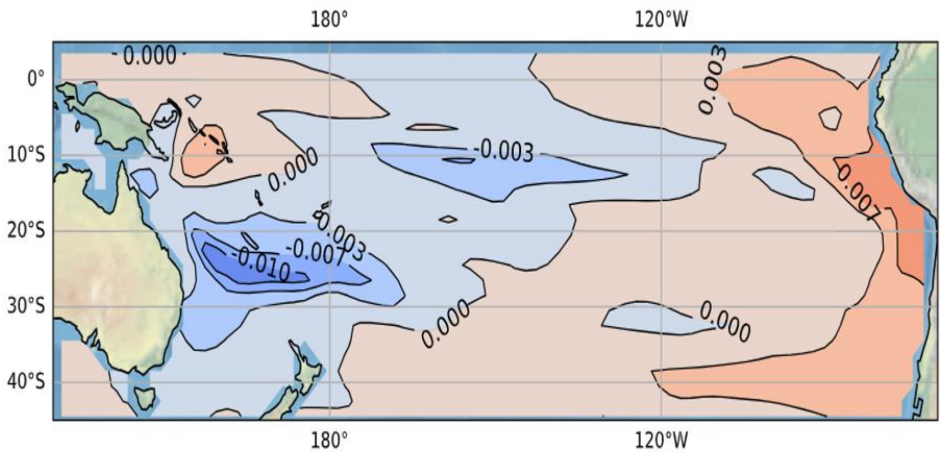


Figure 2.13 Projected differences (negative = blue; positive = red) between future (2046-2055) and historical (2001-2010) periods of mean distributions of total biomass in tonnes km^{-2} of South Pacific albacore across the Pacific Ocean under RCP8.5. The projection uses the high emissions scenario (RCP8.5) from the ensemble simulation. Source: Pacific Community (SPC).

Table 2.19 Projected impact of RCP8.5 emissions scenario on biomass of South Pacific albacore over the decade 2046–2055 (2050) relative to the 2001–2010 in a) the exclusive economic zones (EEZs) of the 14 countries participating in the Programme; and b) high-seas areas (see Supplementary Figure 1 in Appendix 2-K for the locations of these areas). Source: Lehodey et al. (in press)[204]

a)

EEZ	Biomass change (%)
Cook Islands	-5
Federated States of Micronesia	15
Fiji	-10
Kiribati-Gilbert	14
Kiribati-Phoenix	-7
Kiribati-Lines	8
Marshall Islands	0
Nauru	15
Niue	-4
Palau	38
Papua New Guinea	17
Samoa	-5
Solomon Islands	18
Tonga	8
Tuvalu	0
Vanuatu	-9

b)

High-seas area	Biomass change (%)
I1	4
I2	12
I3	
I4	-3
I5	-3
I6	
I7	-1
I8	-9
I9	-10
H4	5
H5	7
EPO-N	
EPO-C	8
EPO-S	19

2.9.8 Implications for fisheries management

The projected climate-driven redistribution of tuna biomass and purse-seine catches also have potential implications for sustainable management of the world's largest tuna fishery. In a scenario where a lower proportion of tuna resources is under the jurisdiction of the PNA VDS (Box 2.1), the sustainability of tuna catches could be at greater risk because the monitoring, control and surveillance (MCS) described in Chapter 1 required to combat illegal, unreported and unregulated fishing, and impose penalties for non-compliance, are more difficult in high-seas areas.[205] This is because responsibility for compliance with fishing regulations on the high seas rests with the states that 'flag' fishing vessels (often resulting in self-regulation), whereas compliance within EEZs is under the purview of coastal states. With continued GHG emissions, the onus will be on WCPFC to implement tighter controls on fishing for tropical tuna species by all vessels operating in high-seas areas of the WCPO.

Sustainable management of tropical Pacific tuna resources will also be challenged by the substantial projected increases in average tuna biomass in the EPO-C high-seas area. particularly under RCP8.5 (Figure 2.12a, Table 2.16). This will necessitate closer collaboration between WCPFC and the regional fisheries management organisation (RFMO) for the EPO, the Inter-American Tropical Tuna Commission (IATTC). The shared governance arrangements between WCPFC and IATTC that are already in place for the overlap in their convention areas (see Supplementary Figure 1 in **Appendix 2-K**) will need to be expanded and strengthened to avoid the problems that have accompanied management of climate-driven shifts in fish distribution in other jurisdictions.[206] [207]

The top priority issues to be addressed during development of an expanded framework for cooperation between WCPFC and IATTC have been described[208] and include: 1) a formal mechanism for cooperation to enable effective and efficient joint decision-making and action by the two RFMOs; 2) further cooperative scientific research and modelling to better understand how the shared tuna stocks will respond to climate change, and to inform stock assessments and harvest strategies; and 3) definition of appropriate limits on fishing for each stock in a way that ensures they are compatible across the two organisations.

2.10 Overview and recommendations

2.10.1 Vulnerability of economies to climate-driven tuna redistribution

The world-leading tuna management practices within the EEZs of the nine tuna-dependent Pacific Island countries have resulted in large and consistent combined catches of the four tropical tuna species during the last decade (Table 2.14). These catches demonstrate that the sustainability goal of *the Regional Roadmap for Sustainable Pacific Fisheries* is being achieved. The purse-seine catch of skipjack, yellowfin and skipjack tuna from the combined EEZs of the nine countries, which averages around 1.4 million tonnes per year, delivers extraordinary economic benefits to these countries – tuna fishing access fees contribute an average of 32% of their non-grant government each year.

Climate-driven redistribution of tuna from the EEZs of these countries into high-seas areas threatens to disrupt the tuna-dependent economies. Projections from preliminary modelling indicate that there could be an average collective decline in tuna biomass from these EEZs of 13% per year under a high emissions scenario (RCP8.5) by 2050. In turn, the decline in biomass could result in an average 20% reduction in tuna purse-seine catch each year, a collective annual average loss of $90 million in fishing access fees, and average losses in government revenue of up to 13% per year for individual countries.

Preliminary modelling also indicates the biomass of South Pacific albacore is likely to decline under the RCP8.5 emissions scenario by 2050 in the EEZs of four of the five subtropical countries where this species provides socio-economic benefits through longline fishing.

The projected climate-driven redistribution of tuna biomass from EEZs into high-seas areas also poses a risk to the sustainable management of the purse-seine and longline fisheries in the WCPO because monitoring, control and surveillance of tuna fishing is typically weaker in high-seas areas than in the EEZs. Sustainable management of tropical Pacific tuna resources is also at risk from projected increases in average tuna biomass in the central EPO. This is due to the limited extent of existing arrangements between WCPFC and IATTC to jointly manage shared tuna stocks.[209]

2.10.2 Recommended activities to minimise the impacts of tuna redistribution

A key recommendation from this assessment is that the considerable uncertainties still associated with the SEAPODYM framework[210] [211] need to be reduced substantially and embodied in an 'Advanced Warning System' (AWS) that Pacific Island countries can use to design policies and adaptations that build climate resilience into the contributions of tuna to their economies. These improvements fall into four main categories:

1) operational oceanography for application across the five ecological provinces in the WCPO described in Section 2.6, and the EPO, to inform SEAPODYM;
2) higher spatial and temporal resolution forecasts and projections of tuna biomass from SEAPODYM across the WCPO and EPO;
3) fleet dynamics and economic models based on 2) above to provide robust short-, medium- and long-term forecasts and projections of spatial fishing effort and government revenue from fishing access fees for policy evaluation and adaptation formulation; and
4) observational data to validate EEZ-scale outputs of SEAPODYM and the fleet dynamics and economic models.

Improvements that enable the spatial resolution of SEAPDOYM simulations to be increased from 2^{o} x 2^{o} to at least 1^{o} x 1^{o}, and forecasts to be available on a scale of 0.5 to 10 years, would allow economists to develop sophisticated fleet dynamics models that predict near-term changes in fishing effort and catch within and among EEZs. In turn, such predictions would enable countries to understand the attractiveness of their EEZs to industry with much greater certainty and to adjust access fees accordingly.

The improvements described above would also provide much greater certainty about the extent to which tuna biomass and fishing effort are likely to be redistributed from the combined EEZs of the tuna-dependent economies (where 95% of the tuna from the entire Pacific Island region is currently caught) to high-seas areas, where the countries do not yet have much control of fishing operations. This information will be vital to developing the adaptations that the tuna-dependent countries need to retain the present-day benefits they receive from their tuna resources, regardless of the effects of climate change on the distribution of the fish. Such adaptations will need to centre around the international negotiations required to raise awareness of the vital importance of tuna to the economies of Pacific Island countries and the need to find equitable solutions to the problems that climate-driven tuna redistribution will cause.

Comprehensive collection of tissue samples from tuna species during development of the AWS would also address the key questions about the extent and nature of the spatial population structure of each tuna species. [212] [213] Where strong spatial structuring exists, the improved SEAPODYM modelling approach could then be applied to each stock and, if multiple stocks occur in countries with large EEZs, the accuracy of projected changes in biomass in those EEZs would be improved by integrating the results from simulations of each stock. Such information would also cast new light on the extent to which discrete tuna stocks may be shared by WCPFC and IATTC, empowering the two RFMOs to manage shared tuna resources more effectively.[214]

Further details of the improvements to be made to the modelling during development of the AWS are provided in **Appendix 2-L**.

2.11 Regional climate change adaptation frameworks and policies

The Activities to be implemented during the Programme, including development of the AWS, are expected to inform existing regional and national policy initiatives to build the resilience of the fisheries sector, and the dependent communities and economies, to climate change. They will also inform the Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs) of the participating countries. A summary of these NDCs and NAPs is provided in **Appendix 2-M**.

The most important initiatives being undertaken by the participating countries to build the resilience of the fisheries sector to climate change are summarised below, together with other policy frameworks to address the full range of challenges involved in securing sustainable fisheries and managing threats to coastal and oceanic ecosystems.

2.11.1 WCPFC Resolution 2019-01

The Western and Central Pacific Fisheries Commission's Climate Resolution (CMM 2019-01) is the first declaration by a RFMO to address the inter-related issues of climate change and WCPO fisheries.[215] The resolution was prompted by a delegation proposal from FFA members to the annual Commission meeting in December 2019. The FFA paper brought to the commission's attention a Forum Leaders' declaration from August 2019, declaring the need for urgent climate action.[216] The issues put forward by FFA members are all broadly reflected in the five key points of the WCPFC resolution.

Although the resolution has not, to date, been implemented through a clear action plan, at the 2022 WCPFC meeting it was agreed that annual updates on the climate resolution will be a standing item on the Commission's agenda. Climate Change will also now be considered in the meetings of WCPFC subsidiary bodies. The AWS Component of the Programme will support the practical application of Resolution 2019-01. The key elements of the resolution are:

Resolution point 1:

Consider the potential impacts of climate change on highly migratory fish stocks in the Convention Area and any related impacts on the economies of CCMs and food security and livelihoods of their people, in particular Small Islands Developing States and Participating Territories.

Resolution point 2:

Support further development of science on the relationship between climate change and target stocks, non-target species, and species belonging to the same ecosystem or dependent on or associated with the target stocks, as well as interrelationships with other factors that affect these stocks and species, and estimates of the associated uncertainties.

Resolution point 3:

Take into account in its deliberations, including in the development of conservation and management measures, scientific information available from the Scientific Committee on the potential impacts of climate change on target stocks, non-target species, and species belonging to the same ecosystem or dependent on or associated with the target stocks.

Resolution point 4:

Consider how climate change and fishing activities may be related and address any potential impacts in a manner consistent with the Convention.

Resolution point 5:

Consider options to reduce the environmental impacts of the Commission related to headquarters operation and meetings of the Commission and its subsidiary bodies.

2.11.2 FFA Climate Change Strategic Plan

The Forum Fisheries Committee adopted an FFA Climate Change Strategy[217] at its Special Session in August 2023. The purpose of the strategy is to guide FFA to prepare for and respond to the risks and consequences of climate change to Pacific Island offshore fisheries to ensure that these fisheries and associated economic and social benefits are climate resilient.

Given the all-encompassing and complex nature of climate change, the strategy recognizes that a collective effort is required to prepare and respond to climate-driven threats by taking a proactive approach to managing the potential risks and increasing the resilience of offshore fisheries and associated benefits for the people who depend on them. This will be achieved by maintaining a good understanding of the broader connected impacts of climate change in the region and associated economic, social, security and environmental implications.

Special recognition is accorded to smaller island FFA members who are heavily dependent on tuna fishing access fees for government revenue for key functions, including addressing the effects of climate change for their citizens.

The FFA strategy supports six key objectives with associated specific strategies to deliver on each objective. FFA members and the secretariat are committed to working together in implementing these strategies, under the direction of the Forum Fisheries Committee.

- actioning climate change adaptation and resilience;
- achieving climate justice;
- accessing climate finance;
- contributing to mitigation;
- capacity building and institutional strengthening; and
- advocacy and engagement.

2.11.3 Other relevant regional policies

The pre-eminent regional policy guidance documents on ocean and natural resource management are the *Pacific Island Regional Ocean Policy*[218] (PIROP) and the *Pacific Plan*.[219] Examples of other associated policy responses are the Pacific Island Leaders' *Vava'u Declaration on Pacific Fisheries Resources: Our Fish, Our Future*[220], which called for effective management of coastal fisheries to support food security and sustainable livelihoods; the *Apia Policy*[221] to harness the benefits of coastal fisheries; the Melanesian Spearhead Group's *Roadmap for inshore fisheries management and sustainable development 2014–2023*[222]; the Pacific Islands Forum Secretariat's *Framework for a Pacific Oceanscape*[223]; and the *2014 Palau Declaration: The Ocean: Life and Future*.[224] These documents collectively call on Pacific Island countries and territories to implement integrated coastal resource management arrangements, drawing on the strengths and traditions of community, district, provincial and national levels of government, and regional approaches, to achieve sustainable island life. Further details of a selection of these documents, together with other complementary regional policies, are provided in **Appendix 2-N**.

2.12 Appendices

Appendix 2.A. A brief summary of the development of emissions scenarios by the IPCC as applied in the GCF Regional Tuna Programme Funding Proposal

Appendix 2-B. Bio-physical features of the tropical Pacific Ocean linked to changes in surface climate

Appendix 2-C. Observed and projected changes to key features of surface climate and the tropical Pacific Ocean

Appendix 2-D. Structure and distribution of coastal fish habitats, and changes projected by IPCC

Appendix 2-E. Phytoplankton production: regenerated and new

Appendix 2-F. Structure, variability and vulnerability of food webs in each province

Appendix 2-G. Indirect and direct effects of climate change on coastal fish and invertebrate species

Appendix 2-H. Uncertainties associated with projections of coastal fisheries production

Appendix 2-I. Observed effects of ENSO and other climate variability on tuna

Appendix 2-J. Summary of the vulnerability of the four tuna species to climate-driven changes in ocean variables

Appendix 2-K. Supplementary Information for analysis of climate-driven tuna redistribution

Appendix 2-L. Improvements in modelling needed to develop an 'Advanced Warning System'

Appendix 2-M. Key climate change policy documents in each participating country and contribution of the Programme to advancing climate change strategies.

Appendix 2-N. Regional policy frameworks that will be informed by the Outputs of the Programme

Endnotes

[1] Murawski, S.A. 2011. Summing up Sendai: Progress integrating climate change science and fisheries. *ICES Journal of Marine Science* 68, 1368–1372.

[2] Bell, J.D., Ganachaud, A., Gehrke, P.C., Griffiths, S.P., Hobday, A.J. *et al.* 2013. Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Climate Change* 3, 591–599.

[3] Except in some inland areas remote from the coast in Papua New Guinea, Solomon Islands and Vanuatu.

[4] IPCC, 2023: Sections. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team: H. Lee and J. Romero (Eds.)]. IPCC, Geneva, Switzerland, pp. 35–115, doi: 10.59327/IPCC/AR6-9789291691647

[5] IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above preindustrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (Eds.)] https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_Low_Res.pdf

[6] Oppenheimer, M., Glavovic, B.C., Hinkel, J. et al. 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M, Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. and Weyer, N.M. (Eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 321–445. https://doi.org/10.1017/9781009157964.006

[7] Hoegh-Guldberg, O., Poloczanska, E.S., Skirving, W., Dove, S. 2017. Coral reef ecosystems under climate change and ocean acidification. *Frontiers in Marine Science 4*: 158.

[8] Hoegh-Guldberg, O., Poloczanska, E.S., Skirving, W. and Dove, S. 2017. Coral reef ecosystems under climate change and ocean acidification. *Frontiers in Marine Science 4*: 158

[9] Senina, I., Lehodey, P., Calmettes, B., Dessert, M., Hampton, J., Smith, N., Gorgues, T., Aumont, O., Lengaigne, M., Menkes, C. and Nicol, S., 2018. Impact of climate change on tropical Pacific tuna and their fisheries in Pacific Islands waters and high seas areas. 14th Regular Session of the Scientific Committee of the Western and Central Pacific Fisheries Commission, WCPFC-SC14-EB-WP-01. Busan, Republic of Korea, 8–16 August 2018. 44 pages.

[10] Bell, J.D., Kronen, M., Vunisea, A., Nash, W.J. and others. 2009. Planning the use of fish for food security in the Pacific. *Marine Policy* 33, 64–76.

[11] Source of economic data: Pacific Islands Forum Fisheries Agency.

[12] SPC 2008. Fish and Food Security. SPC Policy Brief 1/2008. https://pacificdata.org/data/dataset/oai-www-spc-intced24e95-7e0a-401a-9f0b-d79316c49cb0

[13] Bell, J.D., Kronen, M., Vunisea, A., Nash, W.J. and others. 2009. Planning the use of fish for food security in the Pacific. *Marine Policy* 33, 64–76.

[14] https://meetings.wcpfc.int/meetings/sc19

[15] Bell J.D. *et al.* 2015. Diversifying the use of tuna for food security and public health in Pacific Island countries and territories. Marine Policy 51:584-591. http://dx.doi.org/10.1016/j.marpol.2014.10.005.

[16] Bell, J.D., Allain, V., Allison, E.H., Andréfouët, S., Andrew, N.L., Batty, M.J., Blanc, M., Dambacher, J.M., Hampton, J., Hanich, Q. and Harley, S. 2015. Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories. *Marine Policy*, *51*, pp.584-591.

[17] FFA and SPC. Regional Roadmap for Sustainable Pacific Fisheries. https://www.spc.int/DigitalLibrary/Doc/FAME/Brochures/FFA_SPC_2015_Roadmap.pdf

[18] Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu, plus Tokelau.

[19] Clark, S., Bell, J., Adams, T., Allain, V., Aqorau, T., Hanich, Q., Jaiteh, V., Lehodey, P., Pilling, G., Senina, I., Smith, N., Williams, P. and Yeeting, A.2021. The Parties to the Nauru Agreement (PNA) 'Vessel Day Scheme': A cooperative fishery management mechanism assisting member countries to adapt to climate variability and change. In: Bahri, T., Vasconcellos, M., Welch, D.J., Johnson, J., Perry, R.I., Ma, X. and Sharma, R. (Eds.) *Adaptive management of fisheries in response to climate change*. Pages 209-224. FAO Fisheries and Aquaculture Technical Paper No. 667. Rome, FAO. https://doi.org/10.4060/cb3095en

[20] Havice, E. 2013. Rights-based management in the Western and Central Pacific Ocean tuna fishery: Economic and environmental change under the Vessel Day Scheme. *Marine Policy*, *42*, pp.259-267.

[21] Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S. *et al.* 2021. Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability* 4, 900-910;

[22] Lam, V.W.Y. *et al.* 2020. Climate change, tropical fisheries and prospects for sustainable development. *Nature Reviews: Earth and Environment.* https://doi.org/10.1038/ s43017-020-0071-9

[23] Pacific Islands Forum Fisheries Agency, fisheries development data for the 4-year period 2015–2018.

[24] Based on the most recent, but as yet unpublished, modelling and economic analyses by the project partners. These analyses update the information in SPC Policy Brief 32.

[25] Pacific Islands Forum Fisheries Agency, fisheries development data for the four-year period 2015–2018.

[26] Ruaia, T., Gu'urau, S. and Wheatley, L. 2023. Economic and development indicators and statistics: Tuna fisheries of the Western and Central Pacific Ocean 2022. Pacific Islands Forum Fisheries Agency, Honiara, Solomon Islands. 74 pages.

[27] SPC 2019. Implications of climate-driven distribution of tuna on Pacific Island economies. SPC Policy Brief 32/2019. https://www.spc.int/DigitalLibrary/Doc/FAME/Brochures/Anon_19_PolicyBrief32_TunaClimate.html

[28] Senina, I. *et al.* 2018. Impact of climate change on tropical Pacific tuna and their fisheries in Pacific Islands waters and high seas areas. Western and Central Pacific Fisheries Commission 14th Scientific Committee, Working Paper SC14-EB-WP-01 https://www.wcpfc.int/node/30981

[29] Table 2.39 updates Annex 1 of the Concept Note utilising new modelling information presented in: Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S. *et al.* 2021. Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability* 4, 900-910.

[30] https://pacificclimatechange.net/document/frdp_2016

[31]https://www.wcpfc.int/doc/resolution-2008-01/resolution-aspirations-small-island-developing-states-and-territories

[32] https://ffa.int/system/files/Roadmap_web_0.pdf

[33] https://www.spc.int/DigitalLibrary/Doc/FAME/Reports/Anon_2015_New_song_for_coastal_fisheries.html

[34] Gallo, N. *et al.* 2017. Ocean commitments under the Paris Agreement. *Nature Climate Change* 10.1038/nclimate3422.

[35] Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K. *et al.* 2007. Observations: oceanic climate change and sea level. In Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. Eds. Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 385–428. Cambridge, UK, Cambridge University Press. (also available at https://www.ipcc.ch/ publications_and_data/ar4/wg1/en/ch5.html).

[36] A brief summary of the development of emissions scenario terminology and categorisation by the IPCC is presented at Appendix 2-A for reference purposes.

[37] Hobday, A.J., Alexander, L.V., Perkins, S.E., Smale, D.A., Straub, S.C., Oliver, E.C.J., Benthuysen, J. *et al.* 2016. A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, 141: 227–238. https://doi.org/10.1016/j.pocean.2015.12.014).

[38] Bell, J.D., Johnson, J.E. & Hobday, A.J., eds. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Noumea, Secretariat of the Pacific Community, 925 pp. (also available at http://www.spc.int/cces/climate-book/spc-publications-onclimate-change/).

[39] Bell, J.D., Ganachaud, A., Gehrke, P.C., Griffiths, S.P., Hobday, A.J., Hoegh-Guldberg, O., Johnson, J.E. *et al.* 2013. Mixed responses of tropical Pacific fisheries and aquaculture to climate change. Nature Climate Change, 3: 591–599. https://doi. org/10.1038/nclimate1838.

[40] Hay, C.C., Morrow, E., Kopp, R.E. & Mitrovica, J.X. 2015. Probabilistic reanalysis of twentieth-century sea-level rise. *Nature*, 517(7535): 481–484. https:// doi.org/10.1038/nature14093.

[41] IPCC. 2014. Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report on the Intergovernmental Panel on Climate Change. Core writing team, R.K. Pachauri & L.A. Meyer, eds. Geneva, Intergovernmental Panel on Climate Change. 151 pp. http://www.ipcc.ch/report/ar5/syr/.

[42] Langlais, C.E., Lenton, A., Heron, S., Evenhuis, C., Sen Gupta, A., Brown, J.N. & Kuchinke, M. 2017. Coral bleaching pathways under the control of regional temperature variability. *Nature Climate Change*, 7: 839–844. https://doi.org/10.1038/nclimate3399.

[43] Royal Society. 2005. Ocean acidification due to increasing atmospheric carbon dioxide. Policy document, 12/05. London, The Royal Society. 57 pp. https:// royalsociety.org/topics-policy/publications/2005/ocean-acidification/

[44] Langdon, C. and Atkinson, M.J. 2005. Effect of elevated pCO_2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. Journal of Geophysical Research, 110: C09S07. https://doi.org/10.1029/2004JC002576.

[45] Langdon, C. and Atkinson, M.J. 2005. Effect of elevated pCO_2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. Journal of Geophysical Research, 110: C09S07. https://doi.org/10.1029/2004JC002576.

[46] Bell, J.D., Allain, V., Sen Gupta, A., Johnson, J.J., Hampton, J., Hobday, A.J., Lehodey, P., Lenton, A., Moore, B.R., Morgan, Pratchett, M.S., Senina, I., Smith, N. and Williams, P. 2018. Climate change impacts, vulnerabilities and adaptations: Western and Central Pacific Ocean marine fisheries. In: Barange, M., Bahri, T., Beveridge, M.C.M., Cochrane, K.L., Funge-Smith, S. and Poulain, F. Eds. 2018. Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper No. 627. Rome, FAO. 22 pages.

[47] Hu, D., Wu, L., Cai, W., Sen Gupta, A., Ganachaud, A., Qiu, B., Gordon, A.L. *et al.* 2015. Pacific western boundary currents and their roles in climate. *Nature*, 522(7556): 299–308. https://doi.org/10.1038/nature14504.

[48] Sen Gupta, A., McGregor, S., van Sebille, E., Ganachaud, A., Brown, J.N, and Santoso, A. 2016. Future changes to the Indonesian throughflow and Pacific circulation: The differing role of wind and deep circulation changes. *Geophysical Research Letters*, 43(4): 1669–1678. (also available at http://doi.org/10.1002/2016GL067757).

[49] Bell, J.D., Johnson, J.E. and Hobday, A.J. Eds. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Noumea, Secretariat of the Pacific Community, 925 pp. http://www.spc.int/cces/climate-book/spc-publications-onclimate-change/.

[50] Waycott M., McKenzie L.J., Mellors J.E., Ellison J.C., Sheaves M.T., Collier C., Schwarz A-M., Webb A., Johnson J.E., Payri C.E. (2011) Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate

change. In: Bell JD, Johnson JE and Hobday AJ (Eds). Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change in the tropical. Secretariat of the Pacific Community, Noumea, New Caledonia.

[51] Guannel G., Arkema K., Ruggiero P., Verutes G. (2016) The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience. Plos One 11, e0158094.

[52] Veitayaki J., Waqalevu V., Varea R., Rollings N. (2017) Mangroves in small island development states in the Pacific: An overview of a highly important and seriously threatened resource. Participatory Mangrove Management in a Changing Climate: Perspectives from the Asia-Pacific, 303-327.

[53] Bell, J.D., Allain, V., Sen Gupta, A. et al. 2018. Climate change impacts, vulnerabilities and adaptations: Western and Central Pacific Ocean marine fisheries. In: Barange, M., Bahri, T., Beveridge, M.C.M., Cochrane, K.L., Funge-Smith, S. and Poulain, F. Eds. Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper No. 627. Rome, FAO. 22 pages.

[54] Sanciangco J.C., Carpenter K.E., Etnoyer P.J., Moretzsohn F. (2013) Habitat Availability and Heterogeneity and the Indo-Pacific Warm Pool as Predictors of Marine Species Richness in the Tropical Indo-Pacific. PLoS ONE 8(2): e56245. doi:10.1371/journal.pone.0056245

[55] Souter D., Planes S., Wicquart J., Logan M., Obura D., Staub F. (Eds) (2021) Status of Coral Reefs of the World: 2020 Report. Chapter 9. Status and trends of coral reefs of the Pacific region. Global Coral Reef Monitoring Network (GCRMN) and International Coral Reef Initiative (ICRI).

[56] Souter D., Planes S., Wicquart J., Logan M., Obura D., Staub F. (Eds) (2021a) Status of Coral Reefs of the World: 2020 Report. Global Coral Reef Monitoring Network (GCRMN) and International Coral Reef Initiative (ICRI). DOI: 10.59387/WOTJ9184

[57] McKenzie L.J., Yoshida R.L., Aini J.W., Andréfouet S., Colin P.L., Cullen-Unsworth L.C., Hughes A.T., Payri C.E., Rota M., Shaw C., Skelton P.A. (2021) Seagrass ecosystems of the Pacific Island Countries and Territories: A global bright spot. Marine Pollution Bulletin, 167, 112308.

[58] McKenzie L.J., Yoshida R.L., Aini J.W., Andréfouet S., Colin P.L., Cullen-Unsworth L.C., Hughes A.T., Payri C.E., Rota M., Shaw C., Skelton P.A. (2021) Seagrass ecosystems of the Pacific Island Countries and Territories: A global bright spot. Marine Pollution Bulletin, 167, 112308.

[59] Cullen-Unsworth L., Unsworth, R. (2013) Seagrass meadows, ecosystem services, and sustainability. Environment: Science and policy for sustainable development, 55(3), 14-28.

[60] Senilolia H., Skelton P.A., Tuiwawa M.V. (2014) A field guide to the mangrove and seagrass species of Fiji. USP Press, Suva, Fiji.

[61] Veitayaki J., Waqalevu V., Varea R., Rollings N. (2017) Mangroves in small island development states in the Pacific: An overview of a highly important and seriously threatened resource. Participatory Mangrove Management in a Changing Climate: Perspectives from the Asia-Pacific, 303-327.

[62] Hoegh-Guldberg O., Mumby P.J., Hooten A.J. et al. (2007) Coral reefs under rapid climate change and ocean acidification. Science, 318, 1737–1742.

[63] IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/SROCC_FullReport_FINAL.pdf

[64] IPCC, 2023: Sections. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

[65] Hughes T.P., Kerry J.T., Baird A.H. et al. (2018) Global warming transforms coral reef assemblages. Nature, 556(7702), 492-496.

[66] Hughes T.P., Kerry J.T., Alvarez-Noriega M. et al. (2017) Global warming and recurrent mass bleaching of corals. Nature, 543, 373.

[67] IPCC (2018) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner et al. (eds.)] https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_Low_Res.pdf

[68] Hoegh-Guldberg O., Kennedy E.V., Beyer H.L., McClennen C., Possingham H.P. (2018) Securing a long-term future for coral reefs. Trends in Ecology & Evolution, 33(12), 936-944.

[69] UNEP (2017) Coral Bleaching Futures - Downscaled projections of bleaching conditions for the world's coral reefs, implications of climate policy and management responses. United Nations Environment Programme, Nairobi, Kenya.

[70] Doney S.C., Busch D.S., Cooley S.R., Kroeker K.J. (2020) The impacts of ocean acidification on marine ecosystems and reliant human communities. Annual Review of Environment and Resources, 45, 83-112.

[71] Evenhuis C., Lenton A., Cantin N.E., Lough J.M. (2015) Modelling coral calcification accounting for the impacts of coral bleaching and ocean acidification. Biogeosciences, 12, 2607–2630.

[72] Wenger A.S., Harris D., Weber S., Vaghi F., Nand Y., Naisilisili W., Hughes A., Delevaux J., Klein C.J., Watson J., Mumby P.J., Jupiter S.D. (2020) Best-practice forestry management delivers diminishing returns for coral reefs with increased land-clearing. Journal of Applied Ecology, 57 (12), 2381–2392. https://doi.org/10.1111/1365-2664.13743

[73] van Hooidonk R., Maynard J.A., Manzello D., Planes S. (2014) Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. Global Change Biology, 20, 103–112.

[74] Waycott M., McKenzie L.J., Mellors J.E. et al. (2011) Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate change. In: Bell JD, Johnson JE and Hobday AJ (Eds). Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change in the tropical. Secretariat of the Pacific Community, Noumea, New Caledonia.

[75] Adams M.P., Koh E.J., Vilas M.P. et al. (2020) Predicting seagrass decline due to cumulative stressors. Environmental Modelling & Software, 130, p.104717.

[76] Waycott M., McKenzie L. (2010) Indicators and thresholds of concern for seagrass ecosystem health for the Great Barrier Reef. Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns, 56pp.

[77] McKenzie L.J., Yoshida R.L. (2020) Over a decade monitoring Fiji's seagrass condition demonstrates resilience to anthropogenic pressures and extreme climate events. Marine Pollution Bulletin, 160, p.111636.

[78] Duke N.C., Hutley L.B., Mackenzie J.R. Burrows D. (2021) Processes and factors driving change in mangrove forests: An evaluation based on the mass dieback event in Australia's Gulf of Carpentaria. Ecosystem collapse and climate change, 221-264. Cham: Springer International Publishing.

[79] Waycott M., McKenzie L.J., Mellors J.E. et al. (2011) Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate change. In: Bell JD, Johnson JE and Hobday AJ (Eds). Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change in the tropical. Secretariat of the Pacific Community, Noumea, New Caledonia.

[80] Lovelock C.E., Cahoon D.R., Friess D.A. et al. (2015) The vulnerability of Indo-Pacific mangrove forests to sea-level rise. Nature, 526(7574), 559-563.

[81] Leahy S.M., Robins J.B. (2021) River flows affect the growth of a tropical finfish in the wet-dry rivers of northern Australia, with implications for water resource development. Hydrobiologia, 848(18), 4311-4333.

[82] Duke N.C., Hutley L.B., Mackenzie J.R. Burrows D. (2021) Processes and factors driving change in mangrove forests: An evaluation based on the mass dieback event in Australia's Gulf of Carpentaria. Ecosystem collapse and climate change, 221-264. Cham: Springer International Publishing.

[83] The section draws significantly from Chapters 3 and 4 in Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 2. pp. 49–100. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[84] Ganachaud, A.S., Sen Gupta, A., Orr, J.C., Wijffels, S.E., Ridgway, K.R., Hemer, M.A., Maes, C., Steinberg, C.R., Tribollet, A.D., Qiu, B. and Kruger, J.C. 2011. Observed and expected changes to the tropical Pacific Ocean. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 3. pp. 101–188. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[85] Pomeroy, L.R. 1979. Secondary production mechanisms of continental shelf communities. In: Livingstone, R.J. (Ed) Ecological processes in coastal and marine systems. Plenum Press, New York, United States of America, pp. 163–186.

[86] Longhurst, A.R. 1991. Role of the marine biosphere in the global carbon cycle. *Limnology and Oceanography* 36, 1507–1526.

[87] Fasham, M.J.R. 2003. Ocean biogeochemistry. The role of the ocean carbon cycle in global change. Springer Verlag, Berlin, Germany.

[88] Lehodey, P., Hampton, J., Brill, R.W., Nicol, S., Inna Senina, I., Calmettes, B., Pörtner, H.O., Bopp, L., Ilyina, T., Bell, J.D. and Sibert, J. 2011. Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In: Bell

J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 8. pp 433–491. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[89] Lehodey, P., André, J.M., Bertignac, M., Hampton, J. and others. 1998. Predicting skipjack tuna forage distributions in the equatorial Pacific using a coupled dynamical biogeochemical model. *Fisheries Oceanography* 7, 317–325.

[90] Lehodey, P., Chai, F. and Hampton, J. 2003. Modelling climate-related variability of tuna populations from a coupled ocean-biogeochemical-populations dynamics model. *Fisheries Oceanography* 12, 483–494.

[91] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[92] Azam, F., Fenchel, T., Gray, J.G., Meyer-Reil, L.A. and Thingstad, T. 1983. The ecological role of water-column microbes in the sea. *Marine Ecology Progress Series* 10, 257–263.

[93] Sherr, E. and Sherr, B. 2008. Understanding roles of microbes in marine pelagic food webs: A brief history. In: Kirchman, D.L. (Ed) Microbial Ecology of the Oceans. John Wiley and Sons Inc., Hoboken, New Jersey, United States of America, pp. 27–44.

[94] Richardson, T.L. and Jackson, G.A. 2007. Small phytoplankton and carbon export from the surface ocean. *Science* 315, 838–840.

[95] Roger, C. 1994. Relationships among yellowfin and skipjack tuna, their prey-fish and plankton in the tropical western Indian Ocean. *Fisheries Oceanography* 3, 133–141.

[96] Ganachaud, A.S., Sen Gupta, A., Orr, J.C., Wijffels, S.E., Ridgway, K.R., Hemer, M.A., Maes, C., Steinberg, C.R., Tribollet, A.D., Qiu, B. and Kruger, J.C. 2011. Observed and expected changes to the tropical Pacific Ocean. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 3. pp. 101–188. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[97] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[98] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[99] Legand, M., Bourret, P., Fourmanoir, P., Grandperrin, R. and others. 1972. Relations trophiques et distributions verticales en milieu pélagique dans l'océan Pacifique intertropical. Cahiers ORSTOM, *Série Océanographie* 10, 303–393.

[100] Potier, M., Marsac, F., Lucas, V., Sabatié, R. and others. 2004. Feeding partitioning among tuna taken in surface and mid-water layers: The case of yellowfin (Thunnus albacares) and bigeye (T. obesus) in the Western Tropical Indian Ocean. *Western Indian Ocean Journal Marine Science* 3, 51–62.

[101] Young, J.W., Lansdell, M., Riddoch, S. and Revill, A. 2006. Feeding ecology of broadbill swordfish, Xiphias gladius (Linnaeus, 1758), off eastern Australia in relation to physical and environmental variables. *Bulletin of Marine Science* 79, 793–811.

[102] Graham, B.S., Grubbs, D., Holland, K. and Popp, B.N. 2007. A rapid ontogenic shift in the diet of juvenile yellowfin tuna from Hawaii. *Marine Biology* 150, 647–658.

[103] Ménard, F., Lorrain, A., Potier, M. and Marsac, F. 2007. Isotopic evidence of distinct feeding ecologies and movement patterns in two migratory predators (yellowfin tuna and swordfish) of the western Indian Ocean. *Marine Biology* 153, 141–52.

[104] Graham, B.S., Grubbs, D., Holland, K. and Popp, B.N. 2007. A rapid ontogenic shift in the diet of juvenile yellowfin tuna from Hawaii. *Marine Biology* 150, 647–658.

[105] Landsell, M. and Young, J.W. 2007. Pelagic cephalopods from eastern Australia: Species composition, horizontal and vertical distribution determined from the diets of pelagic fish. *Reviews in Fish Biology and Fisheries* 17, 125–138.

[106] Young, J.W., Lansdell, M., Hobday, A., Dambacher, J. and others. 2009. Determining Ecosystem Effects of Longline Fishing in the Eastern Tuna and Billfish Fishery. Final Report 2004/063, Fisheries Research and Development Corporation, Canberra, Australia.

[107] Revill, A.T., Young, J.W. and Lansdell, M. 2009. Stable isotopic evidence for trophic groupings and bioregionalization of predators and their prey in oceanic waters off eastern Australia. *Marine Biology* 156, 1241–1253.

[108] Source: *Institut de Recherche pour le Développement* cited in: Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[109] Defined by: Longhurst, A.R. 2006. Ecological geography of the sea. Academic Press, New York, United States of America.

[110] Le Borgne, R., Barber, R.T., Delcroix, T., Inoue, H.Y. and others. 2002. Pacific warm pool and divergence: Temporal and zonal variations on the equator and their effects on the biological pump. *Deep-Sea Research II* 49, 2471–2512.

[111] Ganachaud, A.S., Sen Gupta, A., Orr, J.C., Wijffels, S.E., Ridgway, K.R., Hemer, M.A., Maes, C., Steinberg, C.R., Tribollet, A.D., Qiu, B. and Kruger, J.C. 2011. Observed and expected changes to the tropical Pacific Ocean. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 3. pp. 101–188. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[112] Herbland, A. and Voituriez, B. 1979. Hydrological structure analysis for estimating the primary production in the tropical Atlantic ocean. *Journal of Marine Research* 37, 87–101.

[113] Ganachaud, A.S., Sen Gupta, A., Orr, J.C., Wijffels, S.E., Ridgway, K.R., Hemer, M.A., Maes, C., Steinberg, C.R., Tribollet, A.D., Qiu, B. and Kruger, J.C. 2011. Observed and expected changes to the tropical Pacific Ocean. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 3. pp. 101–188. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[114] Eldin, G. and Rodier, M. 2003. Ocean physics and nutrients fields along 180° during an El Niño-Southern Oscillation cold phase. *Journal of Geophysical Research* 108, 8136, doi:10.1029/2000JC000746

[115] Mackey, D.J., O'Sullivan, J.E. and Watson, R.J. 2002. Iron in the western Pacific: A riverine or hydrothermal source for iron in the Equatorial Undercurrent. *Deep-Sea Research I* 49, 877–893.

[116] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[117] Le Borgne, R., Barber, R.T., Delcroix, T., Inoue, H.Y. and others. 2002. Pacific warm pool and divergence: Temporal and zonal variations on the equator and their effects on the biological pump. *Deep-Sea Research II* 49, 2471–2512.

[118] Murtugudde, R.G., Signorini, S.R., Christian, J.R., Busalacchi, A.J. and others. 1999. Ocean color variability of the tropical Indo – Pacific basin observed by Sea WiFS during 1997–1998. *Journal of Geophysical Research* 104, 18,351–18,366.

[119] Rodier, M., Eldin, G. and Le Borgne, R. 2000. The western boundary of the equatorial Pacific upwelling: Some consequences of climatic variability on hydrological and planktonic properties. *Journal of Oceanography* 56, 463–471.

[120] Ganachaud, A.S., Sen Gupta, A., Orr, J.C., Wijffels, S.E., Ridgway, K.R., Hemer, M.A., Maes, C., Steinberg, C.R., Tribollet, A.D., Qiu, B. and Kruger, J.C. 2011. Observed and expected changes to the tropical Pacific Ocean. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 3. pp. 101–188. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[121] Murtugudde RG, Signorini SR, Christian JR, Busalacchi AJ and others (1999) Ocean color variability of the tropical Indo – Pacific basin observed by Sea WiFS during 1997–1998. *Journal of Geophysical Research* 104, 18,351–18,366.

[122] McClain, C.R., Christian, J.R., Signorini, S.R., Lewis, M.R. and others. 2002. Satellite ocean color observations of the tropical Pacific Ocean. *Deep-Sea Research II* 49, 2533–2560.

[123] Ishii, M., Saito, S., Tokieda, T., Kawano, T. and others. 2004. Variability of surface layer CO2 parameters in the western and central equatorial Pacific. In: M Shiyomi, H Kawahata, H Koizumi, A Tsuda and Y Awaya (eds) Global environmental change in the ocean and on land. Terra Pub, Tokyo, Japan, pp. 59–94.

[124] Lough, J.M., Meehl, G.A. and Salinger, M.J. 2011. Observed and projected changes in surface climate of the tropical Pacific. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and

aquaculture to climate change. Chapter 2. pp. 49–100. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[125] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[126] Lehodey, P., Hampton, J., Brill, R.W., Nicol, S., Senina, I., Calmettes, B., Pörtner, H.O., Bopp, L., Ilyina, T., Bell, J.D. and Sibert, J. 2011. Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 8. pp 433–491. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[127] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[128] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[129] Ganachaud, A.S., Sen Gupta, A., Orr, J.C., Wijffels, S.E., Ridgway, K.R., Hemer, M.A., Maes, C., Steinberg, C.R., Tribollet, A.D., Qiu, B. and Kruger, J.C. 2011. Observed and expected changes to the tropical Pacific Ocean. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 3. pp. 101–188. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[130] Ganachaud, A.S., Sen Gupta, A., Orr, J.C., Wijffels, S.E., Ridgway, K.R., Hemer, M.A., Maes, C., Steinberg, C.R., Tribollet, A.D., Qiu, B. and Kruger, J.C. 2011. Observed and expected changes to the tropical Pacific Ocean. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 3. pp. 101–188. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[131] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[132] Composite of sources provided in: Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189-–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[133] Legand, M., Bourret, P., Fourmanoir, P., Grandperrin, R. and others. 1972. Relations trophiques et distributions verticales en milieu pélagique dans l'océan Pacifique intertropical. Cahiers ORSTOM, Série Océanographie 10, 303–393.

[134] Bertrand, A., Le Borgne, R. and Josse, E. 1999. Acoustic characterization of micronekton distribution in French Polynesia. Marine Ecology Progress Series 191, 127–140.

[135] Roger, C. 1986. Macroplancton et micronecton dans le Pacifique tropical sud-ouest. *Océanographie Tropicale 21*, 153–165.

[136] Hidaka, K., Kawaguchi, K., Tanabe, T., Takahashi, M. and Kubodera, T. 2003. Biomass and taxonomic composition of micronekton in the western tropical-subtropical Pacific. *Fisheries Oceanography 12,* 112–125.

[137] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[138] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189-250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[139] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and

Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.
[140] Tagliabue, A., Bopp, L. and Aumont, O. 2008. Ocean biogeochemistry exhibits contrasting responses to a large scale reduction in dust deposition. *Biogeosciences* 5, 11–24.
[141] Ganachaud, A.S., Sen Gupta, A., Orr, J.C., Wijffels, S.E., Ridgway, K.R., Hemer, M.A., Maes, C., Steinberg, C.R., Tribollet, A.D., Qiu, B. and Kruger, J.C. 2011. Observed and expected changes to the tropical Pacific Ocean. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 3. pp. 101–188. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.
[142] Langdon, C., Takahashi, T., Sweeney, C., Chipman, D. and others. 2000. Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef. *Global Biogeochemical Cycles 14*, 639–654.
[143] Iglesias-Rodriguez, M., Buitenhuis, E. and Raven, J. 2008. Response to comment on phytoplankton calcification in a high-CO2 world peer reviewed article. *Science* 322, 1466.
[144] Riebesell, U., Bellerby, R., Engel, A., Fabry, V. and others. 2008. Comment on 'Phytoplankton Calcification in a High-CO2 World'. *Science* 322, 1466
[145] Iglesias-Rodriguez, M.D., Halloran, P.R., Rickaby, R.E.M., Hall, I.R. and others. 2008. Phytoplankton calcification in a high-CO2 world. *Science* 320, 336–340.
[146] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.
[147] Bell J.D., Johnson, J.E. and Hobday, A.J., Eds, 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 2. pp. 49-–100. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.
[148] Johnson, J.E., Welch, D.J., Maynard, J.A., Bell, J.D., Pecl, G., Robins, J., Saunders, T. 2016. Assessing and reducing vulnerability to climate change: Moving from theory to practical decision-support. *Marine Policy,* 74, 220–229.
[149] Lough, J.M., Meehl, G.A. and Salinger, M.J. 2011. Observed and projected changes in surface climate of the tropical Pacific. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 2. pp. 49–100. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.
[150] Ganachaud, A.S., Sen Gupta, A., Orr, J.C., Wijffels, S.E., Ridgway, K.R., Hemer, M.A., Maes, C., Steinberg, C.R., Tribollet, A.D., Qiu, B. and Kruger, J.C. 2011. Observed and expected changes to the tropical Pacific Ocean. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 3. pp. 101–188. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.
[151] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.
[152] Lehodey, P., Hampton, J., Brill, R.W., Nicol, S., Inna Senina, I., Calmettes, B., Pörtner, H.O., Bopp, L., Ilyina, T., Bell, J.D. and Sibert, J. 2011. Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 8. pp 433–491. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.
[153] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.
[154] Lehodey, P., Chai, F. and Hampton, J. 2003. Modelling climate-related variability of tuna populations from a coupled ocean-biogeochemical-populations dynamics model. *Fisheries Oceanography* 12, 483–494
[155] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.
[156] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and

Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[157] Le Borgne, R., Allain, V., Griffiths, S.P., Matear, R.J., McKinnon, A.D., Richardson, A.J. and Young, J.W. 2011. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Bell J.D., Johnson, J.E. and Hobday, A.J. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Chapter 4. pp. 189–250. Secretariat of the Pacific Community, Noumea, New Caledonia. 941 pages.

[158] SPC 2008. Fish and Food Security. SPC Policy Brief 1/2008. https://pacificdata.org/data/dataset/oai-www-spc-intced24e95-7e0a-401a-9f0b-d79316c49cb0

[159] FFA and SPC (2015) Regional Roadmap for Sustainable Pacific Fisheries. Pacific Islands Forum Fisheries Agency, Honiara, and Pacific Community, Noumea. https://www.spc.int/DigitalLibrary/Doc/FAME/Brochures/FFA_SPC_2015_Roadmap.pdf

[160] Chapter 9 in Bell J.D., Johnson J.E., Hobday A.J. (Eds) (2011) Vulnerability of tropical Pacific fisheries and aquaculture to climate change. Secretariat of the Pacific Community, Noumea, 925 pp.

[161] https://fishmip.org

[162] Andrew NL, Bright P, de la Rua L, Teoh S J, Vickers M. (2019). Coastal proximity of populations in 22 Pacific Island Countries and Territories. https://doi.org/10.1371/journal.pone.0223249

[163] Pacific Data Hub, 2023 https://pacificdata.org/

[164] Bell, J.D., Sharp, M.K., Havice, E. et al. (2019) Realising the food security benefits of canned fish for Pacific Island countries. Marine Policy, 100, 183-191.

[165] Hoegh-Guldberg O., Poloczanska E.S., Skirving W., Dove S. (2017) Coral reef ecosystems under climate change and ocean acidification. Frontiers in Marine Science, 4, 158.

[166] Olsen Y.S., Collier C., Ow Y.X., Kendrick G.A. (2018) Global warming and ocean acidification: Effects on Australian Seagrass Ecosystems. In Seagrasses of Australia: structure, ecology and conservation, 705-742. Cham: Springer International Publishing.

[167] Similar recent modelling studies have used variable, but usually earlier, reference periods generally resulting in higher projected declines. These studies include: Cheung W.W.L. et al. (2010) Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Global Change Biology, 16: 24–35; Asch, R.G., Cheung, W.W., Reygondeau, G. (2018) Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. ; 285-294; Lam, V.W. et al. (2020) Climate change, tropical fisheries and prospects for sustainable development. Nature Reviews Earth & Environment, *1*(9), 440-454.

[168] With the exception of the large inland population of PNG.

[169] SPC (2008) Fish and Food Security, SPC Policy Brief 1/2008. Secretariat of the Pacific Community. https://www.spc.int/DigitalLibrary/Doc/FAME/Brochures/Policy_Brief1_08.html

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

[171] Gillett R., Fong M. (2023) Fisheries in the economies of Pacific Island countries and territories (Benefish Study 4). Noumea, New Caledonia: Pacific Community. 704pp. https:// purl.org/spc/digilib/doc/ppizh

[172] Gillett R., Fong M. (2023) Fisheries in the economies of Pacific Island countries and territories (Benefish Study 4). Noumea, New Caledonia: Pacific Community. 704pp. https:// purl.org/spc/digilib/doc/ppizh

[173] Welch D.J., Johnson J.E., Fulton E., Blanchard J., Moore B., Fierro Arcos D., Zamborain-Mason J., Sambrook K., Halford A., Molinari B., Tracey D. (forthcoming) Chapter 3. Implications of climate change for coastal fisheries in the Pacific Islands region. In: Johnson JE and Wabnitz CCC (Eds) Climate change implications for fisheries and aquaculture in the Pacific Islands region. Pacific Community (SPC), Noumea, New Caledonia.

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

[175] SPC (2017) Sustainable national artisanal FAD programmes: What to aim for. SPC Policy Brief 31/2017. https://www.spc.int/DigitalLibrary/Doc/FAME/Brochures/Anon_17_PolicyBrief31_FAD_Programmes.html

[176] Bell J.D. *et al.* 2015. Diversifying the use of tuna for food security and public health in Pacific Island countries and territories. Marine Policy 51:584-591. http://dx.doi.org/10.1016/j.marpol.2014.10.005.
[177] https://meetings.wcpfc.int/meetings/sc19
[178] https://fame.spc.int/resources/tools/ikasavea
[179] Ruaia, T., Gu'urau, S. and Wheatley, L. (2022). Economic and Development Indicators and Statistics: Tuna Fisheries of the Western and Central Pacific Ocean 2022. Pacific Islands Forum Fisheries Agency.
[180] FFA and SPC (2015). Regional Roadmap for Sustainable Pacific Fisheries. Pacific Islands Forum Fisheries Agency, Honiara, and Pacific Community, Noumea. https://www.spc.int/DigitalLibrary/Doc/FAME/Brochures/FFA_SPC_2015_Roadmap.pdf
[181] Cai, W. *et al*. (2014). Increasing frequency of extreme El Niño events due to greenhouse warming. *Nat. Clim. Change* **4**, 111–116. https://doi.org/10.1038/nclimate210
[182] Cai, W. *et al*. (2015). ENSO and greenhouse warming. *Nat. Clim. Change* 5, 849–859. https://doi.org/10.1038/nclimate2743
[183] Lehodey, P., Senina, I., Calmettes, B. et al. (2013). Modelling the impact of climate change on Pacific skipjack tuna population and fisheries. *Clim. Change* **119**, 95–109. https://doi.org/10.1007/s10584-012-0595-1
[184] Bell, J.D., Senina, I., Adams, T. et al. (2021). Pathways to sustaining tuna-dependent Pacific Island economies during climate change. Nature Sustainability, 4(10), 900–910. https://doi.org/10.1038/s41893-021-00745-z
[185] Aqorau, T., Bell, J. and Kittinger, J.N. (2018). Good governance for migratory species. Science VOL 361 ISSUE 6408, 1208-1209. 10.1126/science.aav2051
[186] Clark S., Bell J., Adams T. et al. (2021). The Parties to the Nauru Agreement (PNA) 'Vessel Day Scheme': A cooperative fishery management mechanism assisting member countries to adapt to climate variability and change. In Adaptive Management of Fisheries in Response to Climate Change (eds Bahri, T. et al.). *FAO Fisheries and Aquaculture Technical Paper,* 667.
[187] 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, https://doi.org/10.1016/j.pocean.2008.06.004
[188] Lehodey, P., Murtugudde, R., Senina, I. (2010). 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, https://doi.org/10.1016/j.pocean.2009.09.008
[189] Senina, I., Lehodey, P., Sibert, J., Hampton, J. (2020b). Integrating tagging and fisheries data into a spatial population dynamics model to improve its predictive skills. *Canadian Journal of Fisheries and Aquatic Sciences*, 77, https://doi.org/10.1139/cjfas-2018-0470
[190] 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, https://doi.org/10.1016/j.pocean.2008.06.004
[191] Bellenger, H., Guilyardi, E., Leloup, J., Lengaigne, M., Vialard J. (2014). ENSO representation in climate models: from CMIP3 to CMIP5. *Climate Dynamics*, 42, (7–8), 1999–2018, https://doi.org/10.1007/s00382-013-1783-z
[192] Maury, O., Campling, L., Arrizabalaga, H., Aumont, O., Bopp, L. et al. (2017). From shared socio-economic pathways (SSPs) to oceanic system pathways (OSPs): Building policy-relevant scenarios for global oceanic ecosystems and fisheries, *Global Environmental Change*, 45, 203-216, https://www.sciencedirect.com/science/article/pii/S0959378016306343
[193] Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S., Dessert M. et al. (2021). Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability*, 4, 900–910, https://doi.org/10.1038/s41893-021-00745-z
[194] Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S., Dessert M. et al. (2021). Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability*, 4, 900–910, https://doi.org/10.1038/s41893-021-00745-z
[195] Aqorau, T. (2009). Recent developments in Pacific tuna fisheries: the Palau Arrangement and the vessel day scheme. *The International Journal of Marine and Coastal Law*, 24, 557-581, https://doi.org/10.1163/157180809X455647

[196] Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S., Dessert M. et al. (2021). Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability*, 4, 900–910, https://doi.org/10.1038/s41893-021-00745-z

[197] Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S. *et al.* 2021. Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability* 4, 900-910;

[198] Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S. *et al.* 2021. Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability* 4, 900-910;

[199] McNamara, K.E. et al. (2020). An assessment of community-based adaptation initiatives in the Pacific Islands. *Nature Climate Change* **10**, 628–639

[200] Pecl, G.T. et al. (2017). Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science* 355, eaai9214

[201]Lam, V. W. Y. et al. (2020). Climate change, tropical fisheries and prospects for sustainable development. *Nat. Rev. Earth Environ.* **1**, 440–454.

[202] Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S. *et al.* 2021. Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability* 4, 900-910;

[203] Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S., Dessert M. et al. (2021). Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability*, 4, 900–910, https://doi.org/10.1038/s41893-021-00745-z

[204] Lehodey, P., Senina., Nicol, S., Bell, J., Calmettes et al. (in press). Implications of climate change for oceanic fisheries in the tropical Pacific Islands region. Chapter 4. Implications of climate change for coastal fisheries in the Pacific Islands region. In: Johnson JE and Wabnitz CCC (Eds) Climate change implications for fisheries and aquaculture in the Pacific Islands region. Pacific Community (SPC), Noumea, New Caledonia.

[205] MRAG. (2016). Towards the Quantification of Illegal, Unreported and Unregulated (IUU) Fishing in the Pacific Islands Region (MRAG Asia Pacific).

[206] Pinsky, M.L. *et al.* (2018). Preparing ocean governance for species on the move. *Science* 360 (6394), 1189–1191. https://doi.org/10.1126/science.aat2360

[207]Oremus, K.L., Bone, J., Costello, C., Molinos, J.G., Lee, A. *et al*. (2020). Governance challenges for tropical nations losing fish species due to climate change. *Nature Sustainability* **3**, 277–280

[208] Goodman, C., Davis, R., Azmi, K., Bell, J., Galland, G.R. et al. (2022). Enhancing cooperative responses by regional fisheries management organisations to climate-driven redistribution of tropical Pacific tuna stocks. *Frontiers in Marine Science*, 9:1046018, https://doi.org/10.3389/fmars.2022.1046018

[209] Goodman, C., Davis, R., Azmi, K., Bell, J., Galland, G.R. et al. (2022). Enhancing cooperative responses by regional fisheries management organisations to climate-driven redistribution of tropical Pacific tuna stocks. *Frontiers in Marine Science*, 9:1046018, https://doi.org/10.3389/fmars.2022.1046018

[210] Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S., Dessert M. et al. (2021). Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability*, 4, 900–910, https://doi.org/10.1038/s41893-021-00745-z

[211] Lehodey, P., Senina., Nicol, S., Bell, J., Calmettes et al. (in press). Implications of climate change for oceanic fisheries in the tropical Pacific Islands region. Chapter 4. Implications of climate change for coastal fisheries in the Pacific Islands region. In: Johnson JE and Wabnitz CCC (Eds) Climate change implications for fisheries and aquaculture in the Pacific Islands region. Pacific Community (SPC), Noumea, New Caledonia.

[212] Moore, B.R. *et al.* (2020a) Defining the stock structures of commercial tunas in the Pacific Ocean I: Current knowledge and key uncertainties. *Fisheries Research* 230, 105525. https://doi.org/10.1016/j.fishres.2020.105525

[213] Moore, B.R. *et al.* (2020b) Defining the stock structures of commercial tunas in the Pacific Ocean II: Sampling considerations and future directions. *Fisheries Research* 230, 105524. https://doi.org/10.1016/j.fishres.2020.105524

[214] Goodman, C., Davis, R., Azmi, K., Bell, J., Galland, G.R. et al. (2022). Enhancing cooperative responses by regional fisheries management organisations to climate-driven redistribution of tropical Pacific tuna stocks. *Frontiers in Marine Science*, 9:1046018, https://doi.org/10.3389/fmars.2022.1046018

[215] https://www.wcpfc.int/

[216] https://www.forumsec.org/2019/08/28/the-kainaki-ii-declaration-is-a-signal-of-our-strength/

[217] https://www.ffa.int/2024/05/fisheries-officials-approve-plan-for-climate-change-resilience-efforts-in-fisheries/

[218] Pacific Islands Regional Ocean Policy refer – www.spc.int/piocean/MSWG/PIROP/

[219] The Pacific Plan, endorsed by Forum Leaders at the Pacific Islands Forum meeting in Port Moresby in 2006, was a document designed to strengthen Pacific regional integration and cooperation. Its four key pillars were designed for development progress: economic growth, sustainable development, good governance, and security. As a 'living document', it stated that the Pacific, as a region, must work to address these challenges to raise living standards, increase access to opportunity and stimulate pro-poor growth for its peoples. The plan was reviewed in 2013.

[220] https://www.forumsec.org/wp-content/uploads/2018/03/The-Vavau-declaration.pdf

[221] SPC. 2008. *Pacific Islands Regional Coastal Fisheries Management Policy and Strategic Actions (Apia Policy) (2008–2013)*. Commonwealth Secretariat and the Government of Iceland. Endorsed by the Fourth Ministerial Meeting of the South Pacific Forum Fisheries Committee, May 2008, Koror, Palau.

[222] https://spccfpstore1.blob.core.windows.net/digitallibrary-docs/

[223] https://www.sprep.org/att/publication/000937_684a.pdf

[224]https://www.forumsec.org/wp-content/uploads/2017/11/2014-Palau-Declaration-on-%E2%80%98The-Ocean-Life-and-Future%E2%80%99.pdf