Assessment of the vulnerability of Pacific Island communities and food security to the effects of climate change on coastal fisheries

Supplementary Technical Report for GCF Study 1

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Executive Summary

This technical report supports the Green Climate Fund (GCF) proposal being jointly prepared by Conservation International and the Pacific Community (SPC): *Adapting tuna dependent Pacific Island communities and economies to climate change*. Following the endorsement of the concept note by the GCF in 2021, SPC and Conservation International commenced design of the regional programme of work for the 14 Pacific island countries included in the proposal.

This technical report documents the observed impacts of climate variability and change on coastal fisheries in the Pacific region, and delivers an assessment of the vulnerability of fisheries and food security to the effects of climate change. In the Pacific islands region, marine ecosystems are vital to people's culture and well-being, with fisheries making essential contributions to food and nutrition security, livelihoods and economies.

Climate change is an increasingly present and significant threat to marine ecosystems, and is expected to exacerbate pressures already affecting coastal fisheries, through increases in sea temperature, ocean acidification, more intense storms, sea-level rise, and declines in oxygen (IPCC 2019, 2022). These changes are already having and will continue to have profound effects on the structure and function of coastal ecosystems, and impacts on fisheries as a result of climate change will have consequences for the communities and economies that depend on them for food and nutrition security, livelihoods and income (Bindoff et al. 2019, Cooley et al. 2022). There are documented impacts of changing climate on coastal habitats, including coral reefs, seagrass meadows, and mangroves, as well as oceanic food webs and primary productivity. Climate impacts act separately and synergistically with local anthropogenic impacts (Abelson 2020), and since they provide critical habitat for different life history stages of many fisheries species, any habitat changes will have implications for the species and communities they support.

Ecosystem models are crucial tools for projecting the potential effects of climate change on marine ecosystems and species, that incorporate indirect and complex interactive processes within and among trophic groups and/or species. This study applied a range of tailored ecosystem model ensembles to simulate how physiological responses to changing habitats and primary production could affect fish biomass and coastal fisheries (Blanchard et al. 2012, Asch et al. 2018, Tittensor et al. 2018). Despite high uncertainty in some regions, various models consistently predict declines in primary production across the Pacific region, a key determinant of potential fish biomass and catch potential (Cheung et al. 2010, Barange et al. 2014, Free et al. 2019, Williams et al. 2015, Eriksson et al. 2017, Asch et al. 2018, Lam et al. 2020, Tittensor et al. 2021). Coastal productivity and fish biomass are projected to decrease under medium and high emissions scenarios, most notably at low to mid latitudes, with considerable regional variation (e.g. Lam et al. 2020). Moreover, observed changes in tropical species composition and coastal fisheries catches in several locations are already responding to warming waters and altered primary productivity, consistent with projections (Lam et al. 2020).

Current projections of declining productivity and biomass of coastal fisheries in the Pacific Islands region should be of significant concern and are a core component of the food security analysis in this report. Pacific island countries predicted to have a gap in available fish from coastal fisheries will increasingly need to turn to alternative protein sources, such as tuna, to meet their nutritional requirements. The oceanic fisheries modelling suggests that some tuna species will increase in biomass in specific locations (e.g. albacore in southern international waters of the easter Pacific Ocean), which can provide a resource for Pacific island countries in these locations. However, some countries currently consume high quantities of fish, significantly above the minimum nutritional requirements, and any future declines in fish consumption or substitutions will need to consider social and cultural impacts of these dietary changes.

1. Introduction

People began to populate the Pacific Islands region ca. 50,000 years ago through successive migrations and today these communities exhibit vast cultural and lifestyle diversity (Crowley 1999). Communities and their natural resources are commonly governed by customary belief systems and laws that structure society, are the foundation of people's identity, and underpin the use and management of natural resources (Hviding 1996). In recognition of the variation in the physical nature, biogeography, ethnic origin and culture among Pacific Island countries, the region is divided into three subregions – Melanesia, Micronesia and Polynesia (Figure 1).

From an oceanographic perspective, the region is dominated by the Western and Central Pacific Ocean (WCPO), which supports vast areas of coastal and oceanic habitats and many species of fish, invertebrates, and other animals Given the scale of the ocean area, it is unsurprising that the region has the greatest dependence on marine resources in the world (Johnson et al. 2020). These resources, particularly fish and invertebrates, provide a significant source of animal protein, livelihoods from fishing and tourism, and hold important cultural values for communities in the region. For example, fish consumption in the Pacific Islands has been a cornerstone of food security with per capita fish consumption in many Pacific Island countries being 3–5 times the global average, and, in rural areas, up to 50–90% of dietary animal protein (Bell et al. 2018; see GCF Study 2).

Coastal fisheries have long played a significant role in sustaining communities throughout the Pacific Islands region by providing an ongoing resource that provides food and nutrition security, as well as significant local cash flow (Gillett and Tauati 2018). Coastal fishing is generally conducted in habitats adjacent to land masses (e.g. reefs and associated habitats), using a variety of fishing methods and accessed either by land or using small local vessels. Over 500 different species are targeted across the region (Preston 2005), comprising demersal reef fish, nearshore and reef-associated pelagic species, and invertebrates. While the catch quantities and value derived from oceanic fisheries in the region dwarf coastal fisheries, the cultural, nutritional, and economic importance of coastal fishery resources to Pacific Island communities at the local scale is immeasurable (Preston 2005; Gillett and Tauati 2018). Nutritionally, it is reported that coastal marine resources provide 50-90% of animal protein for Pacific Islanders (Bell et al. 2018a; Gillett and Tauati 2018; Johnson et al. 2017), as well as other key macro (e.g. fatty acids) and micronutrients (e.g. minerals and vitamins; Viana et al. 2023). Therefore, the declines in coastal resources that were projected in the previous regional assessment (Pratchett et al. 2011) were of significant concern to all PIC. In this study, we provide a review of the latest observed effects of climate change on coastal habitats, fish and invertebrates, update projected changes in available coastal fish[1] biomass, and determine how this is likely to affect PIC human communities.

1.1 Study objectives

The purpose of this supplementary technical study is to update the components of the SPC vulnerability assessment related to the direct and indirect effects of climate change on coastal fisheries resources, and on the availability of coastal fish for food, to support the climate rationale for the Programme (see Appendix A for further details on the scope of works).

1.2 Scope

This study complements work that has commenced to update the Pacific regional vulnerability assessment for fisheries (published in 2011) for 22 Pacific island countries and territories

[1] Pacific coastal fish and invertebrates are collectively termed "fish" throughout this chapter.

being undertaken by SPC (Johnson and Wabnitz, in press). The scope of this study focuses on 14 Pacific Island Countries (PIC) to deliver estimates of the degradation of coastal habitats (in terms of area of coral reef, seagrass or mangrove likely to decline due to climate change), decreases in average coastal (mainly coral reef) fish production (in tonnes per km^2) due to the direct and indirect effects of climate change, and the food security implications of these changes for Pacific communities.

This study used spatial analysis and ecosystem modelling to deliver results for 2030, noting that future climate trajectories do not diverge by 2030 so only one emissions scenario was applied (SSP5-8.5), and 2050 under SSP5-8.5 and SSP2-4.5 (or equivalent) greenhouse gas emission scenarios.

Pacific Island Countries assessed

The Pacific Island region encompasses 22 Pacific Island countries and territories that span much of the tropical and subtropical Pacific Ocean (Figure 1). The combined exclusive economic zones (EEZ) cover an area of >27 million km^2, but only 2% of their combined jurisdictions is land. Pacific Island countries and territories are therefore often referred to as 'large ocean states'.

This study focused on 14 PIC participating in the GCF regional tuna programme: Cook Islands, Federated States of Micronesia (FSM), Fiji, Kiribati, Republic of the Marshall Islands, Niue, Nauru, Palau, Papua New Guinea (PNG), Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu. These 14 PIC represent independent states in the three subregions of the Pacific Islands region – Melanesia, Micronesia and Polynesia (Figure 1).

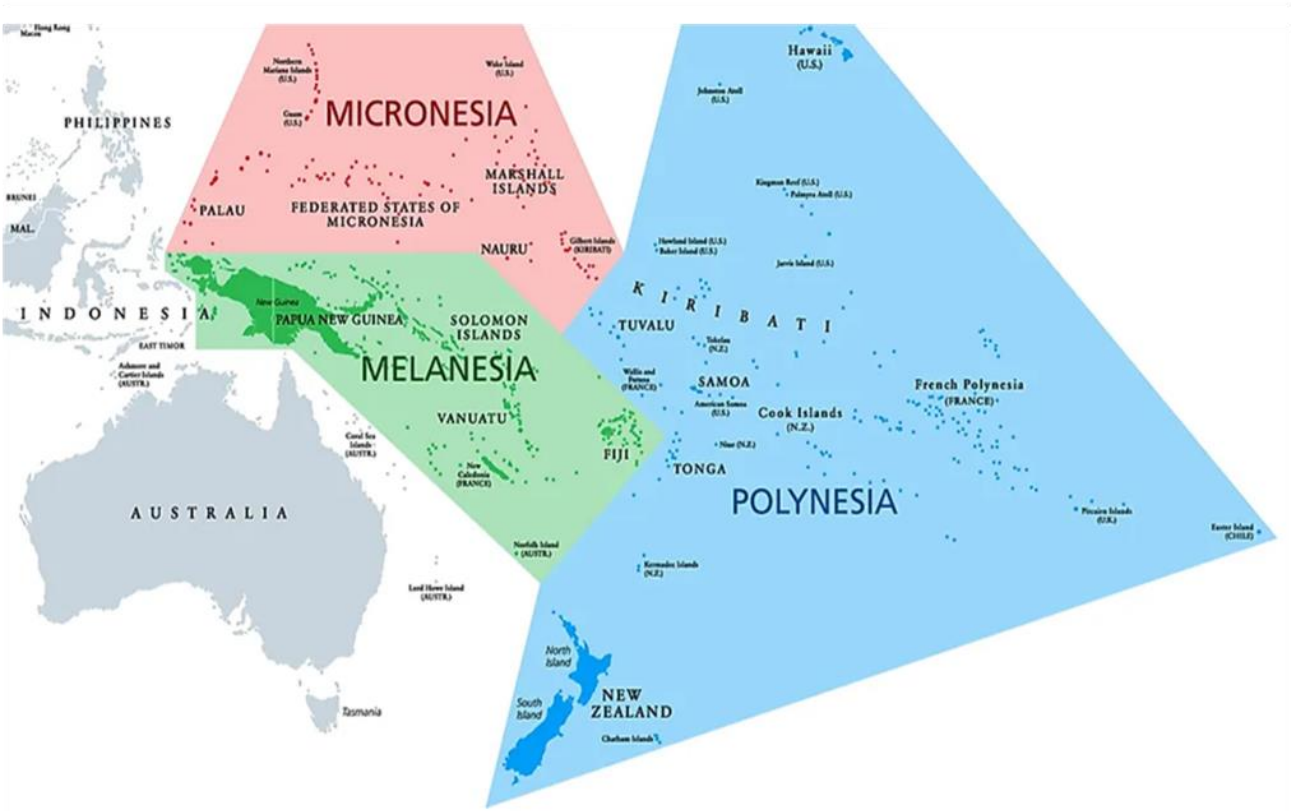

Figure 1. Map of the tropical Pacific Island region with cultural sub-regions shown.

Climate emissions scenarios

The study conducted the analyses using three future greenhouse gas emissions scenarios, representing near-term and medium-term timeframes considered meaningful for planning and policy in the Pacific region.

1. 2030 high emissions that assume continued population growth and energy-intensive development (SSP5-8.5 or where data weren't available RCP8.5). Represents current trajectory of emissions globally.
2. 2050 moderate emissions that stablise global temperature increase and represent the current trajectory (SSP2-4.5 or where data weren't available RCP4.5).
3. 2050 high emissions that assume continued population growth and energy-intensive development (SSP5-8.5 or where data weren't available RCP8.5).

The SSP2-4.5 (or equivalent RCP4.5) scenario assumes that radiative forcing stabilizes at 4.5 W m−2 in the year 2100 without ever exceeding that value. Simulated with the Global Change Assessment Model (GCAM), this moderate emissions scenario includes long-term, global emissions of greenhouse gases, short-lived species, and land-use-land-cover in a global economic framework. This scenario was updated from earlier GCAM scenarios to incorporate historical emissions and land cover information common to the RCP process and follows a cost-minimizing pathway to reach the target radiative forcing.

The SSP5-8.5 (or equivalent RCP8.5) scenario combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and GHG emissions in absence of climate change policies. Compared to the total set of future emissions scenarios, this scenario corresponds to the pathway with the highest greenhouse gas emissions.

The emissions scenarios were applied using CMIP6 outputs under the Shared Socioeconomic Pathways (SSP). These new "pathways" examine how global society, demographics and economics might change over the next century and are being used as important inputs for the CMIP6 climate models, feeding into the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report (AR6 2021). They are also being used to explore how societal choices will affect greenhouse gas emissions and, therefore, how the climate goals of the Paris Agreement could be met. Relevant SSP are summarised in Appendix B.

Range of climate change drivers

Climate variability and change regularly disrupt fisheries and aquaculture productivity, with implications for PIC that depend on them for food, income, jobs, and government revenue. There are a range of climate change variables that drive direct and indirect impacts on fisheries and supporting habitats, and the following have been included in the analyses of this study: sea surface temperature and ocean temperature stratification, ocean chemistry (pH), rainfall, ocean circulation, and tropical storms and cyclones. A summary of the observed and projected changes for these climate variables and further details on future climate change projections is provided in the GCF Feasibility Study.

We assessed the projected impacts of climate change on coastal fisheries using a similar approach to the 2011 assessment by combining the direct and indirect effects of a changing climate on fish. We defined direct effects as changes in environmental conditions directly experienced by fish (e.g. increase in sea surface temperature), while indirect effects are those that affect the interactions with other organisms or their environment (e.g. changes in habitat area). Projected changes in catch were based on the latest (2021) catch estimates derived for each PIC by Gillett and Fong (2023). A significant improvement on the 2011 assessment is

our use of ecosystem model ensembles forced by climate models to estimate future changes in fish biomass (see the Fisheries and Marine Ecosystem Model Intercomparison Project, FishMIP[2]) for the two different emission scenarios: SSP2-4.5 and SSP5-8.5 emissions scenario. Although we explored impacts under these two scenarios out to 2100, we focus our analyses of projected impacts to 2030 (only SSP5-8.5) and 2050 as near-term outlook to focus necessary adaptations. This approach represents a more objective analysis that also provides quantitative estimation of uncertainty in projections.

2. Coastal Habitats that Support Fisheries

Coastal habitats in the Pacific Islands region include coral reefs, seagrass meadows and mangrove forests that are found across the 22 PIC. These habitats form a connected mosaic, with mangroves typically located along the shore and seagrass meadows and coral reefs extending away from the coast (Guannel et al. 2016; Waycott et al. 2011). Collectively, these habitats are important for coastal fisheries due to their role in providing food, shelter, and nursery areas for juvenile fish as well as cover and feeding grounds for adult demersal fish and invertebrate species that move among the different habitats during different life history stages (Adkins et al. 2015; Guannel et al 2016; Sambrook et al 2019). The connectivity between these often-continuous mosaic of habitats sustains a high diversity of commonly harvested species targeted by Pacific communities for food and income (Guannel et al. 2016; Veitayaki et al. 2017). While, in general, coastal habitats in the Pacific Islands region are in good condition (Souter et al. 2021b; McKenzie et al. 2021), there are many drivers of change and increasing threats to their condition.

Since the 1970s, the decline of coastal habitats has accelerated globally, including in the Pacific Islands region (Albert et al. 2017; Guannel et al. 2016; Hassenruck et al. 2015). This is due to poor land management and delivery of terrestrial pollutants, coastal development, increased sedimentation from coastal catchments, and destructive and illegal fishing (Dutra et al. 2021; Veitayaki et al. 2017; Johnson et al. 2020). Climate change, however, is now the strongest driver affecting coastal habitats, through higher sea temperatures and marine heatwaves, sea level rise, ocean acidification, more intense storms and cyclones, El Niño Southern Oscillation (ENSO) events, and the synergistic effects between drivers (Aronson and Precht 2016; Souter et al. 2021b; Johnson et al. 2020). These impacts are accelerating as the climate continues to change and are expected to continue to degrade the condition of coastal habitats (Dutra et al. 2021).

2.1 Vulnerability assessment methodology

This section provides a summary of the coastal habitat vulnerability assessment methods for Pacific Island countries, with further details provided in Appendix C.

The vulnerability of coastal habitats (coral reefs, seagrass meadows and mangroves) was assessed in 14 PIC using spatial data analyses and delivered mapping outputs showing hotspots of vulnerability. Mapping outputs were prepared using the software Python 2.7.3 (PythonWin 2012) and ArcGIS 10.7 (ESRI 2019). The assessment incorporated the latest global spatial data from the World Resources Institute and UNEP-WCMC on the extent of coastal habitats (km2) to map and quantify the expected degradation of coastal habitats (in terms of area of habitat) projected to occur under SSP5-8.5 by 2030, and SSP5-8.5 and SSP2-4.5 (or equivalent) greenhouse gas emission scenarios by 2050 for the 14 PIC participating in the GCF regional tuna programme.

[2] https://fishmip.org

The spatial analyses included data layers for exposure to climate hazards (e.g. projected change in SST, projected change in ocean pH, annual severe bleaching year, warm season SST variability) and sensitivity to those climate hazards (e.g. historic data on severe bleaching conditions [events >8 degree heating weeks], water quality index). Data layers were also included for adaptive capacity (e.g. protected area status). The input data layers for exposure, sensitivity and adaptive capacity for the different coastal habitats are provided in Appendix C (see Table B1). The methods applied map algebra to deliver visual outputs for each PIC showing the area of coastal habitat expected to be vulnerable to climate change, and a quantitative estimate of the percentage of habitat pixels, which was used to calculate area of habitat decline; only for coral reefs and seagrass using the percentage of pixels in the very high and high vulnerability categories.

2.2 Coastal habitats in each PIC

Coastal habitats assessed in 14 PIC included coral reefs, seagrass meadows and mangrove forests, which provide critical habitats for coastal fish and invertebrate species that are targeted by Pacific communities for food and income. These habitats usually form a connected mosaic, with mangroves typically located along the shore and seagrass meadows and coral reefs extending long distances away from the coast (Waycott et al. 2011). Collectively, these habitats are important for coastal fisheries because of the role they play in providing nursery areas for commonly harvested fish and invertebrates. The connectivity between coral reefs, seagrass meadows and mangroves supports this important habitat function for a range of demersal fish species and invertebrates that move among the different habitats.

The same habitats were assessed in the earlier assessment for the Pacific Island region (Bell et al. 2011a) and in adjacent regions using the same structured vulnerability assessment framework (Northern Australia, Welch et al. 2014; Torres Strait islands, Johnson and Welch 2016, Arafura and Timor Seas, Johnson et al. 2021). The estimated area (km^2) of the different coastal habitats for each of the 14 PIC is provided in Table 1 and demonstrates the relative importance of the different habitats to supporting coastal fisheries.

Table 1. Estimated area (km^2) of the different coastal habitats for each Pacific Island Country.

2022	Coral reef (WRI data)	Seagrass meadow (WCMC data)	Mangrove forest (GMW data[3])
Pacific Island Country			
Cook Islands	530.75	0	0.03
Federated States of Micronesia	4,956.95	1,594.55	87.94
Fiji	6,741.66	1,745.64	488.14
Kiribati	3,061.17	499.58	1.46
Marshall Islands	3,581.00	529.27	0.33
Nauru	44.73	0	0
Niue	15.35	0	0
Palau	972.30	732.15	56.88
Papua New Guinea	14,686.64	9,347.38	4,524.74
Samoa	404.15	988.73	2.32
Solomon Islands	6,790.63	1,261.71	526.51
Tonga	1,670.40	3,703.37	10.43
Tuvalu	1,238.21	0	0.09
Vanuatu	1,812.99	1,244.73	15.84

[3] http://www.globalmangrovewatch.org

2.3 Vulnerability results for coastal habitats

A structured semi-quantitative approach was applied for the vulnerability assessment, which provides a framework for determining the potential impacts of climate change on coastal habitats that support fisheries species, their relative level of vulnerability and drivers of vulnerability (Johnson et al. 2016). The vulnerability assessment applied the framework used by the IPCC and United Nations Framework Convention on Climate Change (UNFCCC), which includes the elements of Exposure, Sensitivity and Adaptive Capacity (Figure 2). The habitat vulnerability assessment was conducted for each of the 14 PIC in the study (see Figure 1) to deliver results that informed the coastal fisheries and food security analyses in each PIC. The spatial analyses included coral reefs and seagrass in all 14 PIC that have those habitats (i.e. seagrass analyses were not done for Cook Islands, Niue, Nauru and Tuvalu as they have no documented areas of seagrass). Spatial analyses for mangroves focused only on those PIC with documented areas of mangrove forest (i.e. not Niue or Nauru).

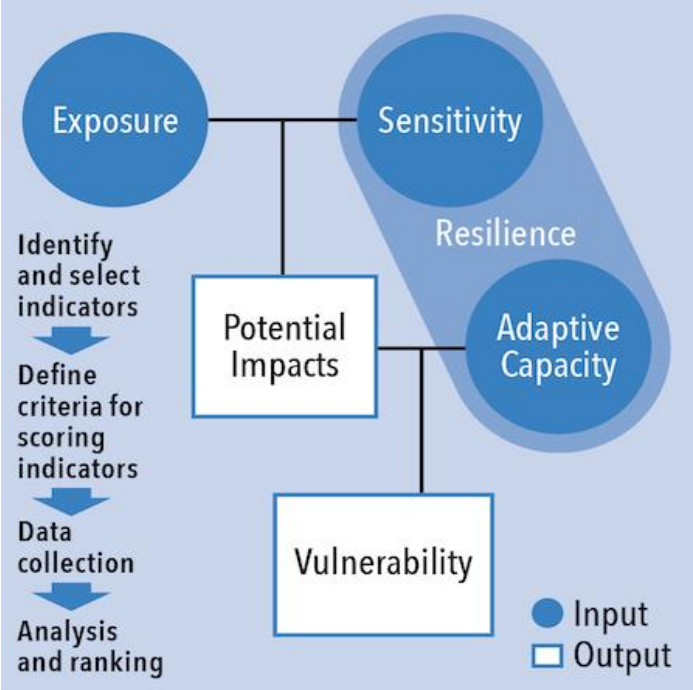

Figure 2. Vulnerability analysis framework adapted from the Intergovernmental Panel for Climate Change framework for semi-quantitative assessments (Johnson et al. 2016).

The spatial analyses results are provided as maps with vulnerability shown along a continuous scale from low to very high, and calculations of pixels and therefore area vulnerability was quantified based on five categories of vulnerability, defined as follows:

1. Very high: ≥ Avg + StDev x 2
2. High: ≥ Avg + StDev
3. Med-High: ≥ Avg and < Avg + StDev
4. Low-Med: ≥ Avg - StDev and < Avg
5. Low: < Avg – StDev

A selection of spatial analysis map outputs are provided for coral reefs in four PIC (Figure 3), seagrass meadows in four PIC (Figure 4) and mangroves in four PIC (Figure 5). They are mapped on a continuous scale from none/low (blue) to very high (red) vulnerability.

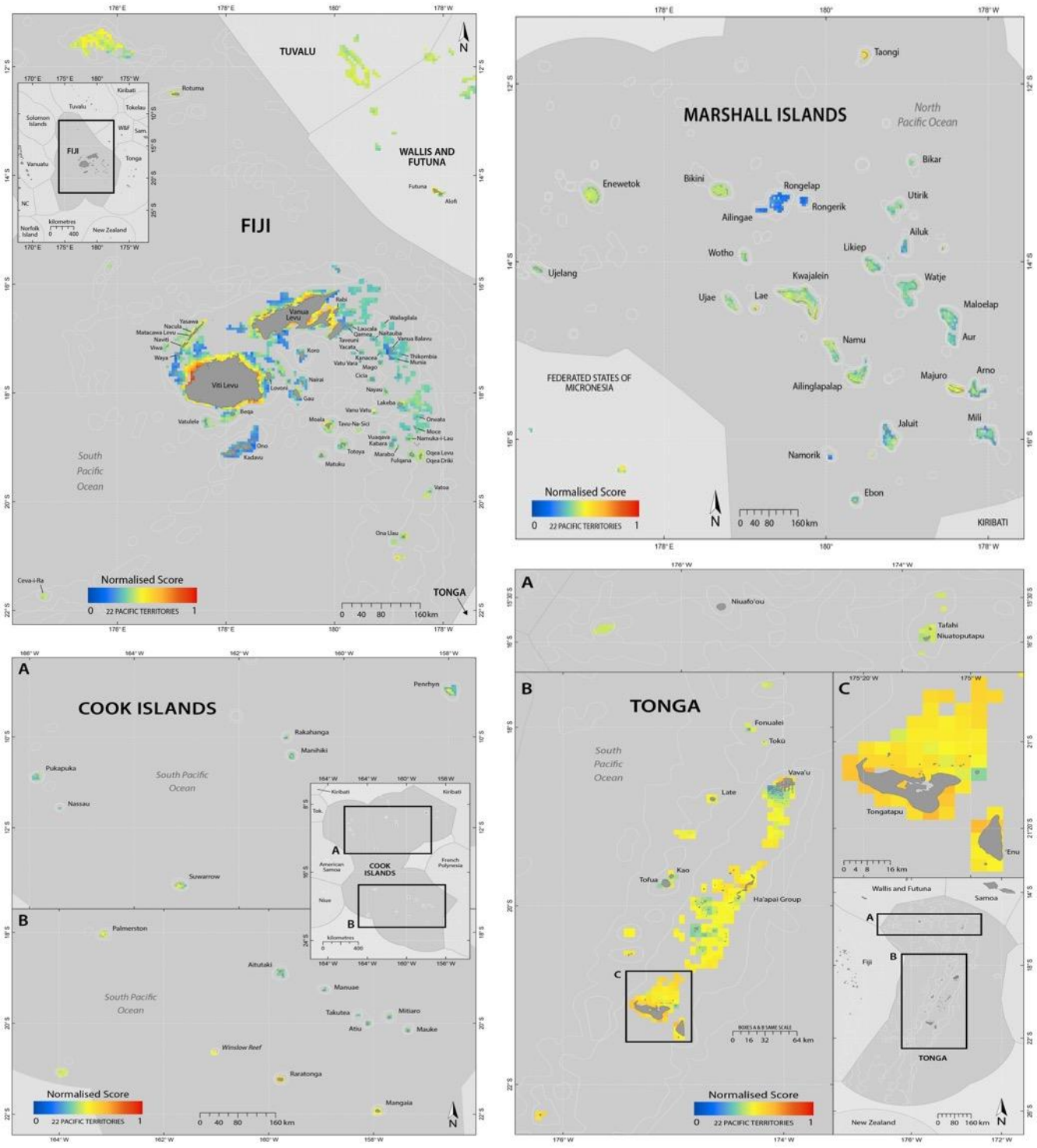

Figure 3. Relative vulnerability to climate change under SSP5-8.5 in 2050 for corals reefs in Fiji (top left), Marshall Islands (top right), Cook Islands (bottom left), and Tonga (bottom right).

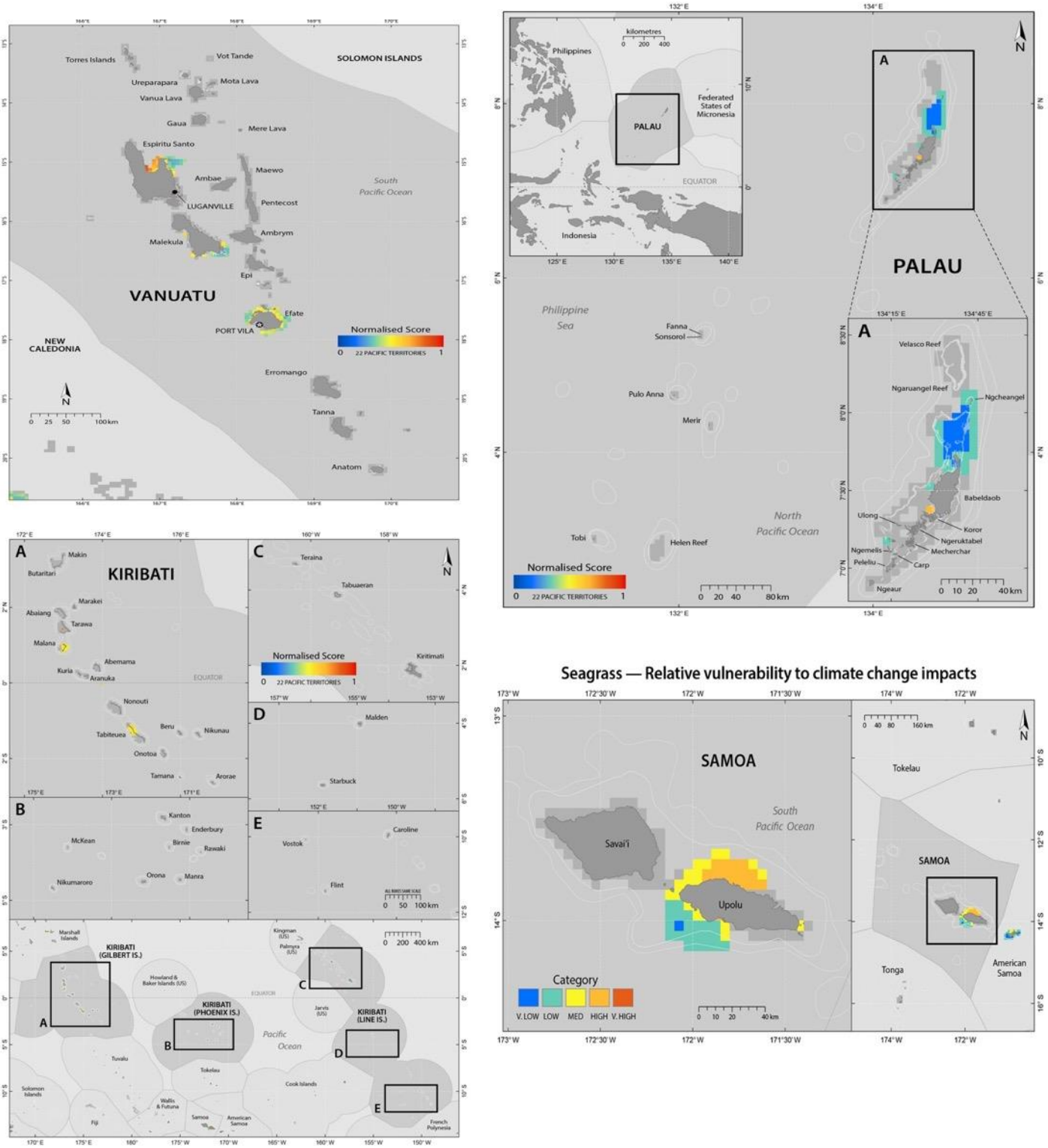

Figure 4. Relative vulnerability to climate change under SSP5-8.5 in 2050 for seagrass meadows in Vanuatu (top left), Palau (top right), Kiribati (bottom left), and Samoa (bottom right).

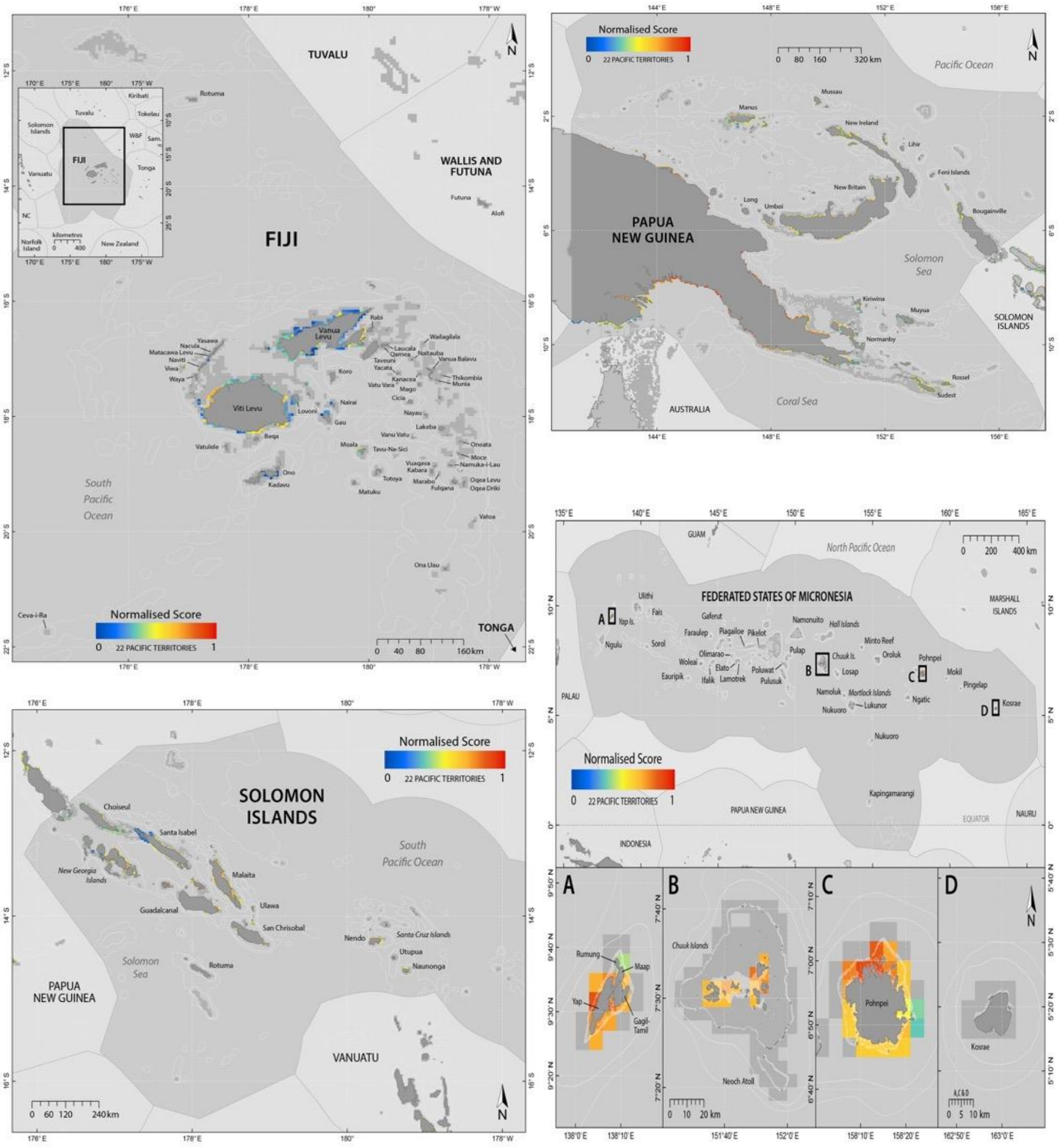

Figure 5. Relative vulnerability to climate change under SSP5-8.5 in 2050 for mangroves in Fiji (top left), Papua New Guinea (top right), Solomon Islands (bottom left), and Federated States of Micronesia (bottom right).

2.4 Potential impacts of climate change on coastal habitats

The vulnerability of coastal habitats to the impacts of climate change was assessed using a structured semi-quantitative vulnerability assessment framework (Johnson et al. 2024) and a method applied previously in the Pacific Islands region (Bell et al. 2011; Johnson et al. 2016b) and in adjacent regions (Northern Australia, Welch et al. 2014; Torres Strait islands, Johnson and Welch 2016; Arafura and Timor Seas, Johnson et al. 2021). The spatial analyses results categorised vulnerability along a continuous scale from low to very high. Calculations of pixels and area of vulnerability were quantified based on five categories, defined as follows[4]:

1. Very high: vulnerability ≥ average + 2 standard deviations
2. High: average + 1 standard deviation≤ vulnerability < average + 2 standard deviations
3. Med-High: average ≤ vulnerability < average + 1 standard deviation
4. Low-Med: average - 1 standard deviation≤ vulnerability < average
5. Low: < average - 1 standard deviation

The analysis of habitat vulnerability determined the likely area of the respective habitat types that will be impacted under climate change scenarios SSP2-4.5 and SSP5-8.5 by 2050. That is, the analysis does not identify actual impacts, but the area of habitats expected to experience degradation based on vulnerability to climate change. The results are inputs for the indirect effects in the analyses of coastal fisheries. Therefore, for the purposes of this analysis, we assumed that total habitat area will decline by the area assessed as having 'very high' and 'high' vulnerability (Table 5). It is expected that the direction of change (i.e. habitat decline) will continue to 2090 with increasing magnitude over time, resulting in greater percentage of habitat degradation or loss.

The results were spatially variable among and within PIC (Table 5). Those with the greatest projected percentage decline of coral reefs by 2050 under both emissions scenarios are Nauru and Samoa. Coral reef decline 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 (Hoegh-Guldberg et al. 2017).

While 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 MHW events, and (2) shifts in the photosynthesis/respiration balance (i.e. increases in temperature results in increased respiration driving higher stress and decline; Olsen et al. 2018). Nevertheless, while the drivers of change to seagrass habitats in the Pacific Islands region potentially includes marine heatwaves later in the century, i.e. by 2090, the main drivers are likely to be turbidity and sedimentation that hinders photosynthesis, and more intense cyclones and storms that physically damage shallow meadows. The Pacific Island Countries with the greatest projected percentage declines of seagrass by 2050 under both emissions scenarios are PNG, Samoa, and Vanuatu.

Mangrove vulnerability is driven by increasing air temperature, sea level rise, and other anthropogenic threats such as land-based runoff. The results for mangroves show the PIC with the greatest projected percentage declines by 2050 under both emissions scenarios are FSM, and Samoa.

Results for Samoa are notable due to the particularly high projected declines for all habitat types. A sensitivity analysis shows that Samoa has low adaptative capacity and high sensitivity due to the influence of rivers on water quality. These factors should be considered, as updated local data would improve certainty of vulnerability results.

[4] Where average is of the vulnerability score across all pixels, and the standard deviation of all scores about the mean.

These values were an input for the coastal fisheries productivity analysis, which calculated the quantity of fish available for communities to catch, based on tonnes that the available healthy area of habitat can produce. Ultimately, climate change is exacerbating local impacts, causing declines in coastal habitats and driving changes to fisheries that have socioeconomic consequences for Pacific communities that depend on them for food, income and livelihoods.

The estimated coastal habitat area expected to experience degradation based on vulnerability to climate change (using spatial analyses/map algebra) were calculated based on the percentage of habitat area in the very high to high (VH+H) vulnerability category (indicative of likely habitat degradation or loss). The primary vulnerability assessment used SSP5-8.5 in 2050 and then the relative quantitative differences between the SSP2-4.5 and SSP5-8.5 emissions scenarios in 2050, and between SSP5-8.5 in 2030 and 2050 were calculated based on a sensitivity analysis using downscaled data. The vulnerability results, in terms of area of habitat expected to experience degradation (VH+H vulnerability), were adjusted accordingly.

The results show that for all 14 PIC, the area of coral reef and seagrass habitat assessed as having very high and high vulnerability to climate change increases between 2030 and 2050, under all emissions scenarios applied in the study (Table 2). For coral reefs, this is largely driven by increasing SST and pH declines, with well-documented impacts on corals due to thermal bleaching and acidification undermining the reef habitat structure (Hoegh-Guldberg et al. 2017). While 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, and (2) shifts in the photosynthesis/respiration balance, i.e. increases in temperature result in increased respiration driving increased stress and declines (Olsen et al. 2018). Therefore, seagrass in the Pacific island region are generally not growing close enough to their thermal thresholds and impacts by 2030 would not be expected in most PIC. The results for mangrove forests show expected declines in habitat area by 2050 under SSP5-8.5 for FSM and PNG only, and no detectable declines for other PIC or by 2030.

Table 2. (%) area of each coastal habitat type assessed as 'very high' or 'high' vulnerability for each Pacific Island country (PIC) participating in the GCF regional tuna programme under medium (SSP2-4.5) and high (SSP5-8.5) emission scenarios by 2030 and 2050. These values represent the estimated percentage decline in area for each habitat type due to climate change. Blank cells are PIC without that coastal habitat type.

PIC	Coral reef			Seagrass meadow			Mangrove forest		
	2030 SSP5-8.5	2050 SSP2-4.5	2050 SSP5-8.5	2030 SSP5-8.5	2050 SSP2-4.5	2050 SSP5-8.5	2030 SSP5-8.5	2050 SSP2-4.5	2050 SSP5-8.5
Cook Islands	5.1	5.37	6.09	-	-	-	0	0	0
FSM	1.0	1.01	1.15	0	56.51	64	0	4.80	5.43
Fiji	11.4	11.83	13.40	0	4.59	5.19	0	17.52	19.84
Kiribati	13.3	13.77	15.59	0	0	0	0	9.29	10.53
Marshall Islands	1.8	1.90	2.15	0	0	0	0	6.62	7.50
Nauru	42.6	44.15	50	-	-	-	-	-	-
Niue	16.0	16.56	18.75	-	-	-	-	-	-
Palau	0	0	0	0	0	0	0	2.01	2.27
PNG	14.6	15.14	17.15	0	14.51	16.43	0	20.74	23.49
Samoa	68.7	77.60	87.88	0	88.30	100	0	36.19	40.98
Solomon Islands	8.8	9.11	10.32	0	0	0	0	3.53	4
Tonga	23.8	24.65	27.91	0	0	0	0	0	0
Tuvalu	0	0	0	-	-	-	0	0	0
Vanuatu	22.4	23.26	26.35	0	0	0	0	20.27	22.95

Notably, the PIC assessed as having more than 20% of their coral reef habitat area in the very high to high vulnerability category in 2030 and 2050 were: Nauru, Samoa, Tonga and Vanuatu. With Samoa having the highest percentage of reef habitat area likely to be degraded at ~68% (2030) and ~80% (2050) under the SSP5-8.5 emissions scenario.

For seagrass meadows, Fiji, PNG, Samoa and Vanuatu were assessed as having more than 20% of their habitat area in the very high to high vulnerability category (indicative of likely habitat degradation or loss) in 2050 under SSP5-8.5.

For mangrove forests, only two PIC were assessed to experience notable habitat loss – Federated States of Micronesia and PNG – with 28% and 24.5% of their habitat area respectively in the very high to high vulnerability category (indicative of likely habitat degradation or loss) in 2050 under SSP5-8.5. All other PIC had no habitat area in the very high and high vulnerability categories.

The detailed quantitative results are available on request and were applied to the coastal fisheries productivity analysis, to calculate the quantity of fish available for communities to catch for food or income, based on tonnes that the available healthy area of habitat can produce.

3. Coastal Fisheries in the Pacific islands region

3.1 Characteristic of coastal fisheries

Coastal fisheries of PIC play a vital role in sustaining communities through continuity of cultural connections to their longstanding ways of living, providing cash for expenses, and food for families. This importance was never more evident than during the recent COVID-19 pandemic lockdowns, when loss of employment for thousands of people left fishing as a primary source of food and income for many families, especially in countries highly dependent on tourism (Gillett and Fong 2023; Ferguson et al. 2022). Recent estimates (Gillett and Fong 2023) indicate fish consumption across PIC averages between 38 and 78 kg per person per year, with large variations between smaller atoll countries, where consumption can be >100 kg per person per year (e.g. Kiribati), and larger countries with significant inland populations where consumption levels are much less. PNG, for instance, has per capita consumption on par with average global levels at ~15 kg per year (Sarkodie and Owusu 2023).

Methods of fishing in the coastal zone are numerous but can be broken into two groups based on whether a vessel is used or not. Gleaning, netting, line, and spear fishing can all be conducted on nearshore habitats in the absence of a vessel. Gleaning is an especially important activity that women participate in and which contributes significantly to food security and income for their families (Ram-Bidesi 2015; Gillett and Tauati 2018; Grantham et al 2020; Lau et al 2023). Recent work in Fiji also highlights that gleaning activities by women across a wide diversity of habitats supports household resilience in the aftermath of disasters, including cyclone Winston (Chaston Radway et al 2016; Kopf et al 2020).

In smaller and/or poorer communities, fishing vessels are usually canoes that are paddled or sailed to the fishing grounds. As nearshore resources have become progressively over-exploited, there is now considerable effort being made to deploy and increase fishing around nearshore anchored Fish Aggregation Devices (FADs) to provide access to more sustainable pelagic fisheries and to potentially relieve pressure from coastal systems (Bell et al. 2015, 2018b). As a complement to FAD programs, there has been training and capacity development to upskill coastal communities in the techniques required to maximise the opportunities provided by nearshore pelagic environments (e.g. Bertram et al. 2023).

While coastal fisheries in the Pacific Islands region are based mainly on subsistence activities to provide food for households, approximately 30% of fishing households also earn an income from selling surplus fish and invertebrates caught from coastal and nearshore waters (Table 3) (Gillett and Fong 2023). Fish markets across the region trade a huge diversity of fish and invertebrates with over 500 species represented (Preston 2005).

The significance of coastal fisheries to the Pacific Islands region is further demonstrated by the financial contributions of subsistence and commercial catches to gross domestic product (GDP) of countries and territories across the region (Table 3). Gillett and Fong (2023) estimated that coastal commercial and subsistence production for 2021 was 173,924 tonnes, which is 10% of regional fishery production and worth an estimated USD450 million. The volume for all coastal fisheries (commercial and subsistence) in PNG is the largest in the region and represents about one quarter of the regional total (Gillett and Fong 2023).

Overfishing has been a sustained problem across most PIC, as elsewhere across the globe (Gillett and Tauati 2018, Karcher et al. 2020). In the Pacific Islands region it has been driven mainly by the rapid growth of human populations, the need for coastal communities to earn cash in increasingly 'monetised' societies, greater demand for export commodities, increased access to 'modern' fishing gears and a lack of alternative livelihoods (Sulu et al. 2015). Exploitation of coastal fisheries resources is strongly linked to economic development at the national level, and availability of alternative income opportunities at the community level (Thebaud et al. 2023). Coastal communities with limited access to alternative livelihoods are most vulnerable because of their high dependence on coastal fisheries resources as demonstrated by the direct relationship between small-scale artisanal invertebrate catches and daily cash expenditure (Franz et al. 2023).

Table 3. Trends in estimated annual catches of coastal fisheries in Pacific Island countries (PIC) participating in the GCF Programme and their estimated value from 2007 to 2021. Coastal fisheries estimates are for subsistence and commercial catch combined, and for 2021 the % of the total catch and total value attributed to subsistence use is also given. Source: Gillett 2009; Gillett 2016; Gillett and Fong 2023.

PIC	Catch (tonnes)			Proportion of subsistence catch (2021)	Value (USD)			Proportion of subsistence value (2021)
	2007	2014	2021		2007	2014	2021	
Melanesia								
Fiji	26,900	27,000	30,100	0.61	67,562,500	67,171,717	65,094,340	0.58
Papua New Guinea	35,700	41,500	46,000	0.87	62,500,000	117,315,176	98,575,499	0.81
Solomon Islands	18,250	26,468	30,000	0.83	14,287,582	45,875,819	50,310,559	0.80
Vanuatu	3,368	3,906	4,400	0.70	7,917,308	13,014,340	16,494,208	0.58
Micronesia								
Federated States of Micronesia	12,600	5,280	5,000	0.68	23,292,000	13,800,000	17,500,000	0.60
Kiribati*	20,700	19,000	19,000	0.58	47,058,824	31,718,852	44,202,898	0.49
Marshall Islands	3,750	4,500	4,200	0.71	7,212,000	10,350,000	9,400,000	0.64
Nauru*	650	373	240	0.42	1,501,681	2,036,713	1,673,913	0.33
Palau	2,115	2,115	2,400	0.58	5,354,000	6,500,000	10,909,800	0.49
Polynesia								
Cook Islands	400	426	430	0.65	2,279,412	2,890,625	2,653,061	0.59
Niue	150	165	169	0.95	676,471	1,252,969	1,234,694	0.93
Samoa*	8,624	10,000	11,000	0.50	34,461,434	30,230,126	37,837,837	0.41
Tonga	6,500	6,900	7,000	0.50	17,469,307	28,118,279	24,780,702	0.41
Tuvalu*	1,215	1,435	1,500	0.77	2,849,212	1,868,238	3,182,971	0.64
Total	**154,722**	**163,936**	**173,924**	**0.71**	**366,057,963**	**453,342,144**	**449,593,345**	**0.62**

** Coastal fisheries catches for Kiribati, Nauru, Samoa and Tuvalu include substantial quantities of tuna and other pelagic fish not dependent on coastal habitats, Gillett and Fong (2023) for further details*

3.2 Effects of environmental changes on coastal fish

Climate change has already begun to impact coastal waters and their associated fisheries in Pacific Island Countries (PIC). The effects of climate change include warming waters, ocean acidification, altered ocean circulation and current patterns, changes to freshwater hydrological regimes, altered precipitation patterns, episodic extreme weather events, hypoxia and sea-level rise (Sydeman et al. 2015; Hoegh-Guldberg et al. 2017). For coastal fishes and invertebrates, climate change can have direct and indirect effects. Direct effects include physiological, behavioural and demographic changes (Roessig et al. 2004, Doney et al. 2012, Pörtner et al. 2014), whereas indirect effects are driven by changes to the availability, structure and connectivity of habitats such as coral reefs, mangroves, macroalgae beds, seagrasses meadows and intertidal flats, as well as other biotic interactions such as predator-prey relationships, food web dynamics and competition (Sydeman et al. 2015). How coastal fishes and invertebrates will respond to climate change may differ depending on taxon, location, and importantly, by life stage. This is because many coastal fishes and invertebrates have complex life histories, which might include spawning migrations, pelagic larval stages, and ontogenetic shifts between different habitat types. Together, the outcomes of these direct and indirect effects may cause significant changes to population and community dynamics.

Direct impacts on coastal fish

Direct impacts on coastal fishes and invertebrates as a consequence of climate change can include physiological, behavioural and demographic changes. The climate change stressors that are likely to have the most direct impact on coastal fishes and invertebrates in PIC are increasing ocean temperatures, ocean acidification and changes to ocean circulation and current patterns.

Long-term ocean temperature warming

As ectotherms, fishes are highly adapted to specific ocean temperature ranges (Sunday et al. 2012). Their ability to persist in warming waters will be determined by their upper temperature tolerance limit (Nati et al. 2021), as well as their capacity for adaptation. The thermal optima refers to the range of temperatures at which physiological processes are optimised and can vary depending on life stage, taxa and geographic location (Dahlke et al. 2020). Changes to water temperature can affect populations by shifting their thermal optima outside of their preferred range which can result in reduced growth, increased energy expenditure and decreased reproductive success. This issue is particularly concerning at low latitudes where many PIC are located because marine taxa are already living close to their thermal optima (Pörtner & Farrell 2008, Donelson et al. 2012, Rummer et al. 2014, Nati et al. 2021).

Warmer water holds less oxygen than cooler water which can influence oxygen uptake, transport and delivery in fishes and invertebrates (Rummer & Munday 2019). Aerobic scope is used to understand the amount of oxygen available to an individual for activities beyond basic maintenance (Clark et al. 2013). It is measured by calculating the difference between an organism's maximum oxygen uptake rate (known as its maximum aerobic capacity) and its basal oxygen uptake rate (known as its standard metabolic rate or SMR). This difference represents the amount of oxygen that an organism can use above and beyond what is needed to maintain basic physiological functions. Reduced aerobic scope means individuals have less energy available for critical activities such as foraging and reproduction (Johansen & Jones 2011, Rummer & Munday 2019). Negative impacts of higher temperatures have been commonly reported on growth (Munday et al. 2008a), performance (Donelson et al. 2012) and reproduction (Donelson et al. 2010, Pankhurst & Munday 2011, Miller et al. 2015), with the negative effects of temperature on reproduction considered much higher than that of ocean acidification (Munday et al. 2019). This has been further corroborated in a recent meta-analysis which identified that embryos and spawners were more vulnerable to higher temperatures than larvae or adults (Dahlke et al. 2020).

While much of the research on the effects of warmer waters on tropical fish has been conducted on smaller-bodied taxa such as damselfishes, similar results have also been reported for larger-bodied taxa, including those captured in fisheries (e.g. trumpet emperor, *Lethrinus miniatus*, Williams et al. 2003, spawning in Nassau grouper, *Epinephelus striatus*, Asch & Erisman 2018, groups and snappers, Brulé et al. 2022). Research into the effects of ocean warming on coral trout (*Plectropomus leopardus*) found no embryos survived above 33.9°C (Pratchett et al. 2013), swimming performance was reduced when trout were acclimated to water 3°C above summer averages, while oxygen consumption and feeding rates increased raising concerns about whether this species will be able to satisfy energetic demands under current climate change scenarios (Johansen et al. 2014, 2015, Pratchett et al. 2017). However, some fisheries species show little response to changing temperatures (e.g. the rabbitfish, *Siganus lineatus*, LaMonica et al. 2021). Collectively, these studies indicate that impacts will be mixed with 'winners' and 'losers' as oceans warm, but given many taxa are already living at their thermal limits, negative effects will be more prevalent, with consequences for fisheries productivity.

Temperature is also critical for invertebrates, controlling growth, development, reproductive, population dynamics and species distributions. The effects of warming on physiological traits appears highly variable in invertebrates with some taxa and life stages robust to the effects of higher temperatures (e.g. crustacean larvae and juveniles), while in others a trade-off exists (e.g. faster development but smaller body size) (Byrne & Przeslawski et al. 2013). And others show a strong negative response (e.g. poor growth in the pearl oyster *Pinctada margaritifera*, Le Moullac et al. 2016). Increased temperatures are predicted to have a positive effect on the growth of sea cucumbers (bêche-de-mer), but this may be offset due to the higher mortality of larvae and juveniles, plus projected declines in seagrass habitat (Plagányi et al. 2013).

Intertidal invertebrates, as well as some fish that live in particularly shallow waters such as reef flats, may have greater adaptive capacity or ability to tolerate more extreme conditions (Harborne 2013, Jennerjan et al. 2017, Shrestha et al. 2021). However, even these taxa may reach their thermal maxima under future climate change scenarios (e.g. snappers and mojarra, Schultz et al. 2016, mud crabs, Ruscoe et al. 2004).

Marine heatwaves

In addition to the effects of long-term ocean warming, marine heatwaves (MHWs), which occur when waters are elevated beyond average temperatures for a prolonged period, can also have direct effects on marine fishes and invertebrates (Dunstan et al. 2018). The frequency, intensity and duration of MHWs is predicted to increase (Frölicher & Laufkötter 2018) and they are forecast to become an annual occurrence in many PIC within the next few decades (Holbrook et al. 2022). MHWs can have sublethal or lethal effects on fish and invertebrates through acute temperature stress or lowered oxygen levels, which can create hypoxic conditions, or drive mobile taxa to relocate to more favourable environmental conditions (Dunstan et al. 2018, Nati et al. 2021, Chamberlain et al. 2023). In Kiribati, within two months of a heat stress event, 50% declines were reported in the abundance and biomass of coral reef fishes, speculated to be caused by mortality (e.g. corallivores) or by more mobile individuals moving to deeper, cooler waters (e.g. piscivores) (Magel et al. 2020). At a remote atoll in French Polynesia, Lecchini et al. (2020) recorded a mass mortality event at a shallow water macroalgal nursery involving several thousand adult and juvenile fishes, as well as juvenile crustaceans and octopus, caused by a lethal combination of high temperatures and hypoxic conditions.

Invertebrates that have a symbiotic relationship with certain algal taxa can be highly susceptible to marine heatwaves. In particular, corals, which are the foundational taxa on reefs, live within a very narrow range of thermal tolerance, and acute heating events can cause corals to bleach. Bleaching occurs when the relationship between the coral and its algal symbionts breaks down.

The coral host expels the algae which causes the coral to become bleached or white (Hoegh-Guldberg 1999). As an important energy source for corals, corals will eventually die if they are unable to acquire more symbionts relatively quickly. In addition to corals, other sessile marine taxa such as anemones and giant clams can also bleach in response to temperature stress (McClanahan et al. 2009, Mies 2019). The global mass bleaching event from 2014 to 2017 was unprecedented in its spatial extent (Eakin et al. 2019) and impacted many bleaching susceptible taxa across the Pacific (e.g. French Polynesia, Andréfouët et al. 2018; Guam, Raymundo et al. 2019). Although mass coral bleaching is predicted to become an annual occurrence by the end of the century, some PIC may start to experience annual bleaching events within the next decade (e.g. French Polynesia, Tuvalu, Tokelau and the Marshall Islands, van Hooidonk et al. 2016, Hoegh-Guldberg et al. 2017).

Range shifts

One way that fish and invertebrates may respond to unfavourable environmental regimes is to shift their geographic range to encompass more suitable conditions. Range shifts will become more common as sea surface temperatures continue to warm. Typically range shifts occur from low to high latitude environments following thermal gradients. This is already evident in some coastal locations with tropicalisation of temperate fish communities described in multiple locations (Vergés et al. 2014, Hyndes et al. 2016). There is some evidence of longitudinal shifts from east to west occurring in terrestrial environments (Lenior & Svenning 2015), but little evidence of this in coastal marine systems. For many PIC, an influx of new taxa to shallow water coastal environments is unlikely, but there may be exceptions (e.g. flowery rockcod, *Epinephelus fuscoguttatus*, Chamberlain et al. 2023). As many taxa at low latitudes already live close to their thermal limits, the more likely scenario in these regions will be localised population declines or extirpations if they are unable to adapt. Another alternative scenario may be that rather than migrating to higher latitudes to escape adverse conditions, some species may move to cooler, deeper waters (e.g. Chamberlain et al. 2023). Both of these scenarios involve movement in some capacity, either via successful larval dispersal or by the movement of adults to more optimal environments. The latter could be an option for larger, more mobile coastal fishes (e.g. snapper, trevally and tuskfish, Chamberlain et al. 2023) which are also more likely to be fisheries targets. Larval dispersal to more suitable habitats may be problematic for some species as warmer temperatures can accelerate development and shorten the pelagic phase (Raventos et al. 2021). Range shifts may therefore have serious implications for coastal fisheries in PIC.

Ocean chemistry

Ocean acidification occurs when carbon dioxide from the atmosphere dissolves into the ocean, leading to a decrease in pH and an increase in acidity. This process can have significant physiological, behavioural and ecological impacts on marine organisms and population dynamics. Studies to date have shown considerable variation in how organisms respond to ocean acidification.

Unlike the effects of temperature, elevated CO_2 levels appear to have a lesser impact on the physiology of fishes (Wernberg et al. 2012, Cattano et al. 2018, Rummer & Munday 2019). This is likely because most fish have well-established mechanisms for acid-based regulation (Rummer & Munday 2019), although under higher CO_2 scenarios (e.g. >1000µatm), it appears functionality may be impaired (Cattano et al. 2018) resulting in tissue damage and reduced growth (Ishimatsu et al. 2008). Acid-based regulation is less well-developed in larvae, indicating they might be more vulnerable to elevated CO_2 levels than other life stages (Cattano et al. 2018). In terms of life history traits, near-future CO_2 conditions can result in a diverse range of responses in early life history stages ranging from negative (e.g. reproductive output, Welch & Munday 2016) to neutral (e.g. embryonic survival, Munday et al. 2009a) and even positive (e.g. larval growth, Munday et al.

2009a, reproductive output, Welch & Munday 2016), Responses however are mixed, even between the same life stages of closely related taxa. For example, growth rates varied between closely related juvenile damselfish, ranging from negative (Miller et al. 2012), to neutral (Munday et al. 2011), to positive (Munday et al. 2009a).

Behavioural changes have been widely reported in several fish taxa (Nagelkerken & Munday 2016), and these changes are evident from as low as 600µatm, increasing in frequency at 1000µatm and higher (Cattano et al. 2018, Munday et al. 2019). The range of behavioural responses affected is very broad including changes to lateralisation (Domenici et al. 2012, Welch et al. 2014), predator-prey dynamics (Pistevos et al. 2015, Ferrari et al. 2017), anxiety (Rodriguez-Dominguez et al. 2018), boldness (Munday et al. 2014), swimming performance (Rossi et al. 2015), homing ability (Devine et al. 2012) and the use of olfactory (Leduc et al. 2013) and auditory cues (Simpson et al. 2011, Rossi et al. 2015). These behavioural responses have been recorded predominantly in larvae or juveniles of small-bodied, site-attached fishes but have also been observed in adults (Devine et al. 2012) and large-bodied taxa (e.g. reduced predator avoidance in juvenile coral trout, *Plectropomus leopardus*, Munday et al. 2013). For instance, larval barramundi (*Lates calcarifer*), an economically important species in many tropical areas, were not only deterred from their preferred settlement habitat type when exposed to elevated CO_2 (Rossi et al. 2015), but they were attracted to irrelevant cues including white noise (Rossi et al. 2018). Other fisheries species also use sensory cues to navigate towards, and settle in, different habitat types including species that undertake ontogenetic shifts between habitats (e.g. sweetlips, Haemulidae. Huijbers et al. 2012). The effects of behavioural changes caused by ocean acidification therefore have the potential to impact on fisheries in PIC.

For invertebrates, calcifying organisms are more sensitive to a decrease in pH (e.g. corals, echinoderms and molluscs, Kroeker et al. 2013, Tai et al. 2021). This is because many taxa rely on calcium carbonate to form their skeletons or shells. However, in more acidic waters, the availability of carbonate ions decreases which makes it harder for these organisms to build and maintain their structures. This can lead to reduced development, growth rates, weaker skeletons, increased vulnerability to predation and risk of disease (Przeslawski et al. 2008, Tan & Zheng 2020). Early life history stages of bivalves (e.g. oysters, mussels, clams) appear particularly sensitive to acidification which may have long-term impacts on population dynamics (Kroeker et al. 2013, Watson 2015). In contrast, non-calcifying taxa or more mobile species (e.g. crustaceans) exhibit a higher tolerance to a decrease in pH. Evidence of behavioural change is also present in invertebrates including altered competitive outcomes in crustaceans (Gherardi et al. 2013). Importantly, ocean acidification also affects benthic alga which can used as critical settlement cues for many taxa, particularly corals, as they metamorphose from their pelagic larval stage into the benthic community (Doropoulos & Diaz-Pulida 2013).

Interactions between multiple stressors

Over the last decade, it has become increasingly evident that climate change stressors are unlikely to operate in isolation (Harvey et al. 2013, Pörtner et al. 2014). Rather, such stressors will act in tandem on individuals, populations and communities (Przeslawski et al. 2008, Doney et al. 2012, Kroeker et al. 2017, Dutra et al. 2021), along with a range of localised stressors such as overfishing (Cinner & McClanahan 2006), pollution (Furby et al. 2014, Lamb et al. 2018), and water quality (Moe et al. 2013, DeCarlo et al. 2015), which have the potential to exacerbate or compound issues (Ateweberhan et al. 2013, Dutra et al. 2021). As a result, there has been a shift away from studies examining the effects of a single stressor, to studies that explore the interactive effects of multiple stressors (Pörtner et al. 2014, Cattano et al. 2018, Munday et al. 2019). Adopting a multi-stressor approach has shown that combining different climate change factors can have additive, synergistic and antagonistic effects on different life stages and taxa (Nagelkerken & Munday 2016, Kroeker et al. 2017, Munday et al. 2019). To date, the interaction between ocean warming and acidification

have been the most commonly tested in both fishes and invertebrates. For both groups, effects can vary considerably depending on the response, life stage and taxa examined which makes generalisations or predictions challenging.

In fish, there are several instances where CO_2 only seems to have an effect in combination with elevated temperatures. For example, high CO_2 levels had limited impact on the juvenile feeding behaviour (Nowicki et al. 2012) and reproductive performance (Miller et al. 2015) of the anemonefish, *Amphiprion melanopus.* However, when the effects of CO_2 were tested in combination with elevated temperature, foraging activity and food consumption increased in juveniles (Nowicki et al. 2012) and offspring quality declined (Miller et al. 2015). In the dottyback, *Pseudochromis fuscus,* predation rates on damselfishes were unaffected when elevated temperature and acidification were considered in isolation but increased twofold under elevated temperature and CO_2 conditions (Ferrari et al. 2015). Temperature can also attenuate the effects of high CO_2 levels. Under high CO_2 conditions, individuals of the damselfish, *Pomacentrus wardi* changed their lateralisation behaviour from a right to left-turning bias, which has implications for shoaling behaviour (Domenici et al. 2014). However, the addition of elevated temperatures reversed the altered lateralisation pattern.

Similarly, invertebrate life stages and taxa exhibit a range of responses when warming and acidification are considered together. In a meta-analysis, Byrne & Przeslawski (2013) found that interactive effects of temperature and CO_2 were widespread in invertebrates (e.g. molluscs, echinoderms, cnidarians). Additive negative effects were most commonly reported and have been recorded in embryos (e.g. starfish survival, Byrne et al. 2013a), larvae (e.g. crown-of-thorns starfish larval size, Kamya et al. 2014) and juveniles (e.g. giant clam, *Tridacna squamosa* survival, Watson et al. 2012). Antagonistic effects were also common, with higher temperatures reducing the negative effects of high CO_2 levels on growth and calcification of bivalve larvae (Byrne et al. 2013b, Kroeker et al. 2014). From the studies so far, it appears that calcifying invertebrate larvae are more susceptible to the effects of warming and acidification compared to taxa with non-calcifying larvae (Byrne & Przeslawski 2013).

An emerging area of research into understanding the effects of climate change on marine taxa is the incorporation of more context dependence variables to simulate real world conditions. So far, this has presented some alternative perspectives on how species and life stages may respond to future change. For instance, accounting for diel CO_2 cycles (Jarrold et al. 2017, Jarrold & Munday 2018) or prior experience in a high-risk environment (Ferrari et al. 2017) has provided some evidence that there can be both physiological and behavioural compensatory effects which may ameliorate or negate some of these effects.

Ocean circulation and currents

Climate change is expected to modify ocean circulation and current patterns, but the potential effect of altered hydrodynamics on coastal fishes and invertebrates continues to be one of the least studied stressors (Hauser et al. 2015). Changes to ocean currents can affect coastal fishes and invertebrates through two main mechanisms. First, currents and eddies play a critical role in larval transport and dispersal patterns (Cowen et al. 2006, Wilson et al. 2016). Considering that around 60-80% of tropical demersal fishes have a pelagic larval stage prior to settlement (Leis et al. 2013), and the limited mobility of many invertebrate taxa following the larval stage, changes to circulation patterns could impact population dynamics and species distributions (Munday et al. 2008a). Larvae may be retained in their parental environment, which could reduce the chance of escaping unfavourable conditions, or could be transported offshore away from suitable settlement habitat (Cetina-Heredia et al. 2015). Connectivity among meta-populations could also be disrupted which might limit the potential for recovery and adaptation (Munday et al. 2009b, Adam et al. 2014). In addition, larvae may face higher energetic costs if they need to swim longer distances

to reach suitable settlement habitat (Booth et al. 2017). Extending the pelagic larval stage to accommodate some of these issues may be impractical if development is accelerated because of higher sea surface temperatures (Raventos et al. 2021). Ocean circulation also plays an integral role in the transportation of nutrients which exerts a strong influence on primary and secondary productivity (Hauser et al. 2015, Häder & Gao 2017). The availability and quality of plankton can influence larval survival (Przeslawski et al. 2008) and is particularly important in oligotrophic waters when food supply can be limited. Any changes to productivity as a result of changing circulation patterns may affect larval stages, but also many taxa of planktivorous fishes that are found on coral reefs (Munday et al. 2008a).

Indirect impacts on coastal fish

As well as the direct impacts on fishes and invertebrates themselves, climate change can also have indirect effects through the alteration of habitat. Indirect effects may present a more immediate threat to fish and invertebrate populations given the sensitivity of coastal habitats (e.g. coral reefs, seagrass) to disturbance (Munday et al. 2019). Many coastal ecosystems are already experiencing impacts associated with climate change which provides us with valuable insights into the future composition of coastal fish and invertebrate communities.

Changes to coral reefs

Coral reefs are exposed to a multitude of localised stressors, with reefs located near to coasts often exposed to higher levels of anthropogenic disturbance than more remote reefs. Climate change stressors have already begun to impact coral reefs and the situation is expected to worsen by 2100. Two of the main climate change stressors that will have indirect impacts on coastal fishes and invertebrates are marine heatwaves and storms.

The frequency, intensity and duration of marine heatwaves (MHWs) are predicted to increase (Frölicher & Laufkötter 2018) and become an annual occurrence for many PIC by the end of the century (Holbrook et al. 2022). As a result, more mass bleaching events are likely to occur which can lead to widespread mortality of corals, which are the foundational taxa of reef ecosystems. Tropical storms can cause immediate and severe damage to the structure of reefs. High winds associated with storms can dislodge slow growing massive corals, break morphologically complex corals, and the debris accumulated from storm damage can scour benthic substrates leaving a depauperate and topographically less complex reef structure. Storms can also result in coral bleaching if sediment or freshwater loads entering the marine system from rivers are particularly high (Meehan & Ostrander 1997, Fabricius 2005).

Marine heatwaves and storms can cause significant declines in the abundance of fishes and invertebrates, through sub-lethal effects, mortality or by displacement to alternative habitats (Jones et al. 2004, Wilson et al. 2006, Przeslawski et al. 2008, Chamberlain et al. 2023). Estimates suggest that around 10% of reef fishes are coral dependent (Pratchett et al. 2008) and even relatively small amounts of coral loss (<10%) can result in marked shifts in community composition (Wilson et al. 2006). The loss of live coral tissue has the greatest immediate impact on marine taxa that feed on corals. Several taxa, for example certain species of butterflyfish and wrasse, are obligate corallivores and feed exclusively on live coral tissue (Cole et al. 2008). For obligate corallivores, reduced body condition has a direct correlation with live coral tissue loss, which can ultimately lead to poor survival outcomes and lagged population declines (Pratchett et al. 2008), with some species consistently absent or experiencing significant declines following a bleaching event (e.g. *Chaetodon trifascialis*, Pratchett et al. 2006, Graham et al. 2009, Magel et al. 2020). In Kiribati, the biomass of corallivores declined by 70% following the 2015/16 bleaching event (Magel et al. 2020). In addition, the presence of live coral is also important for many parrotfish species, both for feeding and settlement (Giddens et al. 2022). For instance, recruits of the Bumphead parrotfish (*Bolbometopon muricatum*) have a settlement preference for live branching corals

(Solomon Islands, Hamilton et al. 2017). Although the coral structure initially remains intact following a bleaching event, over longer timeframes the structure will be eroded.

Loss of structural complexity can have significant and long-term impacts on a wider breadth of coral reef taxa and result in highly altered community composition (Cheal et al. 2008, Adam et al. 2014, Richardson et al. 2017). Small-bodied fishes (e.g. coral-dwelling gobies and many species of damselfishes) and invertebrates use the structure provided by morphologically complex corals (e.g. branching, bushy, corymbose) as refuge from predators (Przeslawski et al. 2008). Declines in the abundance of these taxa are commonly linked with loss of structural complexity (e.g. damselfishes, Ceccarelli et al. 2016). Larger-bodied taxa, including those important to coastal fisheries (e.g. sweetlips, Haemulidae and snappers, Lutjanidae) also benefit from the structure of reefs, for instance, using tabular corals for shade or concealment during the day (Kerry & Bellwood 2012). Structural complexity can moderate species interactions (e.g. predation, competition) and hence loss of structural complexity can disrupt the equilibrium, resulting in community-level change. The presence of bleached or algae-covered corals can also affect predator-prey dynamics, reducing refuge availability for prey as well as making them more conspicuous to predators (Coker et al. 2009).

Although declines in abundance and biomass have been reported for several reef fish taxa following episodic disturbance events such as bleaching events and storms, this is not the case for all taxa. At least in the short-term, some taxa can respond positively to disturbance events, including instances that have led to shifts from coral- to macroalgal-dominated habitats (Robinson et al. 2019b). Positive responses have been most frequently observed in certain functional groups, specifically roving herbivores, omnivores and detritivores – in other words, more generalist taxa (Wilson et al. 2006, Ceccarelli et al. 2016, Robinson et al. 2019, Magel et al. 2020). For instance, several species of rabbitfish (siganids) have shown strong positive increases post-disturbance events, likely assisted by disturbance tolerant traits such as high mobility, diet plasticity, short life spans and rapid growth. However, the longer-term effects and whether there is a lag between a positive initial response to subsequent declines is not fully resolved.

Overall, while it appears that many taxa can tolerate live coral loss, negative effects become increasingly common as structural complexity declines. Immediate and negative impacts are common for corallivores and planktivores, whereas some taxa appear more resilient. Given sufficient time between disturbance events, there is the potential for coral reefs and associated communities to start to recover although this is increasingly unlikely with current climate change predictions. Furthermore, reef recovery can also be impeded by other stressors such as crown-of-thorn starfish outbreaks and disease, leading to a long-term decline in overall reef health.

Changes to seagrass and mangrove habitats

Nearshore coral reefs are often found within a network of habitats that form an interconnected coastal ecosystem mosaic (Sheaves 2009). This mosaic can include mangroves, seagrass meadows, macroalgal beds and intertidal flats as well as coral reefs. Patches of habitat are linked through tidal and other hydrodynamic forces, nutrient transfer and the movement of organisms (Lundberg & Moberg 2003). Climate change is expected to impact shallow water non-reef habitats in a variety of ways. Similar to corals, seagrasses can be severely impacted by marine heatwaves resulting in widespread mortality (Collier & Waycott 2014, Arias-Ortiz et al. 2018). Mangroves may be squeezed out as sea levels rise if they are unable to migrate landwards (Leo et al. 2019). Severe storms can affect all shallow-water habitat types reducing structural complexity and vegetation cover (Duarte 2002, Krauss & Osland 2020). In addition, as the framework of coral reefs begins to break down or as sea level rises above the crest, coral reefs will lose their ability to dissipate wave energy which will have consequences for all habitats found landwards of the reef crest (Saunders et al. 2014). Given the strong links between habitats, degradation of one

component of the seascape mosaic has the potential to adversely affect adjacent habitat patches and the organisms that use them.

There is a growing body of evidence demonstrating that non-reef habitats are important for fisheries productivity (e.g. seagrass beds, Unsworth et al. 2018, macroalgal meadows, Fulton et al. 2020). Multiple habitat use is widespread among coastal fishes, with estimates that 20-35% of coral reef fishes use non-reef habitats during their lives (Sambrook et al. 2019, 2020). For example, in Papua New Guinea, 35% of coral reef fishes were recorded in non-reef habitats, of which >50% were fisheries targets (e.g. snappers, sweetlips, emperors, trevally) (Sambrook et al. 2020). Coral reef fishes use non-reef habitats for a variety of reasons. Several families contain species that undertake ontogenetic shifts from juvenile vegetated habitats to coral reefs as adults (e.g. emperors and snappers, Kimeirei et al. 2013). Others move between habitat patches in search of food, or migration to specific habitats for spawning (Unsworth et al. 2007, Taylor & Mills 2013, Honda et al. 2016). Availability of, and access to, non-reef habitats may therefore be important to population replenishment and stability on coral reefs. The extent of multiple habitat use will vary across the Pacific depending on the availability of each habitat type as well as tidal regime, which can affect the accessibility and usability of the habitat (Igulu et al. 2014). Climate change stressors that result in loss, fragmentation, degradation or isolation could disrupt these critical connections leading to population declines of key fisheries species.

The value of non-reef habitats, and the threats posed by climate change stressors, are also relevant to invertebrates. Sea cucumbers (bêche-de-mer) are one of the most economically important invertebrate taxa in the Pacific (Kinch et al. 2008). However. sea cucumber fisheries have been heavily overfished in many places resulting in long-term fisheries closures to try and rebuild stocks (e.g. Hair et al. 2016). Warming waters are expected to increase mortality rates of larvae and juveniles (Plagányi et al. 2013) impeding population recovery which may be further exacerbated by the loss of critical seagrass habitat. For example, the sandfish *Holothuria scabra* is strongly associated with enduring seagrass taxa that only occur in the Indo-Pacific region, such as *Enhalus acoroides* or *Thalassoma hemprichii* (Mercia et al. 2000, Floren et al. 2021). As a result, loss of suitable seagrass habitat as a result of climate change has the potential to decimate remaining sea cucumber stocks.

A summary of the observed impacts of climate drivers on fish and invertebrates that comprise coastal fisheries is provided in Table 4.

Table 4. Observed impacts of climate drivers on fish and invertebrates that comprise coastal fisheries. Source: Welch et al. (in press)

Climate driver	Observed impacts on fish & invertebrates	Example references
Increasing SST	Reduced growth and smaller body size	Munday et al. 2008, Dahlke et al. 2020, Johansen et al. 2014, 2015, Pratchett et al. 2017, Byrne & Przeslawski et al. 2013, Le Moullac et al. 2016, Lam et al. 2020, Cheung et al. 2013, Cheung and Pauly 2016, Huang et al. 2021
	Altered reproductive success, change in the timing of life history events (e.g. spawning, migration), shorter larval duration	Donelson et al. 2010, Pankhurst & Munday 2011, Pratchett et al. 2013, Dahlke et al. 2020, Raventos et al. 2021, Plagányi et al. 2013, Cheung and Pauly 2016, Pratchett et al. 2017
	Range shifts toward higher latitudes or to deeper water, altered food webs and species composition, declines in species richness, localised extinctions	Vergés et al. 2014, Hyndes et al. 2016, Chamberlain et al. 2023, Cheung and Pauly 2016, Cheung et al 2013a (from Cheung and Pauly)
Ocean acidification	Reduced development and growth rates, weaker skeletons (for calcifying invertebrates), increased vulnerability to predation and risk of disease	Ishimatsu et al. 2008, Przeslawski et al. 2008, Tan & Zheng 2020, Dickinson et al. 2021
	Altered reproductive success	Kroeker et al. 2013, Watson 2015
	Altered behavior affecting function and survival	Pistevos et al. 2015, Rodriguez-Dominguez et al. 2018, Gherardi et al. 2013
Changing ocean circulation & currents	Changes in larval transport and dispersal patterns, changes in connectivity among populations, altered distributions, altered food webs, altered conditions for site attached species	Cowen et al. 2006, Wilson et al. 2016, Munday et al. 2008, Cetina-Heredia et al. 2015, Munday et al. 2009, Adam et al. 2014, Booth et al. 2017,
Primary and secondary productivity	Changes in metabolism, growth, survival, reproductive output and success, lower abundance and population biomass, size-structure, altered food webs	Hauser et al. 2015, Häder & Gao 2017, Przeslawski et al. 2008, Munday et al. 2008, Lam et al. 2020, Free et al. 2019, Williams et al. 2015, Barange et al. 2014
Episodic events (marine heat waves, coral bleaching, cyclones)	Acute temperature stress, hypoxia, relocation, mortality, habitat alteration and degradation, reduced productivity, population and biomass declines, opens up the potential for species turnover or establishment of new or invasive species	Dunstan et al. 2018, Nati et al. 2021, Chamberlain et al. 2023, Magel et al. 2020, Lecchini et al. 2020, McClanahan et al. 2009, Mies 2019, Andréfouët et al. 2018, Raymundo et al. 2019, Jones et al. 2004, Wilson et al. 2006, Przeslawski et al. 2008, Chamberlain et al. 2023, Magel et al. 2020, Coker et al. 2009, Sambrook et al. 2019, 2020, Unsworth et al. 2018, Fulton et al. 2020, Mercia et al. 2000, Floren et al. 2021, Unsworth et al. 2007, Taylor & Mills 2013, Honda et al. 2016
Interactions between multiple environmental changes	Additive, synergistic and antagonistic effects on different life stages and taxa – increased metabolism, reduced reproductive success, altered predation rates, changes in behavior, reduced survival, lower biomass, reduced productivity, altered community structure and ecosystem function	Kroeker et al. 2017, Byrne et al. 2013a, Byrne & Przeslawski 2013, Fulton 2011, Free et al. 2019, Williams et al. 2015, Barange et al. 2014, Heneghan et al. 2021

4. Vulnerability of Coastal Fisheries to Climate Change

4.1 Methodology overview

This section provides a summary of the coastal fisheries vulnerability assessment methods for PIC, with further details provided in Appendix C.

We estimated the impacts of climate change on coastal fisheries biomass (including fish and invertebrates) using a similar approach to the 2011 assessment. That is, we combined projected changes in available fish biomass (direct effects) and in habitat area (indirect effects) to derive projected changes in catch levels for each PIC. Projected changes in catch by PIC were based on the latest (2021) catch estimates by Gillett and Fong (2023). A significant improvement on the 2011 assessment was the use of an ecosystem model ensemble forced by climate models to project changes in marine organism biomass (see the Fisheries and Marine Ecosystem Model Intercomparison Project, FishMIP; https://fishmip.org). The FishMIP models provide projections of change in biomass for two shared socio-economic pathways (SSPs), which capture the effects of the implementation of different climate change mitigation plans and changes in greenhouse gas emissions (Gidden et al. 2019). FishMIP models include marine biomass projections under SSP1-2.6 (high mitigation, low emissions) and SSP5-8.5 (no mitigation, high emissions), and an estimate of marine biomass under SSP2-4.5 (intermediate mitigation, intermediate emissions) was derived from the SSP1-2.6 and SSP5-8.5 projections. This represents a less subjective analysis approach that also provides quantitative estimation of uncertainty in projections. Projected changes in exploitable biomass was combined with projected changes in habitat area to derive estimates of future catches under each of our climate scenarios (2030 SSP5-8.5; 2050 SSP2-4.5 and 2050 SSP5-8.5) for each PIC EEZ.

4.2 Projected changes in fish biomass

The impacts of climate change are projected to result in declines in coastal fish biomass in most Pacific Island Countries participating in the GCF regional tuna programme, noting that there is also high variability spatially and temporally (Table 5). When aggregating across all the models used to make the projections, overall, the largest declines in biomass are projected to be in PIC closest to the equator and in the western Pacific region.

The locations most likely to experience declines occur at lower latitudes with progressively larger declines over time expanding to higher latitudes and in an easterly direction (Welch et al. in press). While biomass is projected to decline between 20–30 % in some parts of the equatorial western Pacific by 2050, it is important to note that the spatial variability means that impacts within a Pacific Island Country EEZ may also be highly variable. For example, even under the lower emission scenario by 2050 some coastal areas of PNG are expected to experience biomass declines of up to 30 % while other areas are expected to experience very little change, or even modest increases in biomass in some cases. Given the spatial variability in these projections, the modest increases may or may not benefit fisheries catches in the respective Pacific Island Countries. It is important to note that the projected changes are relative to a reference period of 2010–2020[5].

[5] Similar recent modelling studies have used variable but usually earlier reference periods generally resulting in higher projected declines, e.g. Cheung et al. 2010, Asch et al. 2018, Lam et al. 2020.

Table 5. The average (median), upper and lower values across the model ensemble of projected % change in biomass for each Pacific Island country (PIC) participating in the GCF regional tuna programme for the SSP5-8.5 emissions scenario in 2030 and the SSP2-4.5 and SSP5-8.5 emissions scenarios for 2050. Averages are calculated using the median (or upper or lower) value of the model ensemble for the 20-year period around 2050 (2041–2060) for SSP2-4.5 and SSP5-8.5 and the 10-year period around 2030 (2026-2035) for SSP5-8.5. % change is referenced against the baseline period of 2010-2020. Source: Welch et al. (in press)

PIC	Projected change in fish biomass (%)								
	2030 SSP5-8.5			2050 SSP2-4.5			2050 SSP5-8.5		
	Average	Lower	Upper	Average	Lower	Upper	Average	Lower	Upper
Melanesia									
Fiji	-1.0	-15.3	+15.6	-0.8	-22.6	+13.3	-2.5	-29.1	+13.7
Papua New Guinea	-5.5	-28.0	+6.3	-18.0	-49.8	-2.1	-24.0	-55.5	-2.6
Solomon Islands	-7.1	-28.9	+3.2	-15.8	-43.3	-1.8	-18.1	-52.6	-0.5
Vanuatu	-1.4	-13.4	+9.5	-2.2	-23.8	+10.4	-2.8	-30.9	+12.8
Micronesia									
FSM	-7.3	-25.6	+4.4	-18.4	-47.6	-1.0	-24.2	-51.1	-1.3
Kiribati – Gilbert Islands	-1.5	-22.6	+21.6	-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	-6.0	-19.1	+5.7	-9.9	-38.8	+3.0	-14.5	-42.8	+1.8
Nauru	-2.5	-24.9	+21.9	-10.7	-33.8	+1.8	-13.4	-40.4	+4.4
Palau	-10.6	-33.6	+7.7	-19.9	-43.9	-2.3	-28.4	-48.0	-2.9
Polynesia									
Cook Islands	+0.5	-10.6	+17.2	-6.8	-21.7	+2.7	-11.0	-25.2	+2.3
Niue	+1.7	-21.7	+30.4	-2.6	-25.8	+27.2	-3.9	-29.7	+31.5
Samoa	+0.5	-15.0	+18.3	-9.9	-31.0	+0.8	-12.3	-35.9	+0.8
Tonga	-0.6	-18.4	+23.1	-0.5	-23.4	+19.0	-4.7	-27.3	+16.1
Tuvalu	-6.7	-24.6	+9.3	-15.7	-33.3	-0.6	-19.1	-42.5	+2.7

Aggregating results across EEZ to give annual trends in the predicted exploitable coastal fish biomass per Pacific Island Country highlights the uncertainty of the projections (Figures 7–9), as the different models do not always agree on the magnitude of change. The median and range for the trends suggests that predicted coastal fishery biomass tend to continue a declining trend into the future regardless of the climate change scenario, with some PIC showing greater declines than others, and declines occurring at different time frames (Figures 7–9). Several PIC are projected to experience only modest declines in biomass for most of the time series under either emission scenario (e.g. median trends for Fiji, Niue, and Vanuatu) (Figures 7–9, Table 5). The wide range of projections suggest that exceptions to a general decline may be possible in some PIC where there may be no apparent overall change in biomass projected over the future time series or even some increases.

Figures 7–9 highlight high inter-annual variability, reflecting differences between the models but also the potential for increased natural variability in environmental conditions. This is important to recognise as it may result in higher than usual inter-annual variability in catches from coastal fisheries, and in some cases these may be significant. For example, in several instances for many Pacific Island countries, biomass is projected to change by 20–30% in time periods as short as only 1-2 years. It is also not possible to predict if these rapid changes in fishable biomass will be experienced across the whole jurisdiction or at local scales. These projections do not incorporate sudden onset or episodic climate (or other) events, such as marine heatwaves, cyclones, tsunamis, or large flood events. To be well prepared for future conditions, this type of variability should be factored into adaptation strategies for each Pacific Island country.

The range in predicted values in Figures 7–9 become increasingly greater the more forward-looking (i.e. further into the future) which reflects the increasing uncertainty in the models at predicting changes over longer time frames. This is the reality of current modelling capacity and, it simply isn't clear which processes will dominate, how certain specific species will respond (by acclimating to conditions, changing behaviour) or how changes in species will buffer overall ecosystem productivity. Different models make different assumptions, and this leads to different projections. This emphasises the importance of focusing on the nearer-term projections where confidence in projections is higher, while also recognising that trends over the longer-term are affected by decisions taken now, captured by different SSP-RCP scenarios.

When projecting the future, it is important to consider both the spread and the median of the results. The median values give an indication of where there is more model agreement, while the range in upper and lower estimates reflects the level of uncertainty in modelling outputs, but also possible future outcomes. One way of thinking about this is to treat the upper estimate as "best case", median as "most plausible" and lowest estimate as "worst case". Therefore, we recommend that adaptation strategies should consider the full potential magnitude of projected change in the future, as well as the likely inter-annual variability in coastal fish biomass in the future.

While it is important to acknowledge that the projected declines in biomass continue to consistently decline in the longer-term, given the uncertainties around the model projections the analysis focuses on the projected impacts on coastal fisheries in the medium-term outlook of 2050. The future out to 2050 is also more tangible to current generations and decision makers (Figures 7–9, Table 5).

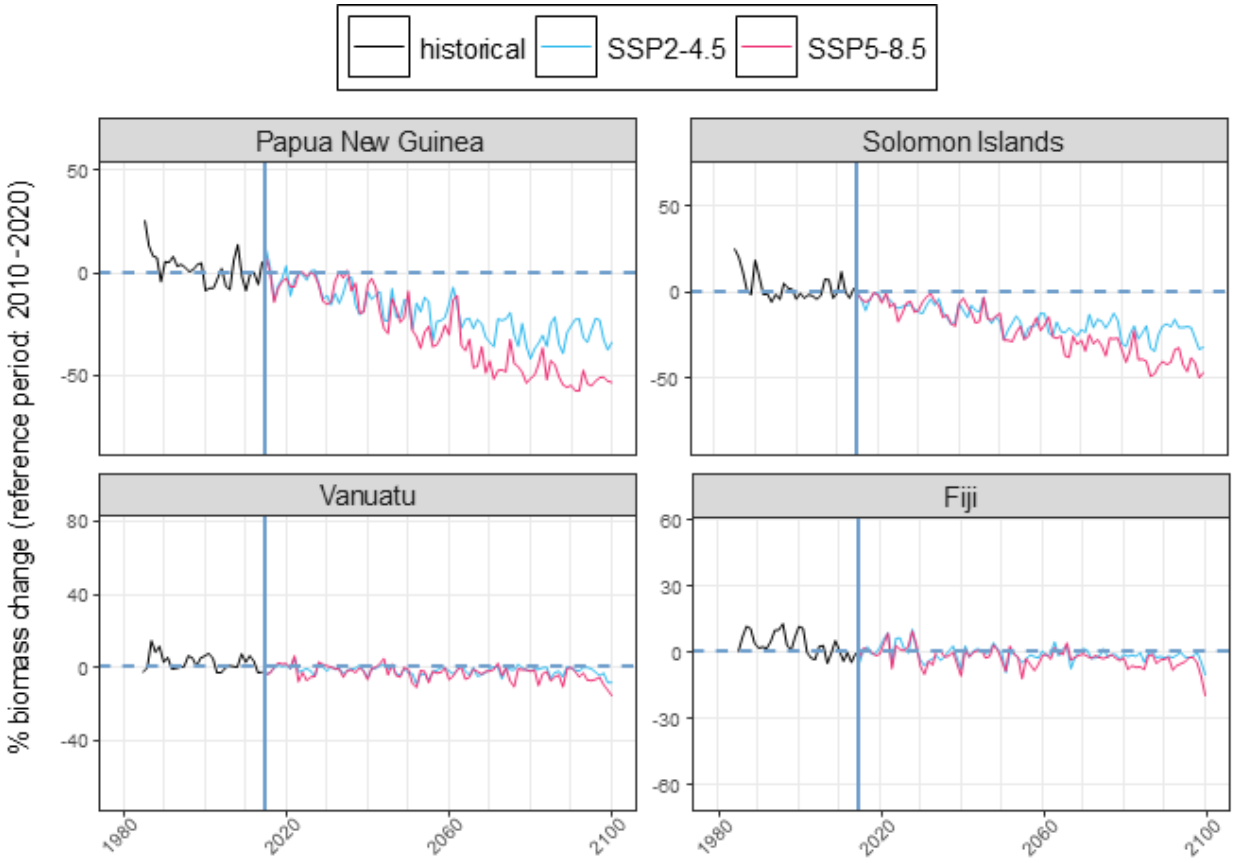

Figure 6. Trends in model ensemble median relative (%) change in coastal fishery biomass for Pacific Island countries participating in the GCF regional tuna programme in Melanesia for the historical period of 1985–2014 (black line) and projected changes up to 2100 for the climate change emission scenarios of SSP2-4.5 (blue line) and SSP5-8.5 (pink line). The blue line indicates the period separating historical from projected periods. The SSP2-4.5 scenario represents averaged projections of SSP1-2.6 & SSP5-8.5. Source: Welch et al. (in press).

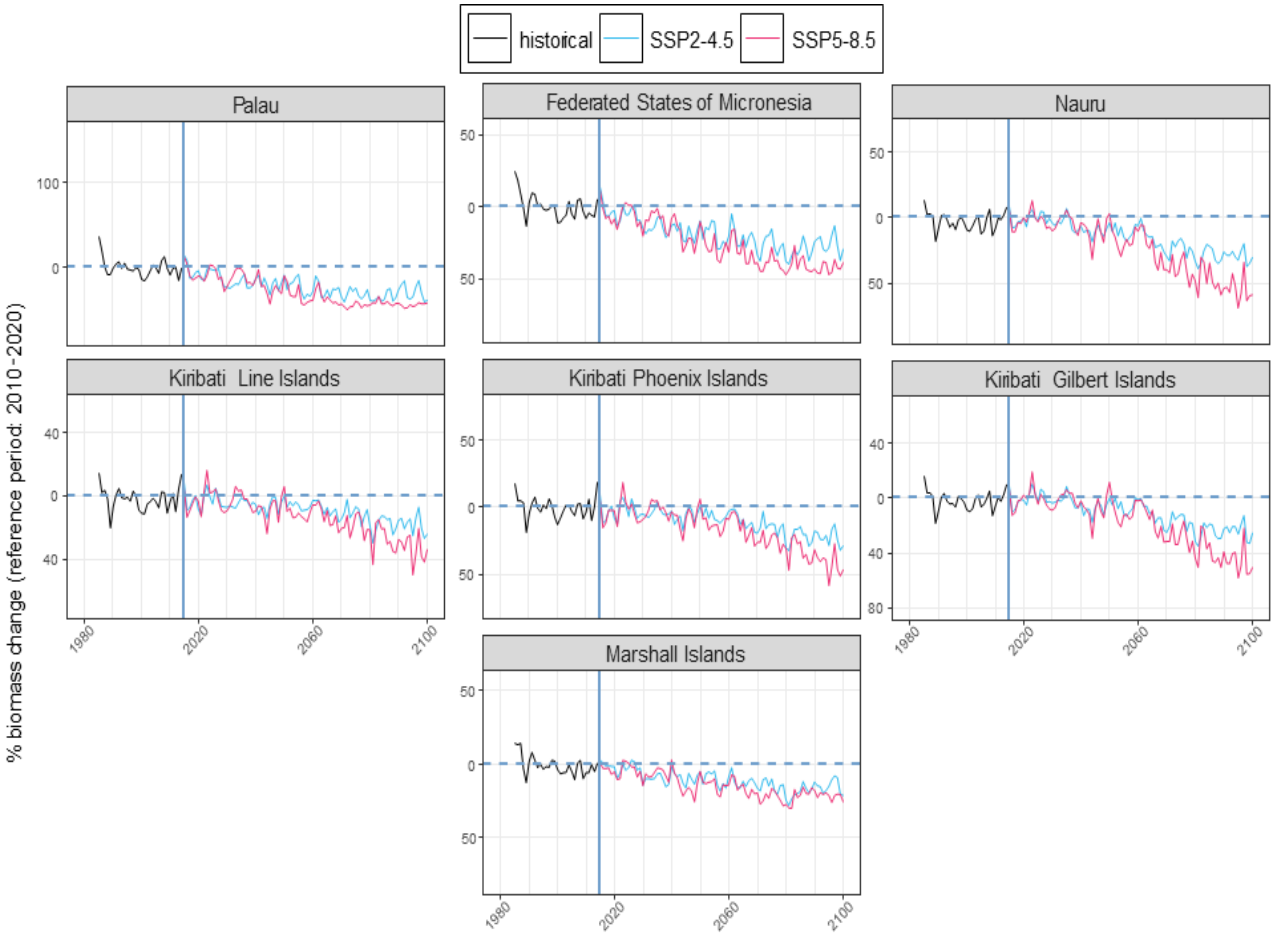

Figure 7. Trends in the model ensemble median relative (%) change in coastal fishery biomass for Pacific Island countries participating in the GCF regional tuna programme in Micronesia for the historical period of 1985-2014 (black line) and projected changes up to 2100 for the two climate change emission scenarios of SSP2-4.5 (blue line) and SSP5-8.5 (pink line). The blue line indicates the period separating historical from projected time periods. The SSP2-4.5 scenario represents averaged projections of SSP1-2.6 and SSP5-8.5. Source: Welch et al. (in press).

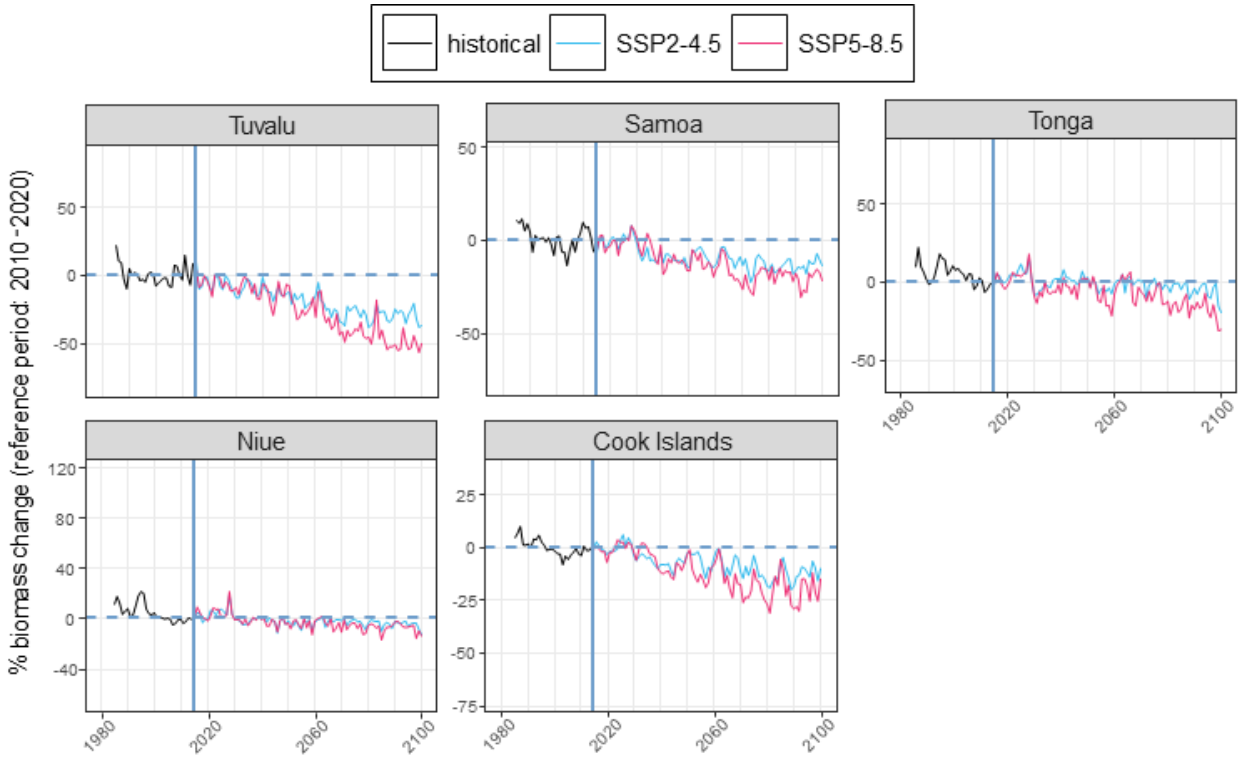

Figure 8. Trends in model ensemble median relative (%) change in coastal fishery biomass for Pacific Island countries participating in the GCF regional tuna programme in Polynesia for the historical period of 1985-2014 (black line) and projected changes up to 2100 for SSP2-4.5 (blue line) and SSP5-8.5 (pink line) emissions scenarios. The blue line indicates the period separating historical from projected time periods. The SSP2-4.5 scenario represents averaged projections of SSP1-2.6 and SSP5-8.5. Source: Welch et al. (in press).

4.3 Projected changes in coastal fish catch

To estimate the impacts of climate change on coastal fisheries catches, current catch levels were multiplied by the projected percentage changes in fish biomass and the percentage changes in habitat. We also continue to focus on projected impacts on coastal fishery catches for each Pacific Island Country for 2030 and 2050, noting the variability and uncertainty discussed previously.

On average across all 14 PIC, incorporating projected changes in habitat results in a larger overall impact on projected catches relative to projected changes in biomass alone. In all 14 PIC, it is projected that catches of coastal fisheries resources on average will decline, in some cases significantly (Table 6). Even under the lower emissions scenario (SSP2-4.5), FSM, the Line Islands in Kiribati, Nauru, Niue, Palau, PNG, Samoa, Solomon Islands, and Vanuatu, are predicted to experience significant reductions in food available from coastal fisheries catches by 2050. Once again, it should be acknowledged that the variability and uncertainty in projected biomass changes is high and transferred to estimates of changes in catch (Table 5). Further, the uncertainty does not incorporate uncertainty associated with estimated changes in habitat and current catch.

One of the key assumptions of the analysis of projected impacts on catch is that the characteristics of coastal fisheries in each PIC, such as fisher activity and efficiency, market demand, and the current management situation, remains constant into the future (see Barange 2019). Although changes in habitat area were considered in estimating projected changes in catch, it is assumed that estimates of projected catch are proportional to projected changes in biomass; this is unlikely to be the case (Barange 2019).

Table 6. Recent catch levels (tonnes), projected change (%) in habitat area and projected change (%) in catches for 2030 under SSP5-8.5 and 2050 under SSP2-4.5 and SSP5-8.5 emissions scenarios. Projected habitat changes were based on expected declines in coral reef and seagrass areas combined, except for PNG which also included mangrove area declines. Projected changes in catch also take into account projected changes in biomass (see Table 5). Source: Gillett and Fong, 2023; Welch et al. (in press).

Pacific island countries	Projected change in habitat area (%)			Recent catch (t) (2021)	Projected change in annual catch (%)		
	2030 SSP5-8.5	2050 SSP2-4.5	2050 SSP5-8.5		2030 SSP5-8.5	2050 SSP2-4.5	2050 SSP5-8.5
Melanesia							
Fiji	-9.06	-13.0	-14.7	30,100	-10.0	-13.7	-16.9
PNG	-7.51	-16.9	-19.1	46,000	-12.6	-31.8	-38.5
Solomon Islands	-7.42	-8.2	-9.3	30,000	-14.0	-22.7	-25.8
Vanuatu	-13.28	-22.0	-25.0	4,400	-14.5	-23.8	-27.0
Micronesia							
FSM	-0.76	-1.9	-2.2	5,000	-8.0	-20.0	-25.9
Kiribati – Gilbert Islands	-11.43	-1.67	-1.89	17,204	-12.7	-7.9	-10.7
Kiribati – Line Islands		-62.4	-70.67	1,790		-64.7	-73.4
Kiribati – Phoenix Islands		0	0	7		-7.0	-10.4
Marshall Islands	-1.57	-2.5	-2.8	4,200	-7.5	-12.2	-17.0
Nauru	-42.6	-44.2	-50.0	240	-44.0	-50.1	-56.7
Palau	0	-0.9	-1.0	2,400	-10.6	-20.6	-29.1
Polynesia							
Cook Islands	-5.1	-5.4	-6.1	430	-4.7	-11.8	-16.4
Niue	-16.0	-16.6	-18.8	169	-14.6	-18.8	-21.9
Samoa	-19.93	-48.2	-54.6	11,000	-19.5	-53.3	-60.2
Tonga	-7.4	-7.7	-8.7	7,000	-8.0	-8.1	-13.0
Tuvalu	0	0	0	1,500	-6.7	-15.7	-19.1

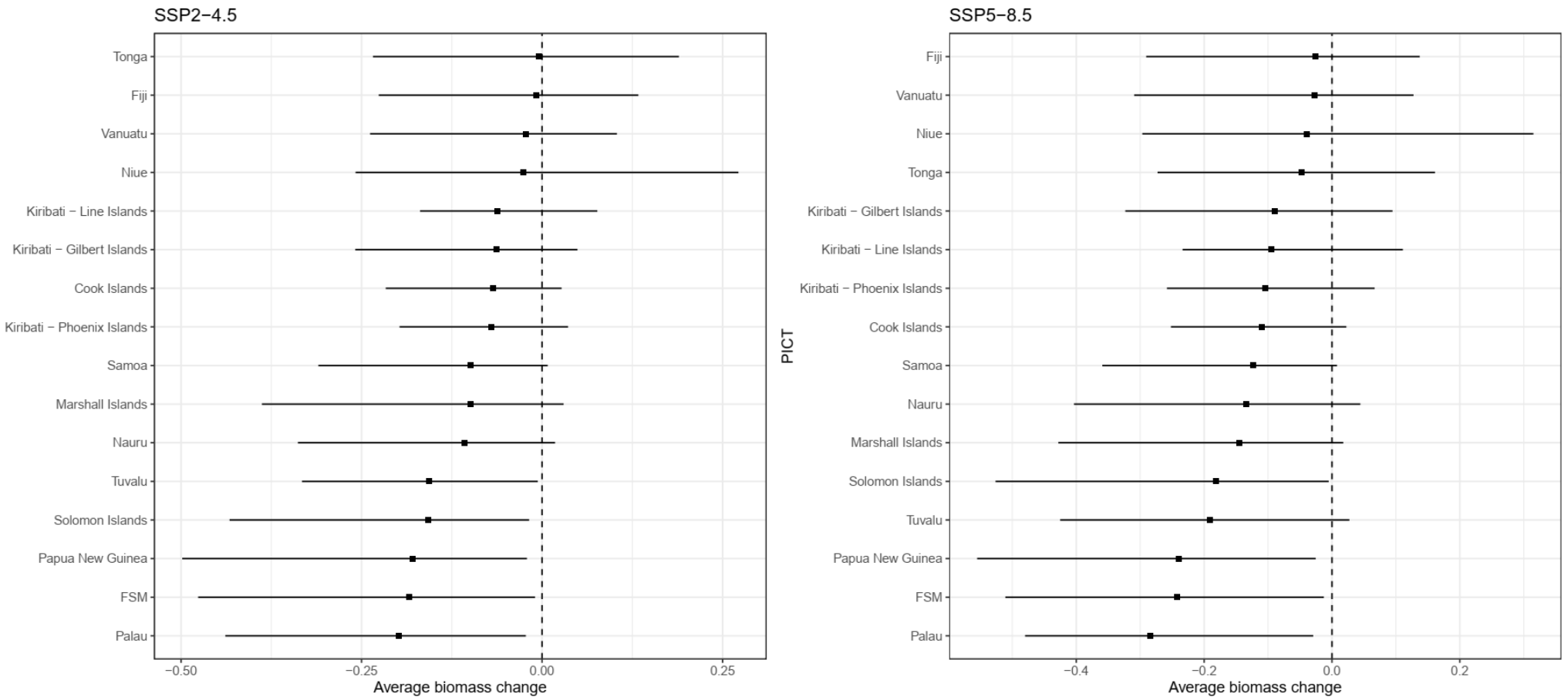

Figure 9. Projected change (%) in average biomass for each Pacific Island country (PIC) participating in the GCF regional tuna programme under the SSP2-4.5 (middle panel) and SSP5-8.5 (right panel) emission scenarios by 2050. The lines for projected change in biomass represent the upper and lower bounds of estimates. FSM = Federated States of Micronesia.

5. Implications for Coastal Fisheries Management

5.1 Main observations

The predicted impacts of climate change on Pacific coastal fisheries productivity is for declines, and in some cases these will be significant. The biggest impacts occur earlier at lower latitudes with progressively larger declines over time expanding to higher latitudes and in an easterly direction. This is consistent with changes predicted in the extent and area of the Pacific warm pool suggesting that SST is a key driver of this change. Predicted changes in catches considered not only changes in productivity (direct climate change impacts) but also predicted changes in habitat area (indirect climate change impacts).

Notably, catch declines are likely to already be occurring since every PIC is projected to experience declines by 2030, some significantly (e.g. projected catch decline for Nauru by 2030 is 44%). In fact, the average projected decline in catches across all PIC by 2030 is over 13%. This increases to 22% and 29% by 2050 under the moderate and high emissions scenarios respectively, with projected declines 73% under the high emissions scenario.

5.2 Uncertainty

While the model outputs characterise uncertainty for projected changes in biomass, the level of uncertainty has not been estimated for several other inputs used in our analyses. Brander (2015) discusses the compounding effects of multiple layers of uncertainty and the importance of accurately acknowledging these in climate change studies. For our analyses there are several inputs obtained from various sources, each with their own biases and error. Here we briefly discuss the main inputs and confidence in these (details in Appendix D).

Catch estimates

Catch estimates for each PIC are taken directly from Gillett and Fong (2023) who reviewed all available data to derive these estimates and here we used these to estimate future catches under the different climate change scenarios. The author discusses extensively the issues with the data sources used to provide catch estimates, highlighting the different methodologies used within and among the different PIC, as well as differences in how the methods were applied. The currency of data sources used was also highly variable. Ultimately the uncertainty in catch data is considered high as well as being highly variable among PIC.

Coastal habitat area change

Coastal habitat area data for the current period (2020) used global datasets from the World Resources Index (WRI) coral reefs, the UNEP WCMC Ocean Data Viewer for seagrass, and the Global Mangrove Watch data for mangroves that is a sub-set of the UNEP WCMC dataset. See section 2.2 for further details and habitat area estimates.

The projected declines in habitat area were based on the percentage of each coastal habitat type in the high and very high vulnerability categories under the different emissions scenarios in 2030 and 2050, to calculate the potential area change. Some PIC are projected to experience no or minimal loss of coral reef habitat area under all future emissions scenarios, e.g. Tuvalu and Palau. While other PIC are projected to experience significant declines in reef area, e.g. Samoa and Nauru. However, noting the potential data and analysis issues for Samoa. No projected declines in seagrass are expected by 2030 for any PIC, and declines projected only under the high emissions scenario by 2050. For details see Appendix C.

6. Food Security Gaps and Implications of Climate Change

The implications of climate change on coastal fisheries ultimately affects food resources and therefore food security for Pacific communities. The extent of this influence depends on several variables, and thisanalysis seeks to understand whether protein derived from coastal marine resources is likely to meet consumption needs under different climate change scenarios in 14 Pacific Island Countries participating in the GCF regional tuna programme.

Populations across the Pacific region have historically been largely subsistence-based with food security heavily dependent on coastal fisheries for protein. As a result of this relationship, marine resources have also been an integral part of socio-cultural identity. (Cubillo et al. 2023, Johnson et al. 2020). While sociocultural change and increasingly monetised economies are affecting this dependence and relationship at difference scales and in different ways across PIC, this study is focused on coastal resources supporting subsistence-based food security.

Food security is defined as “when all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preference for an active and healthy life” (World Bank, 1996). The dimensions and determinant of food security are summarised in Table 8 (Giuné et al. 2021, OECD, n.d.).

Table 7. OECD Dimensions and Determinants of Food Security (OECD., n.d.). Appendix E details how these factors are considered in this study.

Dimension	Determinant
Availability	**Domestic production**
	Import capacity
	Food Stocks
	Food Aid
Access	**Income and purchasing power**
	Transport and market infrastructure
	Food distribution
Utilisation	Food Safety and Quality
	Health and Sanitation
	Diet Quality and Diversity
Stability	**Weather Variability**
	Price Fluctuations
	Political Stability
	Economic Factors
	Ecological Factors

When undertaking a food security assessment, the OECD (n.d.) recommends addressing these dimensions and determinants of Food Security, while considering:

1. All four dimensions in policy design.
2. Interactions between dimensions.

3. How policies targeted at one dimension may affect other dimensions (i.e. economic development and ecological health).
4. Context specific factors (i.e. the resource availability and cultural context of the country).

Of particular importance in the Pacific context is point 4, where fish plays a central role in ceremonial traditions, creating important ties between families and individuals and embodying their symbolic ties to the environment (Hooper, 2005). Levels of fish supply beyond minimum nutritional requirements therefore are likely to be important in ensuring these traditional practices and social cohesion are maintained.

6.1 Methodology

This section provides a summary of the food security analysis methods for Pacific Island countries, with details on criteria selected and assumptions provided in Appendix C.

A semi-quantitative method (Johnson et al. 2016) was used, building on the prior components on this study (Section 4) and applying the OECD guidelines for assessing food security (OECD, n.d.). Determinants of food security that specifically apply to the purposes and scope of this study were selected for analysis (Appendix E), while further exploring adaptive capacity (i.e. how the population in the PIC context might access alternative protein sources through economic and primary production means). The study is focused on the population living within 5km of the coast based on the assumption that inland populations are more dependent on other forms of primary production (i.e. farming, livestock and poultry, and freshwater fisheries), and less dependent on marine resources. The 5 km distance was selected as it is considered 'walkable' and with extensive interaction with coastal resources (Andrew et al. 2019).

Section 4 provided data for the 'availability' and 'stability' dimensions of food security (Appendix C) through the current coastal habitat area, projected change in habitat area, available habitat area, estimated total annual change, and catch per area habitat estimate, to calculate estimated total annual catch.

The predicted coastal population was calculated using the percentage of the total population in coastal areas (5km from the coast) (based on Andrews et al. 2019), applied to 2030 and 2050 national population estimates (Pacific Data Hub 2023). The indicators used to assess the 'access' dimension of food security are presented in Table 9[6].

To enable fish availability data presented in Section 4 to be utilized in the food security assessment, the baseline Maximum Catch Potential (MCP) was converted to a per capita basis for the coastal region (see Section 6.2). This was done by dividing the total predicted catch for each scenario by predicted coastal population (within 5 km) for that given time, to determine kg/person for each future emissions scenario.

For the sake of compatibility between components of this GCF study, the total whole harvest requirement to meet minimum nutrition (t/yr) is drawn from estimated fish consumption has been informed by the outputs of GCF Supporting Study 2, (Table 10) (Brewer et al. 2024). The data from the GCF Supporting Study 2 is based on an assumption that 50% of dietary protein will come from fish. The study does not consider the consumption of invertebrates. The study uses average body mass estimates, population demographics and estimated protein composition of food types to determine what 50% of 0.7 g of protein per kg of body weight per day would equate to in whole harvest fish (refer to Study 2 for full detail on methodology). The study included urban and rural populations with per capita estimates based on the coastal

[6] Determinants of the Utilisation Dimension are considered beyond the scope of this study.

population living within 5 km of the coast. It is important to note that exact consumption habits are likely to vary significantly across island groups and communities according to cultural practices, local preferences and other factors (e.g. biophysical, cultural, political, and economic characteristics) suggesting that the percentage of protein that comes from fish stocks verse other protein sources is likely to vary significantly across regions.

The availability and stability dimensions of this analysis include invertebrates. The whole harvest considered by Brewer et al. (2024) to calculate consumption rates excludes invertebrates. As a result, there is a possibility that human populations may need less fish than expected in the results of this analysis, as some of their protein may come from invertebrates (or other sources): the gap could be smaller.

A more detailed breakdown of the access criteria used, including data sources, assumptions and uncertainty is provided in Appendix C.

Drawing on these data, the study calculated:

- how much fish (including invertebrates) is predicted to be available per capita for each future climate scenario (Section 6.4),
- the shortfall or surplus of fish available to meet the dietary requirements of the population in 2030 and 2050 based on Brewer et al, (2024) (Section 6.5), and
- how likely it is that the population will be able to access fish, accounting for changing trends in access to fisheries for subsistence, and the capacity of populations to acquire protein sources through economic means or other forms of primary production (i.e. adaptive capacity) (Section 6.7).

An assessment of the impact of population change only on the availability of fish has also been conducted to enable the impacts of climate to be better understood.

Completing calculations 1–3 (above) allowed grouping of PIC based on whether their populations are likely to be able to access sufficient protein to meet their expected nutritional requirements under different fisheries management and climate scenarios. These groups are:

1. Coastal fisheries are expected to meet the demand for fish with urban centres having low food security vulnerability. Climate change is likely to have few implications on fish availability and fish for nutrition for these countries.
2. Food security issues likely, especially in urban areas, if fisheries are poorly managed.
    - Coastal fisheries unlikely to meet the demand for fish under all climate scenarios and there is a high risk of food insecurity at a sub-national level.

Table 8. Food security indicators: Access (to fish) dimension

Indicators	Reasoning
Percent of population in urban conditions	What percentage of the urban population is living in urban conditions. While the fisheries analysis accounted for overall population and projected population growth (which determines how much fish is available per person), the population indicator used in that analysis assumes equal distribution or equal access. The % urban population is intended to give an indication of the population's accessibility to coastal resources *(access)*.
Alternative food access: GDP per Capita	Gross Domestic Product per Capita. Building on considerations discussed by Bell et al (2011) associating income with ability to buy alternative food resources, this criterion gives an indication of the capacity of the population to adapt to emerging conditions and meet nutritional requirements through other means *(adaptive capacity)*.
Alternative food access: projected economic growth	Rate of GDP change, looking at predicted change in 2027 (IMF data) and volatility and fragility of the system. Building on considerations discussed by Bell et al (2011) associating income with ability to buy alternative food resources, this criterion gives an indication of the capacity of the population to adapt to emerging conditions and meet nutritional requirements through other means *(adaptive capacity)*.
Alternative food access: Arable land	Are their alternative food sources available e.g. agriculture, aquaculture. Based on arable land (hectares per person, 2020, World Bank). This indicator gives an indication of the capacity of the population to adapt to emerging conditions and meet nutritional requirements through other primary production means *(adaptive capacity)*.
Island structure (dispersed atolls vs single central island)	Access to reef. While the fisheries analysis accounted for overall population and projected population growth (which determines how much fish is available per person), the population indicator used in that analysis assumes equal distribution or equal access. The island structure indicator is intended to add texture regarding the population's access to coastal resources. It is assumed that with a larger ratio of coastline to land mass and generally significant reef system, atolls will provide greater access to coastal marine resources *(access)*.

The methodology has many inherent assumptions, particularly for predicting future conditions in 2030 and 2050. The food security analysis is also constrained by availability of data and by the complexity of system dynamics. Given the high uncertainty of social factors[7] and the complex dynamics and feedbacks between humans and ecological systems, the level of uncertainty in the analysis is high (see Appendix C). Despite uncertainty, this analysis builds on the work of Bell et al. (2011), building on this previously established approach to assess projected food security derived from coastal marine resources for PIC. When further data is available, it is recommended to conduct the same analysis at a sub-national scale given inequities in food access may be masked by national-level results.

[7] Including, but not limited to, culture, politics, economics, technology, and unexpected events such as COVID-19

Methodology Case Study Example – Cook Islands

Based on current catch levels, Cook Islands has a predicted catch of 389 tons under SSP5-8.5 in 2030, decreasing to 359 tons (SSP2-4.5) and 340 tons (SSP5-8.5) in 2050 (refer to Section 4). Dividing this amount by the coastal population gives the following estimated per capita fish availability.

	2030 SSP5-8.5 projected catch (kg/person)	2050 SSP2-4.5 projected catch (kg/person)	2050 SSP5-8.5 projected catch (kg/person)
Fish availability (based on current catch trends)	24.5	22.7	21.5
Gap analysis	Insufficient fish to meet supply at national level in 2030 (deficit of 25kg/person/year)	Deficit of approximately 27-28 kg per person/year in 2050	

The amount of whole fish required to meet minimum nutrition requirements for the Cook Islands is estimated as 49 kg/person by GCF study 2 (UOW, 2023). Therefore it is predicted that there is likely to be insufficient fish catch available at a national scale to meet expected fish consumption in 2030, and beyond this, both 2050 climate scenarios show that a shortfall of over 28 kg/person will exist. Access factors were then assessed using a semi-quantitative approach. The Cook Islands has a high percentage of urban population suggesting more limited direct access to coastal fisheries by the population. This trend is projected to increase. Meanwhile, adaptive capacity through GDP per capita and projected economic growth are considered relatively high for the region, and adaptive capacity through alternative primary production is considered low given the percentage of land currently developed for agriculture. Finally, the mixed and dispersed island structure suggests that populations will have relatively greater direct access to coastal resources. As a result, the Cook Islands has a risk score of 1 for availability and a 2 for access, resulting in 1.5 (see Section 5.7 for calculations). Cook Islands then fall into *Group 2 – Food security issues likely, especially in urban areas, if fisheries are poorly managed*.

Table 9. Estimated annual per capita whole fish requirements (kg/person/year) to meet minimum nutrition requirements (rounded to the nearest kg) from GCF Supporting Study 2.

Pacific Island Country	Total whole harvest requirement to meet minimum nutrition in 2030 (t/yr)	Total whole harvest requirement per person to meet minimum nutrition in 2030 [1] (kg/person/yr)	Total whole harvest requirement to meet minimum nutrition in 2050 (t/yr)	Total whole harvest requirement per person to meet minimum nutrition in 2050 [1] (kg/person/yr)
Cook Islands	782	49	785	50
Federated States of Micronesia (FSM)	35,552	51	37,009	51
Fiji	4,091	38	3,936	40
Kiribati	5,444	39	8,138	45
Republic of the Marshall Islands (RMI)	1,933	36	1,920	37
Niue	504	40	584	41
Nauru	66	57	65	57
Palau	736	41	678	41
Papua New Guinea (PNG)	70,809	31	100,524	32
Samoa	8,772	43	9,758	44
Solomon Islands	27,485	34	42,242	35
Tonga	4,297	44	4,214	45
Tuvalu	460	41	496	42
Vanuatu	12,200	36	17,574	37

[1] *Based on population estimated to live within 5 km of the coast (Andrews et al. 2019)*

**Where data were not available, total kilograms per person per year is based on the minimum recommended annual per capita fish consumption of 35 kg (Bell et al. 2009).*

6.2 Fish availability for PIC

Impacts of population change only

The decline in availability of fish per capita is heavily influenced by the increasing human population within 5 km of the coast (Figure 10 an

Table 11).

For many PIC, the influence of population growth on available fish per person is greater than the influence of climate change. For example, in the Solomon Islands, approximately 60% of the change in fish supply can be attributed to population growth, with the change driven by climate change only making a minor contribution to the shortfall.

It is predicted that the coastal populations of Fiji, PNG, Kiribati, Nauru, Samoa, Solomon Islands, Tuvalu and Vanuatu will experience increasing coastal populations by 2050, while Tonga, Cook Islands, Micronesia, Marshall Islands, Niue and Palau are predicted to decline. Population growth is particularly large in PNG, Solomon Islands and Vanuatu. For those PIC projected to experience a rapid growth in urban populations (PNG, Solomon Islands and Vanuatu), there is expected to be a deficit in fish supply by 2050 based on current catch rates even without the impact of climate change.

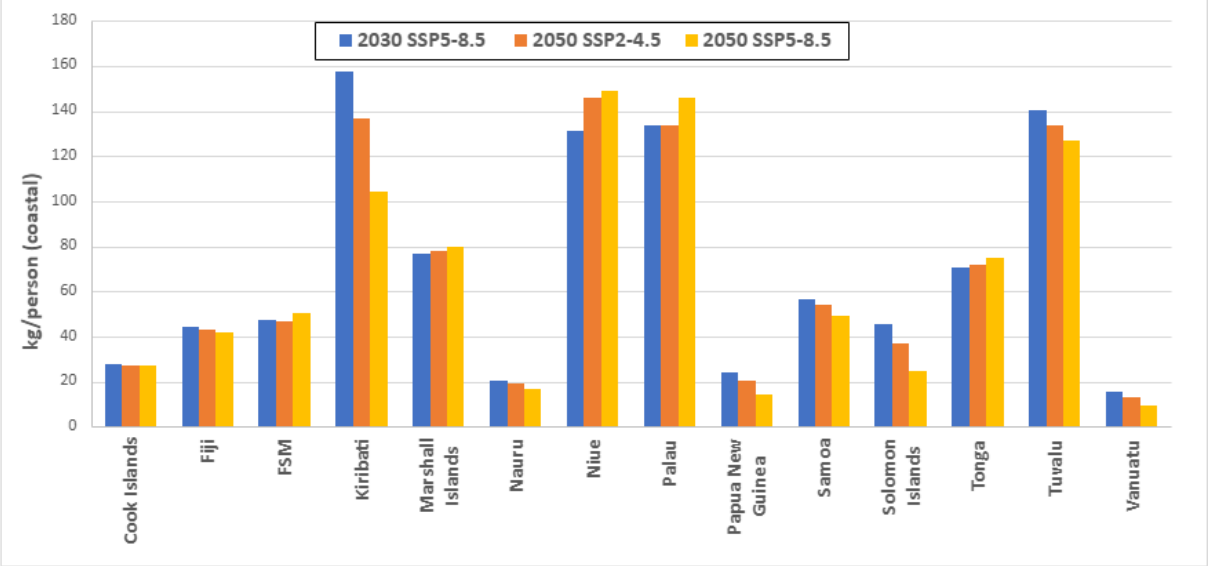

Figure 10. Trends in fish availability based on predicted population change for each PIC participating in the GCF regional tuna programme (excluding any impacts of climate change).

Table 10. Predicted fish availability per capita (for coastal population) based on impacts of predicted population change only in each PIC participating in the GCF regional tuna programme.

Pacific Island country	2021 whole fish availability per person (kg/person/yr)	2030 whole fish availability per person (kg/person/yr)	2050 whole fish availability per person (kg/person/yr)
Cook Islands	28.03	27.06	27.24
Fiji	44.08	43.00	41.76
FSM	47.28	46.95	50.68
Kiribati	157.37	136.76	104.49
Marshall Islands	77.04	77.80	80.06
Nauru	20.28	19.07	16.63
Niue	131.45	146.17	148.95
Palau	133.65	133.85	145.98
Papua New Guinea	24.01	20.24	14.51
Samoa	56.74	54.16	49.00
Solomon Islands	45.28	36.95	24.72
Tonga	70.33	71.97	75.02
Tuvalu	140.46	133.33	126.70
Vanuatu	15.54	12.89	9.21

Combined Impacts of climate and population change

An analysis of the combined effects of reduced catch due to climate change and changes in population size is provided below to identify the future gap (or surplus) in the supply of coastal fish per capita relative to the fish supply recommended for good nutrition (see Table 17 in Brewer et al. 2024, Study 2). The difference was calculated for each PIC and future climate scenario, by subtracting the estimated whole fish needed for good nutrition (whole fish kg/person) from the estimated available whole fish (whole fish kg/person) (**Error! Reference source not found.**and Figure 12). This gives an indication of the likely surplus or shortfall at a national level under SSP5-8.5 (2030 and 2050) and SSP2-4.5 (2050) under the combined effects of population change and climate impacts. Extreme climate-related events or other factors could result in compounding pressures of fisheries add high uncertainty to these results.

This analysis shows that eight countries will have a gap in recommended fish availability by 2030 under SSP5-8.5. The number of countries with a gap in fish supply increases to nine in 2050, with the gap widening in countries with existing deficits. Five countries will retain a surplus in fish supply by 2050, with the surplus reducing from 2030 to 2050.

Assuming that fisheries are managed in a similar way to current practices, the quanitity of fish available for each person (for the coastal population) will significantly decline in all 14 PIC under the SSP5-8.5 scenario (Table 12). There was no deviation in the 2050 results between SSP5-8.5 and SSP2-4.5 in terms of coastal fish availability. In interpreting these results in the context of food security, it is important to highlight this data represents the fish that is *available* through catch, not the entire fish population.

Table 11. 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.

	2030			2050				
Pacific Island country	2030 Population estimate within 5 km of coast [1]	SSP5-8.5N		2050 Population estimate within 5 km of coast [1]	SSP2-4.5		SSP5-8.5	
		Coastal fish catch (tonnes) [4]	Fish per capita (kg) [2]		Coastal fish catch (tonnes) [4]	Fish per capita (kg) [2]	Coastal fish catch (tonnes) [4]	Fish per capita (kg) [2]
Cook Is	15,889	389	24.5	15,786	359	22.7	340	21.5
Fiji	699,945	24636	35.2	720,733	22599	31.4	21336	29.6
FSM	106,507	3970	37.3	98,667	3924	39.8	3623	36.7
Kiribati	138,935	14692	105.7	181,848	16483	90.6	15846	87.1
Marshall Is	53,983	3824	70.8	52,460	3595	68.5	3388	64.6
Nauru	12,588	77	6.1	14,431	67	4.6	52	3.6
Niue	1,156	121	104.9	1,135	114	100.9	107	94.5
Palau	17,930	2146	119.7	16,441	1888	114.9	1686	102.6
PNG	2,273,165	37185	16.4	3,169,671	26070	8.2	22887	7.2
Samoa	203,088	7090	34.9	224,506	2661	11.9	2268	10.1
Solomon Is	811,805	23886	29.4	1,213,589	21288	17.5	20190	16.6
Tonga	97,257	5963	61.3	93,310	5938	63.6	5560	59.6
Tuvalu	11,250	1400	124.4	11,839	1265	106.8	1214	102.5
Vanuatu	341,408	3262	9.6	477,626	2615	5.5	2409	5.0

1. Based on percentage of population with 5 km of the coast from Andrew et al. (2019) Coastal proximity of populations in 22 Pacific Island Countries and Territories. PLoS One, 14 (9), e0223249-1-e0223249-15. and SPC population estimates https://sdd.spc.int/dataset/df_pop_proj
2. Whole fish (not just edible portion)
3. Projected catch from Table 6

Table 12 Coastal fish supply for minimum nutrition gap assessment.

Pacific Island country	**Coastal fish supply surplus or gap (kg whole fish/person)** Noting a negative value equates to a gap and a positive value equates to a surplus of fish for food		
	2030 SSP5-8.5	**2050 SSP2-4.5**	**2050 SSP5-8.5**
Cook Islands	-24.7	-27.0	-28.2
Fiji	-15.6	-20.0	-21.7
FSM	-1.1	-0.1	-3.2
Kiribati	66.6	45.9	42.4
Marshall Islands	35.0	31.9	28.0
Nauru	-33.9	-35.8	-36.9
Niue	47.8	43.6	37.2
Palau	78.6	73.6	61.3
Papua New Guinea	-14.8	-23.5	-24.5
Samoa	-8.3	-31.6	-33.4
Solomon Islands	-4.4	-17.3	-18.2
Tonga	17.1	18.5	14.4
Tuvalu	83.5	64.9	60.6
Vanuatu	-26.2	-31.3	-31.8

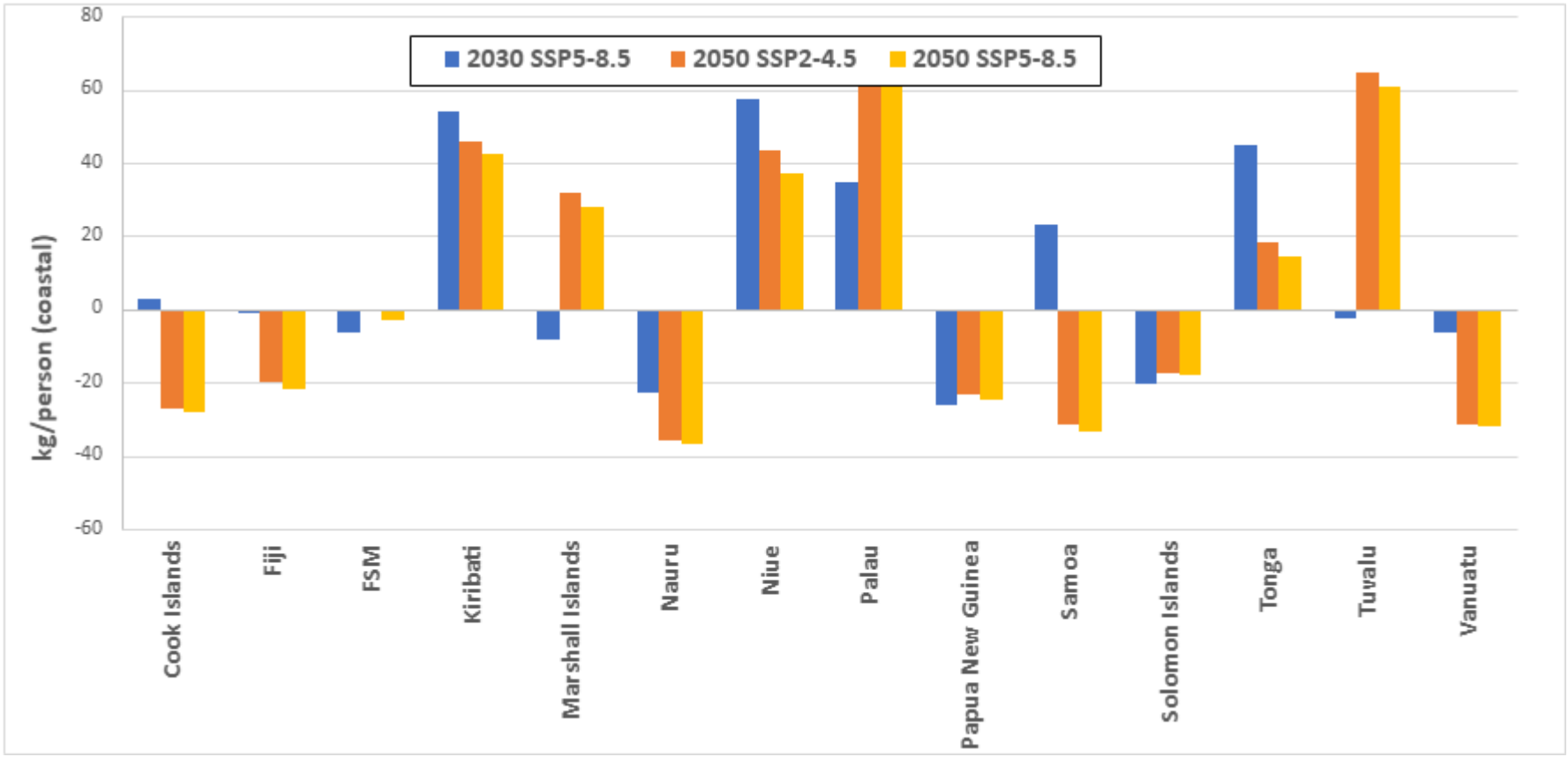

Figure 11. Coastal fish supply for minimum nutrition gap assessment (whole fish)

6.3 Fish accessibility within nations

Even though there may be sufficient fish available to meet the recommended per capita consumption requirements in some countries, availability does not necessarily guarantee that the population can access this supply to meet future needs. In this assessment, each PIC is scored against the indicators outlined in Table 8.1, to determine access to fish as a key dimension of food security derived from coastal resources. This gives an indication of any potential food security issues at a sub-national scale. The detailed analysis methodology is provided in Appendix C.

PIC assessed as low risk (score of 0–1) are expected to have populations that can access the available fish (or adapt and be able to access alternative fish protein). Medium risk (score of 1.1–2) indicates populations throughout the country may not be able to access sufficient fish for food, and high risk (score of 2.1–3) indicates population that are unlikely to be able to access sufficient fish for food. All PIC assessed have either medium or high risk of not being able to access the available fish (Table 15). Tuvalu and Vanuatu are projected to shift from medium risk to high risk by 2030 and 2050, respectively. In Kiribati, Solomon Islands, Tuvalu and Vanuatu, the assessment shows a decrease in access to fish over time.

Table 13. Fish access risk assessment. PIC likely to increase in risk identified with an asterisk.*

Risk level and trend	Pacific Island country
Medium Risk	Cook Islands
	Federated States of Micronesia
	Fiji
	Niue
	Palau
	Tonga
	Tuvalu*
	Vanuatu*
High Risk	Kiribati
	Marshall Islands
	Nauru
	Papua New Guinea
	Solomon Islands
Risk level likely to increase	Kiribati
	Solomon Islands
	Tuvalu
	Vanuatu

6.4 Food security analysis

Combining the results of the availability of fish and access to fish assessments shows the projected food security for each PIC, and the likelihood of the population having sufficient protein derived from coastal marine resources to meet dietary needs under each of the future climate change scenarios.

The following equation was used[8] to develop a food security vulnerability rating:

> ***Food security vulnerability = Availability score + Access risk score***
>
> *Where:*
>
> ***Access risk*** *(*Table 13*) ranges from 0.5 for medium access risk + 1 for high access risk with a maximum possible score of 3; and,*
>
> ***Fish availability*** *(*Table 11. 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.*Table 11) was simplified to one of three scores:*
>
> ***1 = Sufficient fish-based protein to meet minimum dietary requirements;***
>
> ***2 = Insufficient fish-based protein to meet minimum dietary requirements less than 20kg/person; and***
>
> ***3 = Insufficient fish-based protein to meet minimum dietary requirements greater than 20kg/person.***

A high final score indicates high vulnerability and greater likelihood of food insecurity. The baseline value is availability, since even high access with no availability cannot increase the available fish for food.

Based on the final score (Table 16), each PIC is placed in a food security group in terms of the future availability and accessibility of fish for food (Table 17). Notably, there are no PIC that falls into group 1 where coastal fisheries are expected to meet the demand for fish. By 2050, under the high emissions scenario (SSP5-8.5), all PIC are within group 3, where coastal fisheries are unlikely to meet the demand for fish and are at high risk of food insecurity.

The food security assessment was conducted at a national level due to data availability. Sub-national factors may mean that actual food security is quite different in certain geographies within each country and among different parts of society. It is also important to remember that this study is specifically assessing the availability of whole fish per capita from coastal fisheries required to provide the recommended level of protein for good nutrition identified in Study 2 (Brewer et al. 2024) for communities living within 5 km of the coast. As seen in the OECD determinants of food security, there are several factors beyond the scope of this assessment that will determine overall food security of each country. For example, if there is a shortfall in coastal fish supply, a country may have the adaptive capacity to develop alternative food sources or improve food access to offset any shortfall. Sustainable fisheries management, climate action, and other factors, including supporting alternative rural livelihoods and well-being of rural communities may help mitigate the projected trends of food insecurity.

[8] This methodology has many uncertainties, with additional determinants (discussed in Table 5) outside the scope and objective of this study that will influence food security.

Table 14. Food security assessment that combines the availability of fish and populations being able to access fish for food to determine food security vulnerability. Scores greater than 2 are classified as high vulnerability (Group 3), 1–2 as medium vulnerability (Group 2), and below 1 as low vulnerability (Group 1).

	2030 (SSP5-8.5)			2050 (SSP2-4.5)			2050 (SSP5-8.5)		
	Availability Risk Score	**Access Risk Score**	**Food Security Vulnerability Group**	**Availability Risk Score**	**Access Risk Score**	**Food Security Vulnerability Group**	**Availability Risk Score**	**Access Risk Score**	**Food Security Vulnerability Group**
Cook Islands	3	2	2.5	3	2	2.5	3	2	2.5
Fiji	2	1	1.5	2	3	2.5	2	3	2.5
FSM	2	2	2	2	2	2	2	2	2
Kiribati	1	3	2	1	3	2	1	3	2
Marshall Islands	1	2	1.5	1	3	2	1	3	2
Nauru	3	3	3	3	3	3	3	3	3
Niue	1	2	1.5	1	2	1.5	1	2	1.5
Palau	1	2	1.5	1	2	1.5	1	2	1.5
Papua New Guinea	2	3	2.5	3	3	3	3	2	3
Samoa	2	2	2	3	3	3	3	3	3
Solomon Islands	2	3	2.5	2	3	2.5	2	3	2.5
Tonga	1	2	1.5	1	2	1.5	1	2	1.5
Tuvalu	1	3	2	1	3	2	1	3	2
Vanuatu	3	2	2.5	3	3	3	3	3	3

Table 15. Summary of the food security analysis for each PIC and the resulting classification, (based on results from Table 14 and Table 12) under three future climate change emissions scenarios.

Food Security Group	Description	2030 (SSP5-8.5)	2050 (SSP2-4.5)	2050 (SSP5-8.5)
1	Coastal fisheries are expected to meet the demand for fish including in urban centres; Climate change unlikely to impact fish availability and access to fish for nutrition			
2	Food security issues likely, especially in urban areas, if fisheries are poorly managed	• Fiji • FSM • Kiribati • Marshall Islands • Niue • Palau • Samoa • Tonga • Tuvalu	• FSM • Kiribati • Marshall Islands • Niue • Palau • Tonga • Tuvalu	• FSM • Kiribati • Marshall Islands • Niue • Palau • Tonga • Tuvalu
3	Coastal fisheries unlikely to meet the demand for fish with high risk of food insecurity at a sub-national level (i.e. urban areas will face greater food insecurity)	• Cook Islands • Nauru • Papua New Guinea • Solomon Islands • Vanuatu	• Cook Islands • Nauru • Papua New Guinea • Solomon Islands • Vanuatu • Fiji • Samoa	• Cook Islands • Nauru • Papua New Guinea • Solomon Islands • Vanuatu • Fiji • Samoa

7. Conclusions

Climate variability and change regularly disrupt fisheries and aquaculture productivity, with implications for Pacific Island countries that depend on them for food, income, jobs and government revenue. This study focused on the implications of climate change for coastal habitats and fisheries, and food security for PIC communities, as part of a broader regional climate change vulnerability assessment for the tropical Pacific. The assessment results show that there will be spatial and temporal variability across Pacific Island countries in terms of climate change impacts on their coastal habitats, fisheries and the food they provide. Importantly, the results identify areas of high vulnerability to climate change, which can provide targets for management and adaptation.

Coastal habitats

The assessment of climate change impacts on coastal habitat area found that some PIC are projected to experience no or minimal loss of coral reef area under all future emissions scenarios, e.g Tuvalu and Palau. While other PIC are projected to experience significant declines in coral reef area under all future emissions scenarios, e.g. Samoa and Nauru. No projected declines in seagrass are expected by 2030 for any PIC due to the different mechanisms that drive thermal stress responses in seagrass, and declines of seagrass area are projected only under the high emissions scenario (SSP5-8.5) by 2050, with the highest projected declines in Samoa, PNG and Vanuatu. Implications of climate change for mangrove habitats are only notable in PNG and FSM that are expected to experience declines.

Coastal fisheries

Overall, the indirect effects of climate change are expected to impact coastal fish and invertebrate communities earlier than most direct effects. Ecological versatility will be important for the resilience and persistence of coastal taxa. Habitat or resource specialists (e.g. corallivores) will face the most immediate impacts, whereas more generalist taxa may benefit over the short-term, with longer-term effects less well understood. Direct effects on species will occur as many species already live at the limits of their thermal threshold. Therefore, factors linked to temperature change are likely to have the greatest impact on PIC species, resulting in local extirpations, range shifts, more frequent mass mortality events during marine heatwaves.

Pacific coastal fisheries productivity is projected to decline due to climate change, and for some PIC the declines will be significant, e.g. Tuvalu and Nauru. The biggest impacts occur earlier at lower latitudes with progressively larger declines over time expanding to higher latitudes and in an easterly direction. The average projected decline in coastal fisheries catches across all PIC as soon as 2030 is approximately 13%. This increases to 22% and 29% by 2050 under the moderate and high emissions scenarios respectively, with projected declines as high as 73% under the high emissions scenario.

Food Security

Assessment results indicate that under future climate scenarios, by 2030 all PICs are likely to experience some level of food security challenges related to the availability, stability, and access to fish-derived protein to meet the needs of coastal populations. By 2050 over half PIC will be unlikely to meet the demand for fish to meet these nutritional requirements, indicating a high risk of food insecurity and worsening trends. Sub-national factors may mean that actual food security varies across geographies within each country and among different parts of society (i.e. urban populations are likely to face greater food insecurity).

Fish availability and stability (within the scope of this assessment) will be influenced by population growth, climate trends, the impacts of these trends on fisheries, and fisheries management. There exists the opportunity to reduce food insecurity through the improvement of fisheries management practices.

For many PIC, the influence of population growth on available fish per person is greater than the influence of climate change. For example, in Nauru, approximately 50% of the change in fish supply can be attributed to population growth, with the change driven by climate change only making a minor contribution to the shortfall.

Food security will depend on how accessible the available fish is to the population, determined by factors such as the distribution and density of population in urban areas, adaptive capacity of the population, and the geographic characteristics of the country. When planning for the future, improving the resilience and diversity of food supply systems, and addressing issues of access, will be vital to reducing vulnerability and addressing food insecurity trends.

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Appendix A Scope of Works

A fundamental building block for all GCF Funding Proposals is the climate change rationale for the proposed programme activities. SPC has co-ordinated a comprehensive assessment of the vulnerability of fisheries resources, and the communities and economies that depend on them, to climate change (https://www.spc.int/cces/climate-book/spc-publications-on-climate-change#tab-682-2). However, that vulnerability assessment is now 10 years old. The purpose of this supplementary technical report is to update the components of the SPC vulnerability assessment related to the direct and indirect effects of climate change on coastal fisheries resources, and on the distribution of tuna resources, to document the climate rationale for the Programme.

In particular, the following assessments have been completed.

(i) Update the SPC 2011 analysis of the vulnerability of coastal fisheries resources (particularly coral reef fish and invertebrates) in the Pacific Island region to the effects of ocean warming and acidification on coastal fisheries production. This analysis should consider both the direct effects on the target species, and the indirect effects on growth and survival on these species expected to occur as a result of climate-driven degradation of coral reefs. The results of the analysis should then be used to update the SPC 2011 assessment of the implications of the projected decrease in coral reef fish production for the food security of coastal communities in the 14 Pacific Island countries participating in the Programme .

(ii) The updated vulnerability assessment should incorporate relevant information from the recent literature to focus on the latest estimates for the degradation of coral reef habitats (in terms of percentage live coral cover), decreases in average coastal (mainly coral reef fish) fish production (in tonnes per km2) due to the direct and indirect effects of climate change, and increases in the gap in fish supply for food security (in kg of fish per person per year), projected to occur under the SSP2-4.5 and SSP5-8.5 (or equivalent) greenhouse gas emission scenarios by 2030 and 2050. These estimates should be updated, where possible, for each of the 14 participating countries.

(iii) Assessments of the gap in supply of fish needed for food security for each participating country under the two emission scenarios by 2030 and 2050 should use the best estimates of national per capita fish consumption and the predicted population for each country in 2030 and 2050 available from SPC's Statistics for Development Division.

(iv) The relative vulnerability of the 14 participating countries to shortages of fish needed for food security should be estimated using the general approach developed by IPCC based on 'exposure', 'sensitivity', 'potential impact' and 'adaptive capacity', as described in Sections 1.8.3 and 12.7 of the 2011 SPC vulnerability assessment (see url above).

(v) The gap in fish supply to be filled by tuna and other oceanic fish species (hereafter grouped as 'tuna') in 2030 and 2050 under SSP2-4.5 and SSP5-8.5 respectively to meet the recommended minimum annual per capita fish consumption of 35 kg per person per year (or current levels if higher) of fish consumption. The total amount of tuna required to fill the gap in fish supply across all 14 countries combined in 2030 and 2050 should also be calculated.

(vi) Estimates of the total number of people in the 14 participating countries that will need increased access to tuna for food security in 2030 and 2050.

Appendix B Shared Socioeconomic Pathways (SSP) narratives[9]

SSP1 Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation). The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP2 Middle of the Road (Medium challenges to mitigation and adaptation). The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

SSP3 Regional Rivalry (High challenges to mitigation and adaptation). A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

SSP4 Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation). Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in carbon-intensive fuels (coal and oil) and low-carbon energy. Environmental policies focus on local issues around middle- and high-income areas.

SSP5 Fossil-fuelled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation). This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and

[9] Narratives for each Shared Socioeconomic Pathway from Riahi et al. 2017.

development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

Appendix C Detailed Methodology

B1. Coastal Habitats Vulnerability Assessment

Habitat area calculation: The base area of coral reefs was calculated from the World Resources Institute[10] layer at 500 m resolution and the spatial analysis used the UNEP-WCMC[11] Coral Reefs of the World layer at 30 m resolution and included every pixel that contained any coral reef polygon or point data. The base area of seagrass meadows used the UNEP-WCMC4 Seagrasses of the World layer and included every pixel that contained any seagrass polygon or point data. The base area of mangroves used the Global Mangrove Watch[12] 2016 layer and included every pixel that contained any mangrove polygon or point data.

Climate change projections: The analyses used SSP5-8.5 as the standard emissions pathway for 2030 and 2050, with minimal divergence in future projections by 2030. However, there is divergence by 2050 and as SSP5-8.5 is the highest emissions scenario and considered less likely in the medium term (2050) as the global population work to reduce greenhouse gas emissions. The vulnerability analyses are normalised so it's primarily the spatial variation in the projections that are provided for relative vulnerability rather than absolute values. As such, we would expect near-identical results to SSP2-4.5 (moderate emissions scenario) in 2050 for the relative results but not the quantitative analysis. Therefore it is worth noting that the percentage of habitat area projected to decline represents the highest emissions scenario and not a moderate emissions scenarios and is therefore a source of (considerable) uncertainty.

A quantitative comparison between SSP2-4.5 and SSP5-8.5 in 2050 and SSP5-8.5 in 2030 and 2050 for coral reefs using data on annual severe bleaching (ASB) shows a proportional reduction in habitat area assessed in the different vulnerability categories. This is an average across all PIC and provides a relative calculation that can be used to determine the area of coral reef expected to degrade due to climate change under SSP2-4.5 in 2050 and SSP5-8.5 in 2030. This was applied across reef habitats in all PIC for the purposes of estimating potential area (km^2) of decline.

For seagrass, the proportion of seagrass pixels that are projected to be exposed to at least 1.5 degrees C of warming under SSP2-4.5 in 2050 and SSP5-8.5 in 2030 was applied. Although 1.5 degrees C of warming is frequently cited as a threshold for limiting future warming in global climate change discussions, and therefore provides a useful benchmark for comparison between emissions scenarios, it is important to emphasize that more research is needed to determine an appropriate ecological threshold for seagrass in relation to sea surface temperature warming, and this should not be interpreted as a definitive threshold for seagrass ecology without further empirical validation. Noting that 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, and (2) shifts in the photosynthesis/respiration balance, i.e. increases in temperature result in increased respiration driving increased stress and declines (Olsen et al. 2018).

[10] https://datasets.wri.org/dataset/tropical-coral-reefs-of-the-world-500-m-resolution-grid
[11] https://data.unep-wcmc.org
[12] https://www.globalmangrovewatch.org/?map=eyJiYXNlbWFwIjoibGlnaHQiLCJ2aWV3cG9ydCI6eyJsYXRpdHVkZSI6MjAsImxvbmdpdHVkZSI6MCwiem9vbSI6MiwiYmVhcmluZyI6MCwicGl0Y2giOjB9fQ%3D%3D

Habitat vulnerability assessment: The exposure and sensitivity of coastal habitats were based on available input layers (Table B1) that were normalised on a scale from 0 to 1. An index of potential impacts was calculated by averaging the normalised exposure and sensitivity layers, then re-normalizing on a scale from 0 to 1. The adaptive capacity of coastal habitats was based on available input layers normalised on a scale from 0 to 1.

Habitat vulnerability was calculated by adding the normalised potential impacts layer with an inverted adaptive capacity layer (1-AC), as per:

V = PI + AC Index

Where: V=vulnerability, PI=potential impact (ExS), AC index=1 – adaptive capacity

The final raw vulnerability layer was then re-normalised on a scale from 0 to 1.

Table B1. *Coastal habitat input layers for assessing climate change vulnerability across the Pacific region.*

	Coral reefs	Seagrass meadows	Mangroves
Exposure	**Projected SST increase** *(under CMIP6 SSP5-8.5)* • Data from (NOAA 2022) at 0.05-degree resolution • Anomaly layer was generated by subtracting the 2019 annual average SST from the projected 2070 SST • 2019 SST was the average of the four seasonal SST rasters: Dec-Feb, Jun-Aug, Mar-May, Sep-Nov • 2019 SST data was resampled from ~500m resolution (World Cylindrical Equal Area projection) to 0.05 dd (WGS84) • 2019 SST resampled layer was interpolated at the edges using focal statistics to replace no data values within the raster with a value statistically derived from neighboring cell values (in this case the mean within a 5x5 pixel rectangle of surrounding cells). • Normalised for each PIC on a scale of 0 to 1.	**Projected SST increase** *(under CMIP6 SSP5-8.5)* • Data from (NOAA 2022) at 0.05-degree resolution • Anomaly layer was generated by subtracting the 2019 annual average SST from the projected 2070 SST • 2019 SST was the average of the four seasonal SST rasters: Dec-Feb, Jun-Aug, Mar-May, Sep-Nov • 2019 SST data was resampled from ~500m resolution (World Cylindrical Equal Area projection) to 0.05 dd (WGS84) • 2019 SST resampled layer was interpolated at the edges using focal statistics to replace no data values within the raster with a value statistically derived from neighboring cell values (in this case the mean within a 5x5 pixel rectangle of surrounding cells). • Normalised for each PIC on a scale of 0 to 1.	**Project air temperature increase** • Data from (NOAA 2020) at 0.05-degree resolution
	Projected annual severe bleaching (ASB) year *(under CMIP6 SSP5-8.5)* • Data provided has been statistically down-sampled from CMIP6 model resolution to 0.05 dd resolution as described in (UNEP 2020). • Normalised for each PIC on a scale of 0 to 1.	N/A	N/A
	N/A	**Projected rainfall change** • Data from NOAA (2020) at 1-degree resolution: % change in annual average precipitation (2040-2069) under CMIP6 SSP5-8.5 compared to historical climate (1955-1984)	**Projected sea-level rise** • Data from NOAA 2020 (ensemble mean of RCP8.5 projections to 2100)

	Coral reefs	Seagrass meadows	Mangroves
		• Resampled to 0.05 dd resolution using simple smoothing (bilinear resampling) in ArcGIS • torical reference period 1976-2005. • Resampled to 0.05 dd resolution using simple smoothing (bilinear resampling) in ArcGIS.	
	Warm season temperature variability (*from the NOAA Coral Reef Watch Coral Temp dataset (1985-2019)* • Data from NOAA (2020) at 1-degree resolution • Resampled to 0.05 dd resolution using simple smoothing (bilinear resampling) in ArcGIS • Normalised for the ATS area on a scale of 0 to 1.	N/A	N/A
	Projected pH decline *(by 2050-2099 under CMIP5 RCP8.5)* • Data from NOAA (2020) at 1-degree resolution • Resampled to 0.05 dd resolution using simple smoothing (bilinear resampling) in ArcGIS • Normalised for the ATS area on a scale of 0 to 1.	N/A	N/A
	Exposure – Final Layer • Exposure was calculated from the normalised input layers as follows: projected SST increase plus (+) projected ASB year plus (+) Projected pH decline minus (-) warm season variability. • Raw exposure was re-normalised on a scale from 0 to 1 (i.e. [(pixel value minus raster minimum)/ (raster maximum minus raster minimum)]).	**Exposure – Final Layer** • Exposure was calculated from the normalised input layers as follows: projected SST increase plus (+) % rainfall change (such that an increase in rainfall = increased exposure). • Raw exposure was re-normalised on a scale from 0 to 1 (i.e. [(pixel value minus raster minimum)/(raster maximum minus raster minimum)]).	**Exposure – Final Layer** • Exposure was calculated from the normalised input layers as follows: projected SST increase plus (+) % rainfall change (such that an increase in rainfall = increased exposure). • Raw exposure was re-normalised on a scale from 0 to 1 (i.e. [(pixel value minus raster minimum) /(raster maximum minus raster minimum)]).
Sensitivity	**History of severe coral bleaching conditions** (*Number of events ≥ 8 degree heating weeks (DHWs) in the NOAA Coral Reef Watch Coral Temp dataset (1985-2019)* • Data from NOAA (2020) at 0.05 dd resolution. • Normalised by dividing by the maximum number of events.	**Water quality** • The "watershed-based pollution" layer from Reefs at Risk Revisited was resampled to 0.05dd and normalised by dividing by the maximum value. • Rivers influence layer using the Free-flowing Rivers FFR v4 dataset. • These two layers were then averaged and normalised on a 0-1 scale. • Anthropogenic threat was calculated as the average of the re-weighted integrated local threat from RARR, and combined individual local threats (aquaculture and sand mining), normalised on a 0-1 scale.	N/A

	Coral reefs	Seagrass meadows	Mangroves
	Coral diversity *(Number of zooxanthellate coral species by ecoregion from* Veron et al. (2016) • Ecoregion boundaries digitized manually in ArcGIS • Species counts ("Total species number") obtained from the Ecoregion Factsheets • Converted from polygon to raster in ArcGIS at 0.05dd resolution and masked to our coral reef pixels • Normalised on a scale of 0 (= 0 species) to 1 (= 545 species, max for the PIC), i.e. normalised by dividing by the max number of species.	N/A	N/A
	Sensitivity – Final Layer • Sensitivity was calculated from the normalised input layers as follows: Number of events ≥ 8 DHWs 1985-2020 minus (-) coral diversity minus (-) coral condition proxy index • Raw sensitivity was re-normalised on a scale from 0 to 1.	**Sensitivity – Final Layer** Details needed	**N/A**
Potential Impacts	**Potential Impacts = Exposure x Sensitivity** Potential impacts calculated by multiplying the normalised exposure and sensitivity layers, then renormalizing on a scale from 0 to 1.		
Adaptive Capacity	**Anthropogenic threats** • Integrated local threat from Reefs at Risk Revisited (Burke et al. 2012) was resampled to 0.05 dd resolution and normalised by dividing by the maximum value. • Spatial data on individual local threats was converted to a binary raster layer of resolution 0.05dd (i.e. 1=presence, 0 = absence): fishing grounds, shipping lanes, destructive fishing, aquaculture, and sand mining. These layers were averaged and normalised to a maximum value of 1 by dividing by the largest value. • Anthropogenic threat was calculated as the average of integrated local threat from RARR, combined individual local threats, and human population within 100km of reef pixels, normalised on a 0-1 scale.	**Anthropogenic threats** • Integrated local threat from Reefs at Risk Revisited (Burke et al. 2012) was resampled to 0.05 dd resolution and normalised by dividing by the maximum value.	**Species richness** • Data from Marine Plants of the World global database (originally published in Jenkins, C.N. and Van Houtan, K. 2016)
	Water quality *(WQ index combined the annual average 2019 surface chlorophyll-a concentration and the land-derived sediment layer from Reefs at Risk Revisited)*	**Recovery potential** • Nearby sources of seagrass as sources of seed, based on the sum of pixel presence in the 8 surrounding pixels	N/A

	Coral reefs	Seagrass meadows	Mangroves
	• 2019 chlorophyll-a concentration was the average of the four seasonal chlorophyll-a rasters: north-east monsoon, southeast monsoon, transition 1, and transition 2 • 2019 annual average chl-a was normalised by dividing by the maximum value • The "watershed-based pollution" layer from Reefs at Risk Revisited was resampled to 0.05dd and normalised by dividing by the maximum value. • Our WQ index was the average of these two layers, normalised by dividing by the maximum value.		
	Marine Protected Areas (*Currently designated MPAs as provided to the project team)* • Existing MPAs were converted from polygon to 0.05 dd raster in ArcGIS using "cell centre" as the cell assignment type. For the MPAs the pixel has to be mostly MPA for it to be considered an MPA pixel • The MPA layer was normalised to 1 or 0 based on the presence or absence of protection within the pixel.	**Marine Protected Areas** (*Currently designated MPAs)* • Existing MPAs were converted from polygon to 0.05 dd raster in ArcGIS using "cell centre" as the cell assignment type. MPAs = no MPA (0), designated MPA (0.5), no-take MPA (1). • The MPA layer was normalised to 1 or 0 based on the presence or absence of protection within the pixel.	**Marine Protected Areas** (*Currently designated MPAs)* • Existing MPAs were converted from polygon to 0.05 dd raster in ArcGIS using "cell centre" as the cell assignment type. MPAs = no MPA (0), designated MPA (0.5), no-take MPA (1). • The MPA layer was normalised to 1 or 0 based on the presence or absence of protection within the pixel.
	Adaptive Capacity – Final Layer • Adaptive capacity was calculated from the normalised input layers as follows: Marine Protected Areas minus (-) anthropogenic threat minus (-) water quality. • Raw adaptive capacity was re-normalised on a scale from 0 to 1.	**Adaptive Capacity – Final Layer** • Adaptive capacity was calculated from the normalised input layers as follows: Recovery Potential plus (+) Marine Protected Areas minus (-) anthropogenic (integrated) local threat. • Raw adaptive capacity was re-normalised on a scale from 0 to 1.	**Adaptive Capacity – Final Layer** • Adaptive capacity was calculated from the normalised input layers as follows: species diversity plus (+) protected areas from WDPA plus (+) integrated local threat from Reefs at Risk Revisited

B2. Coastal Fisheries Vulnerability Assessment

Changes in biomass – Modelling overview

We selected six different marine ecosystem models from FishMIP, which vary in complexity and in the equations used to capture the impacts of environmental change on marine biomass (Titterson et al., 2018, Heneghan et al., 2021). These models were forced with environmental data from two earth system models, GFDL-ESM4.1 (Dunne et al., 2020) and IPSL-CM6A-LR (Boucher et al., 2020), which represent the coolest and warmest model, thereby capturing the entire range of temperature estimates in CMIP6 models (Tittensor et al., 2021, Blanchard et al. 2024). The FishMIP models considered historical data, and projections for two emission scenarios: SSP1-2.6 (high mitigation, low emissions) and SSP5-8.5 (no mitigation, high emissions) (Tittensor et al., 2021). A short description of the six FishMIP models included in our ensemble is included below:

APECOSM: Apex Predators ECOSystem Model, which represents the spatialized dynamics of open ocean pelagic ecosystems in the global ocean.

BOATS: BiOeconomic mArine Trophic Size-spectrum model simulates the global fishery as a coupled ecological-economic system.

DBPM: The Dynamic Benthic Pelagic Model is a dynamic size spectrum model for modelling the coupling of “pelagic” size-based predators and “benthic” detritivores that share an unstructured resource pool (detritus).

EcoTroph: EcoTroph models the functioning of marine ecosystems as flows of biomass from low to high trophic levels, to quantify easily the impacts of fishing at an ecosystem scale.

Macroecological: Macroecological is a static equilibrium model, which uses ecological and metabolic scaling theory to predict mean size composition and abundance of animals (including fish).

ZooMSS: The Zooplankton Model of Size Spectra is a functional size-spectrum model of the marine ecosystem to resolve phytoplankton, nine (9) zooplankton functional groups (heterotrophic flagellates and ciliates, omnivorous and carnivorous copepods, larvaceans, euphausiids, salps, chaetognaths and jellyfish) and three size-based fish groups.

The reported biomass under an intermediate emissions scenario (SSP2-4.5) was not available in any of the FishMIP models. Therefore, we derived biomass estimates for the intermediate scenario based on the two available scenarios in the FishMIP models (SSP1-2.6 and SSP5-8.5). A detailed description of how we calculated this is provided below.

Given the differences across FishMIP models, we do not report biomass values obtained from each model, instead we calculated the percentage change in biomass from a reference period (2010-2020). We also used individual models to calculate an ensemble mean percentage change. We chose to use an ensemble because it is a common technique used to improve the accuracy of model predictions (Araujo and New, 2007). We consider the use of ecosystem model ensembles forced by climate models to estimate changes in fish biomass to be a significant improvement on the 2011 assessment as it represents a less subjective analysis approach that also provides quantitative estimation of uncertainty in projections. Additionally, we calculated the standard deviation across models to report it as a measure of model uncertainty.

Changes in biomass from the model ensemble are reported separately for the 22 Pacific island countries and territories, and are intended to give an indication of the likely impact of a

changing climate on fish biomass under two different scenarios (SSP2-4.5 and SSP5-8.5). Finally, we applied a correction to mean ensemble biomass estimates to better capture the relationships between coral cover, structural complexity, and fish biomass, and using regional data to maximise the likelihood that the outputs from the global models best reflected the Pacific region. A detailed description of the correction applied is provided below.

The workflow described here was implemented in R and it is publicly available in GitHub: https://github.com/Fish-MIP/Extract_PICTs/blob/main/Scripts/04_Biomass_projections_SouthPacific.md. The following sections provide a summary of the modelling approach in the GitHub workflow.

FishMIP ensemble biomass correction

1. *Biomass projections using coral cover relationships*

Since we were using global models to predict changes, we acknowledged that there may be greater uncertainty when applying projections of biomass for the Pacific region. Further, several relationships between coral cover, structural complexity and fish biomass have been established in the literature. Graham and Nash (2013) was selected as a reference because it is the only available downscaled modelling of changes in coral cover under different climate change scenarios for the Pacific region. By applying these corrections to biomass estimates from FishMIP models we expect to improve biomass estimates as we would better capture the relationships between coral cover, structural complexity, and fish biomass. Essentially, we used outputs from regional scale models forced with downscaled oceanographic products to determine the bias in global projections so a correction factor could be determined for application to the PIC ensemble products. We used relationships calculated from data from Graham and Nash (2013) and REEFMOD (Mumby et al. 2007), which describe structural complexity as a function of coral cover (Equation 1), and fish biomass as a function of coral cover (Equations 2, 3 and 4), respectively:

Equation 1 (from Graham & Nash 2013):

$$struct_{complexity} = 3e^{-7} \times coral_{cover}^{4} - 5e^{-5} \times coral_{cover}^{3} + 0.0022 \times coral_{cover}^{2} + 1.3892$$

Equation 2: *REEFMOD lower bound*

$$fish_{biomass} = 12.716 \times coral_{cover} + 146.75$$

Equation 3: *REEFMOD median*

$$fish_{biomass} = 13.56 \times coral_{cover} + 732.15$$

Equation 4: *REEFMOD upper bound*

$$fish_{biomass} = 14.285 \times coral_{cover} + 1325.7$$

Applying these relationships, we incorporated outputs from REEFMOD which predicted mean coral coverage from 2024 to 2100 for the Great Barrier Reef (GBR) under five emissions scenarios: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.

2. *Estimating biases from REEFMOD data*

For scenarios SSP1-2.6 and SSP5-8.5, we divided the yearly FishMIP model ensemble estimates for the GBR only by the yearly biomass estimates calculated from REEFMOD (step 1). We used the result of this division as an indication of bias in the FishMIP ensemble.

However, instead of applying a unique correction for each year in our dataset and potentially introduce more uncertainty to the FishMIP biomass estimates, we averaged the yearly bias across emission scenarios available in FishMIP models (SSP1-2.6 and SSP5-8.5). The average bias per scenario was then used to correct FishMIP ensemble biomass estimates for each PIC. The correction was implemented by simply multiplying the mean scenario bias to the FishMIP ensemble biomass estimates.

Estimating FishMIP biomass for SSP2-4.5

FishMIP models provide biomass estimates under a low emission (SSP1-2.6) and a high emission (SSP5-8.5) scenario. Currently, no FishMIP model provides biomass estimates under the intermediate emissions scenario (SSP2-4.5) which is one of the scenarios presented in this assessment.

We derived a rough estimate of biomass under SSP2-4.5 by calculating the mean biomass under the low (SSP1-2.6) and high (SSP5-8.5) emissions scenarios. We justify the use of this approach based on assessment of REEFMOD data, which includes estimates of coral cover under the three scenarios of interest: SSP1-2.6, SSP2-4.5, and SSP5-8.5. We compared the coral cover estimates from REEFMOD for the three scenarios of interest, as well as the averaged coral cover under SSP1-2.6 and SSP5-8.5 (Figure S1).

Although this approach is simple, it resulted in FishMIP biomass estimates that more closely resembled the patterns seen in REEFMOD data. We attempted to apply bias corrections following the procedure described in the previous section, however the resulting biomass estimates for SSP2-4.5 appeared to be unlikely as they did not resemble the patterns seen in the REEFMOD data and any improvement required applying nonlinear corrections through time. Given all the other uncertainties in the simple approximations being made for the assessment, it was felt this was an unjustified additional step and that use of a simpler mean was advisable at this time. We should note that this approach is not perfect, and before 2060 the averaged values tend to underestimate coral cover, while after 2060 coral cover is overestimated, particularly after 2085 (Figure S1). However, despite these biases, we expect similar biases will appear in biomass estimates, which will not impact the percentage change calculations of biomass.

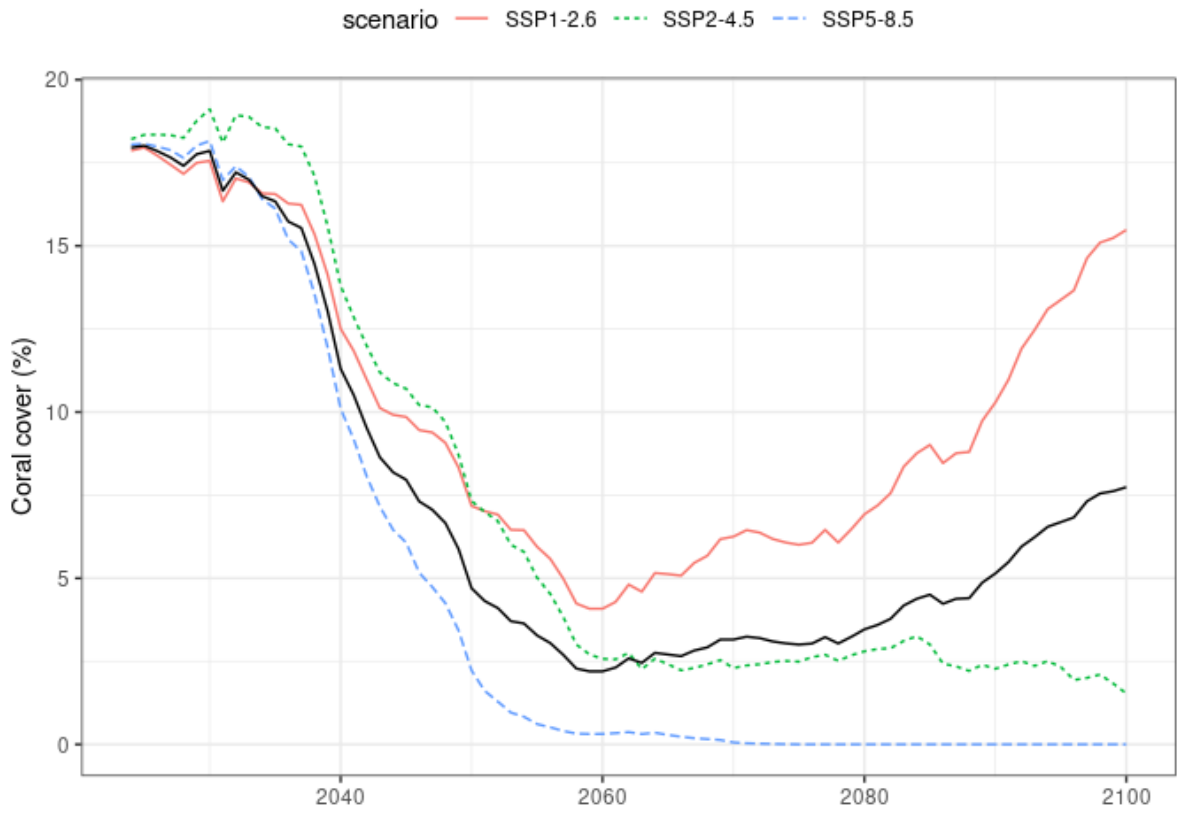

Figure S1. Predicted coral cover from the ReefMod GBR project for a low (SSP1-2.6, red line), medium (SSP2-4.5, green dashed line) and high (SSP5-8.5, blue dashed line) emissions scenario. The black line represents averaged coral cover for the high and low scenarios.

Calculating yearly relative change from FishMIP biomass estimates

Finally, FishMIP biomass estimates for each PIC were used to calculate annual percentage change in biomass relative to the reference period 2010-2020[13].

Estimating changes in catch

We assessed the projected impacts of climate change on coastal fisheries using a similar approach to the 2011 assessment that combines the effects of both direct and indirect impacts on fish. That is, we used the projected changes in available fish biomass (direct effects) and combined this with the projected changes in habitat area (indirect effects) to derive projected changes in catch levels for each PIC. Projected changes in catch were based on the latest (2021) catch estimates derived for each PIC by Gillett and Fong (2023). To estimate catch for the different island groups in Kiribati we used the latest population estimates from the 2020 national census and simply partitioned catch based on the per capita amount. The estimated populations in 2020 for each island group were: Gilbert Island group – 108,145, Line Island group – 11,252, and Phoenix Island group – 41 (Ministry of Finance, 2021).

[13] Similar recent modelling studies have used variable but usually earlier reference periods generally resulting in higher projected declines, e.g. Cheung et al. 2010, Asch et al. 2018, Lam et al. 2020.

Projected catches for each PIC were estimated by:

1. Dividing the current estimated coastal fisheries catch (tonnes; Gillett and Fong, 2023) with the current estimated habitat area (km2; see habitat section above and Equation 1) to derive an estimate of current yield (catch per area of habitat; tonnes/km^2/year). While the 2011 assessment only incorporated coral reefs for their use of habitat area, we used the combined area of coral reef and seagrass meadows habitats. These two habitat types better capture the full area used by all life history stages of coastal finfish and invertebrates (Sambrook et al. 2019). A notable exception was PNG, where we also included mangrove area where it accounts for ~16% of the three main habitats by area; mangrove habitat area in all other PIC was significantly lower (<=6%) and therefore not included. We therefore assumed that projected changes in either habitat would affect coastal fish.

2. For each of the future climate scenarios we applied the average of relative change (%) in fish biomass (2026 and 2035 for 2030; 2046 and 2055 for 2050) to the current (2021) yield to estimate the projected yield.

3. The projected catch (tonnes) was estimated by multiplying the projected yield (current yield x project ted change in exploitable biomass) with the projected habitat area. This was expressed as the projected catch and the projected change (%) in catch (Equation 2).

$$Equation\ 1: Current\ yield = \frac{Current\ catch}{Habitat\ area}$$

$$Equation\ 2: Projected\ catch = (Current\ yield\ x\ Projected\ change\ in\ exploitable\ biomass)\ x\ Projected\ habitat\ area$$

B3. Food Security Assessment

Table B3. *Access dimension of food security. Explanation of indicators, assumptions, and uncertainties.*

Criteria	Explanation	Assumptions	Uncertainties	Data Source
Percent of population in urban conditions (2014/2030/2050)	*Accessibility:* While the fisheries analysis accounted for overall population and projected population growth (which determines how much fish is available per person), the population indicator used in that analysis assumes equal distribution or equal access. The % urban population is intended to give an indication of the population's accessibility to coastal resources.	Urban populations are likely to have: • less access to be able to fish for subsistence and higher dependence on purchasing fish; • higher pressure on resource base; • higher competition for resources; • reduced quality of nearby marine resources resulting from over-exploitation and urban pollution. Rural populations are likely to have: less competition for and more access to better quality marine resource to meet food security needs.	Particularly for the 2030 and 2050 scenarios, unknown factors might result in significant variation from the estimated urban migration rates, rural to urban population ratios, and other population trends used.	Percent of urban population was determined as the percentage of combined rural and urban population. 2014 is used as the baseline year for consistency with the fisheries analysis. Nauru reads as 100% because the dwarf country has is the most densely populated country in the Oceania with 593 inhabitants per km² (World Data, 2023). Data drawn from United Nations, Department of Economic and Social Affairs, Population Division (2018). World Urbanization Prospects: The 2018 Revision, custom data acquired via website.
Alternative food access: GDP per capita	*Adaptive capacity*: Building on considerations discussed by Bell et al (2011) associating income with ability to buy alternative food resources, this criteria gives an indication of the capacity of the population to adapt to emerging	Countries with high GDPs are likely to not have a subsistence-based economy, increasing the likelihood that people are purchasing (potentially imported) food rather than relying on local fisheries for protein. Recent economic trends and the resources they	High uncertainty of long-range economic projections. Lacks texture on how GDP is actually distributed to across the population, potentially camouflaging sectors of the population that are dependent on local fisheries.	Given the high uncertainty of long-range economic projections, a constant value for each country, drawn from most recent complete data set (2018), is also used for 2030 and 2050. 2019 is available for all PIC in study except for the

	conditions and meet nutritional requirements through other means.	depend on will be consistent despite uncertainties. It is assumed that the GDP is spread equally across the population and that those that need funds to purchase food have access to an income source.	Many PIC show a significant drop in GDP in 2020 and 2021 (usually after a general upward trend in recent years). This change coincides with the COVID-19 crisis.	Federated states of Micronesia. Scoring criteria developed relative to the data set by identifying average, low and high values according to for a relative comparison respecting the characteristics of the region. The average GDP of data set is 6741 USD. Data drawn from Pacific Data Hub (2023)
Alternative food access: Projected Economic Growth	*Adaptive capacity*: Building on considerations discussed by Bell et al (2011) associating income with ability to buy alternative food resources, this criteria gives an indication of the capacity of the population to adapt to emerging conditions and meet nutritional requirements through other means.	Countries with high Projected Economic Growth are more likely to continually move away from a subsistence-based economy, with increasing ability to purchase (potentially imported) food rather than relying on local fisheries for protein. Recent economic trends and the resources they depend on will be consistent despite uncertainties. Economic growth is likely to be consistent with pre-COVID-19 trends.	High uncertainty of long-range economic projections. Lacks texture on who is benefiting from economic growth, the source of growth, and whether the approach to growth is negatively impacting fisheries or other key natural resources. The exceptional impact of COVID-19 on economic growth trends and projections for recovery and change	Given the high uncertainty of long-range economic projections, projected growth for 2023 is used as a constant value for each country. Scoring criteria developed according to IMF projected global growth for 2023 of 2.9% (IMF, 2023). Data drawn from Asian Development Bank (2023)
Alternative food access: Available arable land per person	*Adaptive capacity*: This indicator gives an indication of the capacity of the population to adapt to emerging conditions and meet nutritional requirements through other	A greater area of available arable land per person creates the opportunity to undertake agricultural activities to access food sources that are not marine based.	Factors that will determine if arable land will actually be used Impacts of climate change on agricultural production Market pressures directing local production for	Scoring criteria developed according to the world average of .18. (World Bank, 2023) Data drawn from World Bank (2023)

	primary production means.	This increases the adaptive capacity. Farming of arable land is assumed possible and the most desirable alternative use, instead of leaving land as natural areas Suitability of climate for chosen agricultural approach. Arable land is considered stable and not increasing with population pressure or decreasing with land development.	export (benefiting non-local populations) The availability of arable land is likely to decrease with population growth. This is not accounted for in the analysis.	
Island structure (dispersed atolls vs larger and closely clustered or single central islands)	*Accessibility:* While the fisheries analysis accounted for overall population and projected population growth (which determines how much fish is available per person), the population indicator used in that analysis assumes equal distribution or equal access. The island structure indicator is intended to add texture regarding the population's accessibility to coastal resources.	Small-land mass limits population, while increasing the ration between people and reef area. Reef area is productive.	Actual reef area, condition, and productivity per capita. Access to reef by population.	A constant value, determined by geographic characteristics, is used across all years. Island structure is determined by a visual analysis using Google Maps (used instead of Google Earth because all prominent islands within a country clearly marked) and corroborated with additional on-line research.

Appendix D Uncertainty, assumptions and limitations, and knowledge gaps

Caveats, assumptions and uncertainties

Although we consider that the analyses we conducted uses the most recent data, knowledge and state-of the-art modelling approaches, certain assumptions are necessary and inherent uncertainties in the outputs are unavoidable. Brander (2015) discusses the compounding effects of multiple layers of uncertainty and the importance of accurately acknowledging these in climate change studies. For our analyses, there are several inputs obtained from different sources, each with their own biases and error. A significant improvement to the 2011 assessment is the quantitative characterisation of much (not all) of the uncertainty. Below are the major caveats, assumptions and uncertainties we are aware of in our analyses.

1. Our assessment does not include conventional species taken in Pacific oceanic fisheries (principally open-water tuna, sharks and billfish). This was done to minimise overlap with the assessment of oceanic fisheries (Component B of Study 1), and to focus on the predominant species taken by coastal communities.

2. Ecosystem models don't discriminate species groups as done with the 2011 assessment (i.e. demersal fish, nearshore pelagic fish, and invertebrates). While ecosystem models do include all species, to ensure projections were based only on coastal species targeted by Pacific fisheries we used a size-based filter for exploitable biomass that only included animals from 10 g – 10 kg. This ensured the inclusion of small invertebrates collected for food and a review of recent SPC market and creel survey data from PIC coastal fisheries catches indicated that a maximum size of 10 kg was likely to include ~99.99% of coastal fish. Further, this upper size limit ensured that any inclusion of species associated with oceanic fisheries was minimised.

3. Catch estimates for each PIC are taken from Gillett and Fong (2023) who reviewed all available data to derive these estimates, which we used to estimate future catches under the different climate change scenarios. The authors discuss extensively the issues with the data sources used to derive these catch estimates, highlighting the different methodologies used within and among the different PIC, as well as differences in how the methods were applied. Ultimately the uncertainty in catch data is considered high as well as being highly variable among PIC. For example, national estimates of coastal fisheries production are often based largely on extrapolation of fish consumption per person derived from household income and expenditure surveys (HIES).

4. Estimates of projected catch assume a linear relationship between projected changes in biomass and catchability. Although possible, based on surplus production theory, this assumption is unlikely (Beverton and Holt, 1957). Projected changes in future catches also assumes that the effort and catch-per-unit-effort (CPUE) characteristics of coastal fisheries in each PIC that generate current catch levels are maintained to 2050.

5. Current catch estimates are used in conjunction with current habitat area to estimate current yield for each PIC, which in turn is used to estimate future catches by taking into account projected relative changes in biomass and projected changes in habitat area. It should be noted that estimated projected changes in habitat area is not estimated directly, rather it was assumed to be correlated to the percentage of each coastal habitat type (coral reef and seagrass) in the high and very high vulnerability categories under the different emissions scenarios. That is, for a given scenario the future total area of seagrass habitat was projected to decline by the total percentage of seagrass area assessed as having very high and high

vulnerability to climate change. The same was applied separately to coral reefs. The total projected habitat area inputted to the analysis for estimating projected catch combined the future area of both coral reef and seagrass habitats, after climate-driven declines in area. This assumption has not been tested.

6. The habitat assessment included the three major coastal habitats that are most important for coastal finfish and invertebrate species: coral reefs, seagrass meadows and mangrove forests. Changes in habitat area was an important component of the analysis to derive projections of future coastal fisheries catches in each PIC. While the 2011 assessment also used this approach, they only incorporated coral reef habitats. During the current assessment we have combined the area of coral reef and seagrass meadows to capture available habitat area in 2050. Seagrass meadows are often associated with reef flats, a sub-habitat type that is used extensively by coastal fish and invertebrates and may otherwise be under-represented. Therefore, we determined that these two habitat types better capture the full area used by all life history stages of coastal finfish and invertebrates, particularly the juvenile stage. A notable exception was PNG, where we also included mangrove area where it accounts for ~16% of the three main habitats by area; mangrove habitat area in all other PIC was significantly lower (<=6%) and therefore not included.

Appendix E OECD Food Security Dimensions

Table D1. *OECD determinants and food security dimensions*

Dimension	Determinant	How determinant is considered in this study	Section
Availability	Domestic production	Consumption rate versus availability determined by catch rates	Section 3 and Section 4.5
	Import capacity	Not considered applicable for primarily subsistence-based population	
	Food Stocks	Consumption rate versus availability determined by catch rates	Section 3 and Section 4.5
	Food Aid	Not considered applicable to the purposes of this study	
Access	Income and purchasing power	Alternative food access: GDP per Capita; Alternative food access: projected economic growth	Section 4.7
	Transport and market infrastructure	Deeper level of analysis recommended; initial analysis based on island structure and distribution of islands assuming lower population density and increased access to fisheries areas are similar to transport and market infrastructure for a primarily subsistence-based population.	Section 4.7
	Food distribution	Percent of population in urban conditions Deeper level of analysis recommended; initial analysis based on percentage of urban population in urban conditions, assuming urban population have decreased direct access to productive fisheries areas.	Section 4.7
Utilisation	Food Safety and Quality	Not considered applicable to the purposes of this study	
	Health and Sanitation	Not considered applicable to the purposes of this study	
	Diet Quality and Diversity	Not considered applicable to the purposes of this study	
Stability	Weather Variability	Climate change projections	Section 3
	Price Fluctuations	Not considered applicable to the purposes of this study	
	Political Stability	Not considered applicable to the purposes of this study	
	Economic Factors	Not considered applicable to the purposes of this study	
	Ecological Factors	Not considered applicable to the purposes of this study	

Adapted from OECD (n.d).